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Water Supply
and Pollution Control

Symposium on

STREAMFLOW REGULATION FOR QUALITY CONTROL

U.S. DEPARTMENT OF HEALTH,
EDUCATION, AND WELFARE
Public Health Service

SYMPOSIUM ON

STREAMFLOW REGULATION FOR QUALITY CONTROL

Sponsored by the
Technical Services Branch
and
Basic and Applied Sciences Branch
of the
Division of Water Supply and Pollution Control
April 3-5, 1963

Chairman
JOHN E. MCLEAN
Chief, Water Resources Unit
Technical Services Branch, DWS&PC

ROBERT A. TAFT SANITARY ENGINEERING CENTER
Cincinnati, Ohio

U. S. DEPARTMENT OF HEALTH
EDUCATION, AND WELFARE
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The ENVIRONMENTAL HEALTH SERIES of reports was established to report the results of scientific and engineering studies of man's environment: The community, whether urban, suburban, or rural, where he lives, works, and plays; the air, water, and earth he uses and re-uses; and the wastes he produces and must dispose of in a way that preserves these natural resources. This SERIES of reports provides for professional users a central source of information on the intramural research activities of Divisions and Centers within the Public Health Service, and on their cooperative activities with state and local agencies, research institutions, and industrial organizations. The general subject area of each report is indicated by the two letters that appear in the publication number; the indicators are

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PREFACE

The 1961 amendment to the Federal Water Pollution Control Act authorizing the inclusion of storage for water quality control as a feature in multi-purpose reservoir evaluation greatly increased the need for techniques for evaluating the beneficial and adverse effects of streamflow regulation. Particularly important are the effects of storage on reservoir and downstream water quality, thermal stratification, peaking power generation, and consumptive uses of water.

This Symposium on Streamflow Regulation for Quality Control was prompted by observations of low-quality water in the discharge from several projects studied by the Technical Services Branch of the Public Health Service, by similar observations of projects reported by others, and by the interest this has generated in the development of measures to correct these conditions. The Public Health Service has initiated both intramural and extramural studies in this field. The Basic and Applied Sciences Branch is undertaking studies on the effects of streamflow regulation on water quality, which include in the initial phases quality changes in storage reservoirs and the waste contributions of urban and rural runoff. The Research and Training Grants Branch is financing research, training, demonstration, and fellowship grants, the results of which will contribute toward solution of problems in the streamflow regulation field.

The consideration of quality changes is only part of the story, however. Economic implications, which are equally important, are not emphasized in this Symposium as the economics of quality control could be the subject of another symposium of equal importance.

The purpose of this Symposium was to bring together engineers, scientists, and administrators from various levels and agencies of government, from industry, and from universities to:

1. Facilitate exchange of information on the effects of streamflow regulation on water quality,
2. Review available knowledge on the effects of streamflow regulation on water quality,
3. Discuss studies presently in progress on quality control problems associated with streamflow regulation, and
4. Explore research needs in the field of streamflow regulation for quality control.

To obtain a degree of informality and facilitate the exchange of information, preprints of many of the papers were distributed to registrants in advance of the Symposium. The technical papers were presented, discussed by one or more reviewers, and then opened to floor discussion. Discussions were recorded for inclusion in this volume.

The papers and discussions in this volume were prepared for oral delivery in the Symposium and necessarily have been edited to meet publication standards of the Public Health Service. Every effort has been made to present accurately the full data and the original views and meaning intended by the authors. The papers that follow may therefore differ slightly from the preprints made available to Symposium participants. Floor discussions have been edited to standards for written presentation by technical reviewers. Publication of the papers by the Public Health Service is not meant to imply endorsement of the conclusions, or of any commercial products that may be mentioned.

John E. McLean
Program Chairman

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WELCOME

Joseph E. Flanagan, Jr.*
Acting Director, Robert A. Taft Sanitary Engineering Center
U. S. Public Health Service, Cincinnati, Ohio

One of the advantages of appearing on a program like this is that the Program Chairman just says,"Come on down and greet the group and make them welcome." I am always happy to do this. I do not have to prepare a speech, and I am not limited in what I may say. It's a very fine position to be in. I don't stand here to substitute for the Mayor, but I would like to use his usual phrase and simply say to all of you, and particularly those of you who have not been to Cincinnati before, "Welcome to the Queen City." It's a very nice town.

I have been struck by what has happened in the field of symposia since I came to Cincinnati eight and a half years ago. Then, they were held in the auditorium at the main building of the Center. It could seat 150 people and sometimes it wasn't even filled. The subjects were usually quite circumspect. Generally a particular part of a branch had a problem, and it was decided that it might be helpful to both the Service and to some of the outside folks to bring a few technical people together to talk about it, and, hopefully, to come up with a solution. If we were particularly successful in solving a problem, it would show up in one of our training courses, whether it was water pollution, air pollution, radiological health, or something else.

That time has long since passed, and it is interesting that it passed without any pushing on the part of administrative people at the Center or, as far as I know, on the part of administrative people in Washington. I think the group assembled for this Symposium on Streamflow Regulation for Quality Control is a fine example of the tremendous interest on the part of individuals in many different government agencies, in educational institutions, and in private organizations, in the subjects presented. Nobody seems to come unless he is particularly interested in the subject, and I think that the Public Health Service gets a great deal from these meetings. I also like to think the other agencies and individuals who participate get a great deal out of them, too.

Another thing that is happening, in addition to the growth in numbers of people who attend symposia like this is that the subjects are getting more complicated. It would seem that symposia are chosen in proportion to the difficulty of the particular problem. We will talk about streamflow regulation for quality control for three days. This no longer concerns only one of the branches in our water program, it concerns all three of them. It also concerns others besides the Public Health Service.

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*Now Associate Director, Department of Environmental Health, American Medical Association, Chicago.

The next symposium scheduled to be held in Cincinnati is not limited to one program of the Public Health Service. It is of interest to me that it is jointly sponsored by a branch of the Water Supply and Water Pollution Control Division and a branch of the Air Pollution Division. It wouldn't surprise me if some other divisions were also involved in it, too.

I thought you would be interested in what is happening, and that it is happening in spite of administration lines. The technical people see these problems, get their heads together, and, regardless of their particular program, get together and discuss it. As far as I am concerned, this is all to the good. I would estimate that in another 10 or 15 years we are going to see symposia that will stretch across very broad segments of the fields we now refer to as environmental health. And when that day comes, I am sure the Water Division of the Public Health Service will be one of the most important segments in this broad activity.

The Water Pollution Control Advisory Board is also meeting in Cincinnati this week and is attending this session of the Symposium. Mr. James M. Quigley, Assistant Secretary of the Department of Health, Education, and Welfare is with us and will describe the Board and its activities.

Frank E. DeMartini
Chief, Technical Advisory and Investigations Section
Division of Water Supply and Pollution Control, USPHS
Robert A. Taft Sanitary Engineering Center, Cincinnati

Dr. Weinberger and I are shown on the program as part of the welcoming group. Our comments, however, are primarily intended to set a background for the meeting. I want to add to Mr. Flanagan's welcome. Speaking for the Technical Services Branch, which is one of the co-sponsors of the meeting, we are very pleased to see this tremendous turnout and hope when these 3 days are over you will all feel that it has been very worthwhile to have participated. We in the Service believe we are going to gain a good deal from the papers and discussions presented.

As to the purposes and objectives of the Symposium, they are given in your program. Our objective was to bring together engineers, scientists, and administrators from agencies of government, from industry, universities, private institutions, and organizations to discuss flow regulation for quality control. We planned the program so that time would be available after each presentation not only for a formal, prepared discussion, but also for contributions and participation by those who are in attendance. I think this is one of the chief values that will come from this meeting. We urge your participation.

Another bit of background that should be mentioned is the Federal Water Pollution Control Act. Recent amendents provide that in the survey or planning of any reservoir by a Federal agency, consideration shall be given to the inclusion of storage for the purpose of flow regulation for quality control, but that such storage is not intended to be provided as a substitute for adequate treatment or other means of control of wastes at their source. The need for and the value of such storage is to be determined by the construction agencies with the advice of the Secretary of the Department of Health, Education, and Welfare, and his views are required to be included in any report submitted to Congress proposing authorization for construction of any reservoir that includes such storage.

Within the Public Health Service, the Division of Water Supply and Pollution Control is responsible for evaluating these needs. The Technical Services Branch of the Division directs the Regional Offices, the Comprehensive Water Pollution Control Projects, and the Technical Advisory and Investigation Section, located at Cincinnati, in these endeavors.

In making these evaluations, the various subjects to be discussed in the next 3 days that may be pertinent to the particular reservoir undertaking are considered, and the best engineering estimates possible are arrived at as to the effects of the proposed reservoir project on water quality. Based upon the reservoir, the downstream uses, the effects of wastes reaching the waters, the treatment that can be provided, the operating schedule of the reservoir, and other pertinent factors, the need for storage and its value for quality control are determined.

These engineering estimates can be improved as we gain more adequate knowledge in many areas. Gaps in our knowledge point up the need for research and field studies. I have listed a few of the areas that are worthy of further consideration:

1. The accounting for all wastes that reach our streams. We need to know more about land drainage, urban run-off, chemical poisons, pesticides, and weedicides that reach our waters.

2. The pollutional characteristics of new wastes. We must know more about new types of wastes, many of which are the result of the technological development taking place.

3. The treatment or control of persistent undesirable wastes that are not easily oxidized.

4. The effects of recreational use of waters.

5. The control of siltation. Silt from highway construction, timber harvesting, and land clearing for urban development is a serious threat to streams and to reservoirs, and means of control are needed.

6. The fate of radioactive materials in water.

7. The effects of impoundments on the assimilation of organic wastes, deoxygenation and reaeration, bacteriological changes, patterns of biological life, and temperature changes. A great need for more pre- and post-impoundment studies exists to develop a better basis for quantitatively predicting water quality in reservoirs as it affects the uses of water for various purposes including residual waste disposal.

This mention of some of the problem areas indicates there is still much we need to know about and do. Many interests can contribute in arriving at answers and in fortifying our positions in these areas. Among them are Federal, State, and interstate agencies, universities, private research institutions, and industry.

Dr. Weinberger will give you a brief resume of the work the Public Health Service is doing in these areas, both directly and indirectly by way of contracts and other arrangements. During the 3 days of the Symposium we will be hearing what many others are doing, which will focus attention on many of these problem areas.

I believe we have very high caliber participants; in addition, the enthusiastic response to the Program Committee's invitations to present papers augers well for a very productive meeting. It is certain that significant contributions will come from the sessions of the next 3 days, and that problems for future emphasis will evolve during the discussions.

Dr. Leon W. Weinberger
Chief, Basic and Applied Sciences Branch
Division of Water Supply and Pollution Control, USPHS
Robert A. Taft Sanitary Engineering Center, Cincinnati

It is usually not very difficult to welcome a group and normally I would have felt quite at ease in carrying out this function. You will note, however, that not one, not two, not even three, but four people have already welcomed you. What am I supposed to do? My conclusion is that the Program Committee had some doubts about the meeting starting on time and I am to fill in, if necessary, with a lengthy presentation until we have a quorum.

Since we are gathered I will keep my remarks short.

The function of the Basic and Applied Sciences Branch as the research arm of the Division of Water Supply and Pollution Control is outlined on the front cover page of the program. It indicates that we undertake intramural and extramural studies and research on the effects of streamflow regulation as part of our program.

I would like to expand upon the extramural part of the program. Our program of research grants and contracts has evolved because

of a realization that if we are to accomplish the research goals we have in mind, it must be in cooperation with and through the efforts of all other interested and competent people in this field. So our extramural research grants and contracts in cooperation with other Federal, State, and interstate agencies, universities, research institutions, industries, and individuals, are an essential part of our research program.

INTRODUCTION OF THE WATER POLLUTION CONTROL ADVISORY BOARD

James M. Quigley
Assistant Secretary
Department of Health, Education, and Welfare, Washington, D. C.

I am here in the capacity of Chairman of the Federal Water Pollution Control Advisory Board. I am sure you are all aware that the Federal Water Pollution Control Act provided for the creation of a nine-man advisory board appointed by the President of the United States. The Board serves in an advisory capacity to review, oversee, and comment on the operation of the Federal water pollution control program and to make any suggestions it deems advisable that will improve the operation of the program.

In addition to the nine Board members appointed by the President, the Secretary of the Department of Health, Education, and Welfare has designated me to serve as its Chairman. The Board meets about four times a year. We try to have no more than half our meetings in Washington because we feel that by meeting in other places we accomplish two purposes: First, we educate the Board as to the particular pollution problems of the various areas of the country, which as you know, and as I have learned, vary markedly from one part of the country to the next; and second, we have found from experience that our meetings tend to focus public attention on the water pollution problems of an area. We feel this has served a very constructive and useful purpose. Our presence and our activities help to create an atmosphere in which governors can do more with their legislative bodies; State water pollution control agencies experience a little better cooperation with their appropriation and budgetary officials; and public attention is focused on the need for community action. An example of this was the bond issue in the City of St. Louis where we held hearings some 5 or 6 weeks before the vote was cast. We don't take full credit for the favorable results, but we like to feel that the public attention that was focused on our presence and the Federal government's program helped to make the voters of that city and area much more aware of the problems involved and of their local responsibility — responsibility they faced up to magnificently.

In accordance with this approach, we decided at our December

Board meeting to take advantage of the symposium you are having here and to hold our April meeting in Cincinnati at the same time. In addition to getting a certain exposure to many of the things you are going to discuss, this is an opportunity to show the members of the Advisory Committee the facilities Mr. Flanagan heads at the Taft Sanitary Engineering Center, and generally to get a look at one of the Public Health Service's more important operations in the water pollution control program. So this is why we are here.

The members of the Board are a diversified group, and deliberately so. In making recommendations to the President, the Department tries to put together a group that will be representative of a variety of viewpoints in this very important field. They are diversified as to background, training and experience, geography, and politics. The current members of the Board are:

Mr. John A. Biggs, Director, Department of Game
Olympia, Washington

Dr. Clair S. Boruff, Technical Director
Hiram Walker and Sons
Peoria, Illinois

Mr. Charles H. Callison, Assistant to the President
National Audubon Society
New York, New York

Mr. M. James Gleason,* Commissioner
Multnomah County
Portland, Oregon

Dr. Maurice K. Goddard, Secretary
Pennsylvania Department of Forests and Waters
Harrisburg, Pennsylvania

Mr. Lee Roy Matthias, Executive Vice President
Red River Valley Association
Shreveport, Louisiana

Mr. Tom McCann,* President
McCann Construction Company
Fort Worth, Texas

Mr. Ed E. Reid,* Executive Director
Alabama League of Municipalities
Montgomery, Alabama

Mr. William E. Warne,* Director
California Department of Water Resources
Sacramento, California

In addition to the Board members, Mr. William Towell, Director of State Conservation, State of Missouri, a consultant to the Board, is also present.

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* Not able to attend because of other commitments.

As I have indicated, the purpose of our meeting in Cincinnati, or anywhere, is twofold: (1) to educate the members of the Board, and (2) to educate those who might come in contact with the members of the Board. It is a two-way street. Many of you are here for other purposes, but if you have any suggestions, if you have any ideas as to how the Federal Water Pollution Control Advisory Board might operate more effectively and more efficiently, or any suggestions as to how the Federal Water Pollution Control Act might be changed or extended or amended in a way that you think would make it a better and more effective law to help clean up and purify the waters of this country in the manner and in the time in which we have to do this assignment, we would be very happy to hear from you.

Session 1

WHY REGULATE STREAMFLOW FOR QUALITY CONTROL

Moderator: **John E. McLean**
U. S. Public Health Service

It is appropriate at the outset of this symposium to ask: Why regulate streamflow for quality control? At the Federal level there are at least two answers to this question. The first is in terms of technical solutions to water quality problems; the second is in terms of assigned responsibilities under applicable laws. In this session, five agencies having primary responsibilities or activities significantly affecting quality of water and its control by flow regulation will present their parts of the answer under applicable laws. Technical aspects are treated in the remaining sessions.

PUBLIC HEALTH SERVICE RESPONSIBILITIES FOR STREAMFLOW REGULATION FOR QUALITY CONTROL

Dr. Gordon E. McCallum*

Chief, Division of Water Supply and Pollution Control
U. S. Public Health Service, Washington, D. C.

It is easy this morning to assess the importance of this Symposium on Streamflow Regulation. In this group are representatives of the five great Federal agencies that possess major responsibilities in water management, plus administrators, engineers, and scientists from State and local government, from business, and from our universities. I can think of no phase of water resources other than streamflow regulation that in this year of 1963 could bring together so diversified and influential an audience.

There is no reason for surprise in this. For a good many years we have recognized — and recognized rightly — that the two most effective ways of protecting stream quality are by eliminating wastes at their source or, failing that, by removing them from waste waters. Streamflow regulation is a third method of quality control, necessarily subservient to these other two, but a method nonetheless. It is time we knew more about it — knew, in the rather stately words of your program, of its "beneficial and adverse effects."

The particular event in history most responsible for this symposium took place 2 years ago with the passage of the 1961 amendments to the Federal Water Pollution Control Act. Among these were the amendments concerning streamflow regulation, which now appear in the Act as Section 2(b), and are set forth below:

> Section 2.
>
> (b)(1) In the survey or planning of any reservoir by the Corps of Engineers, Bureau of Reclamation, or other Federal agency, consideration shall be given to inclusion of storage for regulation of streamflow for the purpose of water quality control, except that any such storage and water releases shall not be provided as a substitute for adequate treatment or other methods of controlling waste at the source.
>
> (2) The need for and the value of storage for this purpose shall be determined by these agencies, with the advice of the Secretary, and his views on these matters shall be set forth in any report or presentation to the Congress proposing authorization or construction of any reservoir including such storage.
>
> (3) The value of such storage shall be taken into account in determining the economic value of the entire project of which

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* Dr. McCallum's paper was presented by Mr. Robert R. Harris, U. S. Public Health Service.

it is a part, and costs shall be allocated to the purpose of water quality control in a manner which will insure that all project purposes share equitably in the benefits of multiple-purpose construction.

(4) Costs of water quality control features incorporated in any Federal reservoir or other impoundment under the provisions of this Act shall be determined and the beneficiaries identified and if the benefits are widespread or national in scope, the costs of such features shall be nonreimbursable.

The net effect of these amendments was to put the Federal water pollution control program in partnership with the construction agencies in determining the need of water storage for waste dilution. It has had a further effect, however, both in our program in the Public Health Service and in the scientific and research activities of other government and private agencies. It has served to increase scientific interest in the problem of waste dilution, has encouraged many of our ablest students to turn their attention to this area of water management, not only in their work in the laboratory but in the field. This new interest, most obviously, is reflected in this room today.

Neither in concept nor in practice is streamflow regulation new since 1961. My first assignment within the Public Health Service was along the Ohio River, and our 1938-1940 survey took augmented streamflow into consideration, as did some other surveys of an earlier date. But our approach, I am afraid, was somewhat unsophisticated in terms of today's problems and today's knowledge.

One reason for this use was the specialization of our staff. Until recently, water pollution control was a field occupied almost exclusively by attorneys and engineers, the attorneys to prosecute the transgressor and the engineer to build the remedial work. It takes more than this to understand and manage water quality today. We need the skills of many scientific disciplines, including those of the life sciences and the social sciences, and we are beginning to assemble these skills.

In an earlier day, we suffered from this lack of knowledge and also from lack of legislative authority. The first Federal Water Pollution Control Act, as such, was not passed until 1948, and a permanent Federal law was not enacted until 1956. As I said earlier, streamflow regulation for quality control did not appear in the Federal law until 1961.

The legislative development from 1948 until 1961 occurred against a background of increasing national needs, and increasing public discontent with our inability to meet these needs. The National Conference on Water Pollution held in Washington, D.C., in 1960, expressed this new public feeling very well.

"The goal of pollution abatement," the Conference recorded, "is to protect and enhance the capacity of the water resource to serve

the widest possible range of human needs; this goal can be approached only by accepting the positive policy of keeping waters as clean as possible as opposed to the negative policy of attempting to use the full capacity of water for waste assimilation."

The report of the Senate Select Committee on National Water Resources, published in 1961, related this to water storage and streamflow augmentation.

"Along with . . . waste collection and treatment facilities," the Committee reported, ". . . very substantial reservoir storage will have to be provided to supply water for dilution of the effluent from these plants, if the job of cleaning up our rivers is to be done in the most economical way."

The Committee estimated the cost of such reservoir storage to be $12.1 billion by 1980, and $18 billion by the year 2000. This did not include costs of storage needed for other specific purposes, such as flood control, irrigation, and municipal and industrial water supplies. Some of the storage provided for the purposes will, however, undoubtedly assist in the river regulation job the Committee envisioned for pollution abatement.

The Public Health Service responsibilities in streamflow augmentation for quality control tie in very closely with those stemming from the earlier Water Supply Act of 1958, which provided for storage in Federal reservoirs to meet anticipated future municipal or industrial water supply needs. For this purpose and for the streamflow regulation requirement of 1961, we have by now prepared reports for the Federal construction agencies on 125 projects and have 210 others in progress or scheduled.

Importantly interwoven with these forecast-evaluations is the knowledge gained from our National Water Quality Network. This system of 125 sampling stations on interstate watercourses — due for expansion to 300 — is keeping check on the effects of pollution in our streams. The Network is building up a very useful store of basic data in some 15 physical, chemical, and biological parameters in water — such as radioactivity, organic chemicals, coliform organisms, temperature, and others.

These programs are among 15 or so authorized by the Federal Water Pollution Control Act. Every one of them blend into and complement our comprehensive river-basin planning studies in which many of you are involved and cooperating. These are progressing in various stages now in seven major basins, and four others are scheduled for early starts. We hope to complete studies for all United States basins by the year 1975.

In each of these river basin studies, needless to say, the "beneficial and adverse" effects of streamflow regulation are being studied, and in every case our decision-making process is calling for more information and better understanding. Your symposium subject this afternoon, for example, is the "Effects of Impoundments on Water

Quality in Reservoirs." This is paradoxical, when one stops to think about it, for it suggests that in storing water to protect quality, we may also, to some extent, be impairing that quality. Paradoxical or not, these effects must be determined.

There are many questions, but not yet enough answers. This is why the Public Health Service has called this seminar and why, I take it, you have been good enough to come to Cincinnati to attend it. On behalf of the Division of Water Supply and Pollution Control, I welcome you to this meeting and wish you every success in it.

RELATION OF REGULATION FOR QUALITY CONTROL TO ACTIVITIES OF THE CORPS OF ENGINEERS

Eugene W. Weber*

Chief, Civil Works Planning Division
U. S. Army Corps of Engineers, Washington, D. C.

The enactment of Public Law 87-88 on 20 July 1961, less than 2 years ago, has made it possible to give full consideration in the planning and development of the Corps of Engineers' water resources program to provisions for regulation of stream flow for water quality control purposes on a par with all other project purposes. I will outline briefly the import of this new authority on three categories of projects in the Corps' program; i.e., completed projects, those authorized but not yet completed or started, and those being studied for possible future authorization.

COMPLETED PROJECTS

The Corps, in 1962, had in operation 214 reservoir projects containing 169 million acre-feet of storage capacity, primarily for flood control and power purposes, with provisions for recreational use at most and with storage for water supply at some. Needs for flow regulation for water quality control were considered in planning many of these projects, but because of the absence of a positive policy for Federal participation in providing for such regulation, specific measures for quality control were included in relatively few projects, such as Fall River, Toronto, and Kanopolis Reservoirs in Kansas; Berlin and Mosquito Creek Reservoirs in Ohio; Youghiogheny River Reservoir in Pennsylvania; and Tygart Reservoir in West Virginia.

The importance of low flow augmentation has been amply demonstrated by these earlier projects. For example, the operation of Fall River Reservoir, Kansas, in the very severe drought in the 1950's provided vitally needed water supply and dilution of wastes involving six downstream municipalities and also prevented complete shutdown of three refineries and other industries. As another example, the Berlin project, Ohio, was constructed in the early 1940's, at the request of the War Production Board, primarily for low flow regulation in the Mahoning River Basin, to maintain maximum power and steel production in this highly industrialized valley. In view of the continued critical situation with respect to steel production, the method of operation specifically adopted as a war-time measure was continued until 1949, at which time a more balanced method of operation between flood control and low flow regulation was adopted. Some of our very early studies of low flow augmentation, which were carried out in cooperation with the Public Health Service as far back as the

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* Mr. Weber's paper was presented by Col. Robert J. Kasper, U. S. Corps of Engineers.

late 1930's, established the need for the inclusion of regulatory storage in projects only recently undertaken, such as the Allegheny Reservoir above Pittsburgh. During this same early period, the Ohio River Pollution Survey was completed through our joint efforts. This provided a very valuable background not only in the planning of Corps projects but to all other interests concerned with pollution of the Ohio River.

Although water quality control was authorized as a specific purpose of only a few of our 214 completed reservoirs, some planned regulation for quality control is being made part of reservoir operating plans whenever it is consistent with the purposes for which the projects were authorized. Furthermore, in nearly all cases, the effect of regulation for authorized purposes is incidentally beneficial to water quality. Also, as we learn more about the effects of reservoir operations, steps can usually be taken to prevent adverse effects on water quality.

On these completed projects, two general courses of action are now possible. First, adjustments consistent with the authorized purposes of the projects, particularly in operations, can continue to be made in the light of experience and changing requirements for water quality. Second, completed projects can be restudied, particularly in conjunction with basin-wide studies for additional projects to meet future needs and, when feasible, recommendations made to Congress for modification of existing projects in the interests of quality control. We do not have authority to modify completed projects to include quality control without further action by Congress.

AUTHORIZED PROJECTS UNDER CONSTRUCTION OR NOT STARTED

Including those most recently authorized last year in Public Law 87-874, the Corps has authority to construct over 200 additional projects containing some 90 million acre-feet of storage. Of these, 81 reservoirs with 56 million acre-feet of capacity have been placed under construction. On all of the projects not yet started and on those where planning for certain phases of construction is still under way, the new Public Law 87-88 provides a basis for considering modifications of previously authorized plans to include provisions for flow regulation for water quality control if the following criteria are met:

1. The modification of the project must be economically justified.

2. The status of the planning and construction of the project must be such that it is practicable to accomplish the necessary changes without undue delay or unreasonable increase in cost over that which would have been incurred if water quality control had been originally authorized as a project purpose.

3. The modification must not have a material adverse effect on the purposes for which the project was authorized originally.

4. Satisfactory advice must be received from the Secretary of

the Department of Health, Education, and Welfare relative to the need for and the value of the water quality control storage.

5. The Congress must be informed of our intention to modify the project and of the views of the Secretary of the Department of Health, Education, and Welfare by letters to the Public Works and Appropriations Committees of the Senate and House.

Last year we informed Congress that we were modifying two projects, John W. Flannagan Reservoir, Ohio River Basin, Virginia, and DeGray Reservoir, Ouachita River Basin, Arkansas, to include water quality control storage as a primary project purpose. We feel certain that many other authorized projects can be modified to include this important purpose as detailed planning studies proceed.

PROJECTS BEING STUDIED FOR FUTURE AUTHORIZATION

In the projections developed by Resources for the Future for the 1961 Report of the Senate Select Committee on National Water Resources, it was estimated that by 1980 the United States would need about 94 million acre-feet of additional storage for flood control and about 315 million acre-feet for water quality control and other purposes dependent upon low flow regulation. By the year 2000, it was estimated that about 446 million acre-feet would be required for the latter purpose. These formidable requirements for storage for water quality, the 1980 amount being about double the capacity we have now developed for all other purposes, were based on the assumption that the desired quality of water in rivers would be achieved by the cheapest combination of waste treatment facilities and storage to provide sustained flows for satisfactory dilution of effluent. On this basis it was estimated that the degree of waste treatment at the source can generally be expected to range upward from 70 percent treatment in 1980 and 80 percent treatment in the year 2000, and up to 95 percent or even higher in water-short regions or where costs of reservoir storage are high.

Even with an early breakthrough in efforts to improve methods for treatment of wastes at the source, it would be many years before improved methods could be applied to replace present measures. Accordingly, the Corps has recently estimated that the programs for which it has planning responsibility should be formulated with a view to providing, by 1980, about 320 million acre-feet of reservoir storage capacity. Under immediately prospective conditions, much of this capacity is needed in the interests of water quality control. Even if demands for storage capacity can be reduced by improved waste treatment procedures, comparable requirements for flow regulation will still be needed for other demands for use of our water resources.

This prospective program of reservoir storage, distributed as shown in Table 1, would require a cumulative expenditure for reservoir construction totaling about $15 billion by 1980. This means increasing the program from the current annual rate of about $0.5 billion to about $1.5 billion in 1980.

TABLE 1. ADDITIONAL RESERVOIR CAPACITY NEEDED BY 1980 AND ESTIMATED COST

Region [a]	Flood control	Other purposes [b]	Total	Portion that might be provided under Corps' program	Estimated cost, [c] Millions of dollars
	Millions of acre-feet				
New England	0.8	4.0	4.8	4.8	365
Middle Atlantic	3.2	19.9	23.1	22.1	1,859
South Atlantic	3.7	26.3	30.0	28.0	1,010
Ohio Basin	8.3	13.9	22.2	21.2	1,550
Tennessee Basin	0	6.5	6.5	0	0
Great Lakes	0.4	41.4	41.8	41.8	1,969
Upper Mississippi	9.0	14.8	23.8	23.8	1,020
Lower Mississippi	0.8	18.7	19.5	19.5	370
Ark-White-Red	16.8	27.5	44.3	34.3	927
Gulf Southwest	12.6	38.1	50.7	43.7	1,660
Red of North	0.3	3.0	3.3	1.8	54
Missouri Basin	17.5	31.2	48.7	38.7	1,320
Colorado Basin	0.4	13.4	13.8	3.0	96
Great Basin	0.6	6.8	7.4	1.3	62
California Coastal	1.3	5.7	7.0	3.0	246
Central Valley	3.1	24.0	27.1	10.1	415
Columbia Basin	14.8	16.7	31.5	22.0	1,670
N. Pacific Coastal	0.8	3.3	4.1	3.6	230
Totals	94.4	315.2	409.6	322.7	14,823

[a] Substantially the regions shown on the map of United States Water Resource Development, edition of 1958.

[b] Based upon estimates by RFF of storage required for multiple-purpose river regulation (the controlling factor is generally the flow required to maintain satisfactory water quality).

[c] Cost of capacity that might be provided under the Corps of Engineers' program.

IMPLICATIONS FOR THE FUTURE

What does this prospect of requirements of reservoir storage capacity for water quality control mean for those concerned with water resources planning and development? It means, of course, that water quality considerations must be taken into account much earlier and more completely than they have in past planning and development of water resources. I will discuss three of the many significant implications for the future: projections of needs, evaluation, and research.

PROJECTIONS OF NEEDS

A basic first step in planning for conservation and effective use of water resources is the delineation of the probable future demands for use of water. Since water development projects are and will continue to be an essential part of all human activity, projections of water needs should take into account long-range as well as immediate requirements. It is difficult to get planners, administrators, and legislators to accept the implications of the doubling and tripling of population, gross national product, and other indices of activity that we face in coming decades. We must find ways to translate the current projections of growth and change into estimates of requirements for amounts and qualities of water needed at various times in the long-range future. Insofar as water quality is concerned, this poses many difficult problems, such as predicting what type and amount of contaminants will remain in treated effluents of the future and what standards of quality should be maintained in specific reaches of streams to permit use for water supplies, for recreation, for fish and wildlife, etc.

In our current comprehensive basin-wide studies, such as on the Ohio and the Susquehanna, the Corps is coordinating its arrangements for economic base studies and projections of needs with the Department of Health, Education, and Welfare in order that the formulation of long-range basin-wide plans and specific immediate projects may reflect the best possible consideration of water quality requirements as well as other water needs. Joint undertaking of economic base surveys serves to meet the individual and combined needs of the participants and thus to reduce the overall cost of investigations necessary to devise effective water resource development and management plans.

EVALUATION OF EFFECTS OF FLOW AUGMENTATION

A second area that will demand extraordinary efforts of water planners is the evaluation of the effects of regulation of flows for the purpose of water quality control. With the steadily mounting demands for use of water and the increasing difficulty of finding practicable sites for reservoirs, it is becoming more and more important that we be able to evaluate the effects of prospective water management measures accurately. We need improvement in our evaluations in absolute terms in order to be sure of the justification of our water development proposals, which are becoming more costly as better sites are preempted for various purposes. Even where decisions can safely be made without full determination of absolute values, it is necessary at least to have good definition of relative values or limiting values to insure balanced project formulation in the light of competing or conflicting demands for water use and alternative ways of meeting various demands.

The techniques for evaluating flow regulation effects on flood damage prevention, hydro-power generation, and irrigation in comparable terms have been reasonably well developed. Evaluation of

flow regulation effects from a water quality standpoint presents many more problems. When stream flows are regulated in the interests of water quality, many types of effects may be pertinent. Some of these are removal of sediment during impoundment and the resulting changes in conditions downstream; dilution of acids, alkalis, salts, and poisons; heat dissipation, which affects the amount of oxygen; improved pH and its effects on the speed and character of biological reactions; reduced costs in treatment of domestic water supplies; improved fish and wildlife habitat and sport and commercial fishing; improved recreational potential of waterways; improved quality of domestic, industrial, and irrigation supplies; and reduced corrosion damages to structures and floating craft. Although these end products are deceptively simple in statement, we all recognize that literally thousands of compounds may be introduced into rivers from our municipal, industrial, and agricultural complexes and that these, in combination with many possible patterns of stream use, produce a wide variety of situations that should be considered in the evaluation of flow regulation effects. Experts in practically every area of human activity will have to contribute and work together to establish the parameters of the physical effects from water quality control and provide a basis for evaluation of net benefits in monetary terms for comparability with other project benefits. While some benefits can be determined by existing procedures, many require research and continued analysis. It is simply not enough to continue to use the cost of alternative projects as a measure of water quality control benefits, since, unlike power and municipal and industrial water supply, we have no market-price-related basis for testing the economic justification of such alternatives. We note that even though evaluation and economic aspects are not being emphasized at this Symposium it is contemplated that future meetings will do so. This is essential if we are to make headway in incorporating water quality control into water development programs such as those of the Corps of Engineers.

RESEARCH

The emergence of water quality control as an increasingly important consideration in water resource planning and development has brought about needs for research on many aspects of the problem. For example, the differences in temperature and oxygen content of reservoir releases compared with those of natural flows have effects on fishery resources that we must learn more about so that we can take measures to prevent adverse effects and produce improved conditions if possible. Research is needed on qualitative and quantitative effects on basic biological productivity, general limnology, fish populations, and countless other aspects of the use of streams for recreation and fish and wildlife. We need to know more about both old and new substances being introduced into our rivers and their effects on use of water in both old and new processes.

In the Corps of Engineers' program, we cannot hope to contribute more than a fraction of the basic research that is obviously needed

on matters related to water quality. We can investigate the possibilities for changes in design of our dams to optimize the temperature and oxygen content of water released in the downstream channels or to provide multiple outlets to permit discharge of water from various selected levels in the reservoir. We can, in appropriate cases, monitor the dissolved oxygen content of water at various depths in our reservoirs as we are now doing at the John H. Kerr Reservoir Project on the Roanoke River, Virginia and North Carolina. As we identify the most significant aspects from a water resource planning and development standpoint, we are prepared to undertake and to sponsor or support specific research activities by others as an essential adjunct to our water resource development mission. We visualize as particularly appropriate for our program those research activities that will improve our ability to evaluate flow regulation effects and those that will lead to more effective design of project features to accomplish beneficial control of water quality.

SUMMARY

In summary, water quality considerations have become a major factor in the formulation of the water resource development programs, which are a responsibility of the Corps of Engineers. In fact, present indications are that flow regulation in the interests of maintaining satisfactory water quality may be the dominant and controlling requirement for reservoir storage in many areas in the next few decades at least.

We have had a long-standing interest in this problem. For example, our basic planning for the low flow regulation features of the Allegheny River Reservoir now under construction above Pittsburgh was done in the 1938 to 1940 period with a major assist from the Public Health Service. Over this same period the Ohio River Pollution Survey was completed through our joint efforts. This has provided a valuable background for the water management work — quality and quantity wise — that has since been accomplished in the Ohio Basin.

We are now striving to equip ourselves to understand more about the significance of water quality in our economy, the effects of changes of water quality, the effectiveness and value of measures to control or improve it, and the interrelation of water quality to water resource conservation and use in general.

One of the most significant effects of this situation on the Corps of Engineers' program is that all planning must be carried out with multiple-purpose needs and possibilities in mind. While we must continue to solve and deal with many immediate and urgent problems with whatever resources and data are immediately obtainable, we must also relate these problems and their solutions as best we can to all other existing and prospective needs for water. This has brought about in recent months a concerted effort on our part to move towards the earliest possible completion of integrated, comprehensive plans, both in framework and in detail, for all of the Nation's river basins,

as recommended by the Senate Select Committee on National Water Resources and as adopted as an objective by the President in his policy pronouncements on water resources.

Perhaps the most significant development in water resource planning today is the growing realization that the water problem is so complex that there is no way that all of the responsibility for dealing with it can logically be assumed by any single agency or level of government. We have adapted our procedures to facilitate working with all agencies at Federal, State, and local levels, to achieve maximum possible coordination of water resource planning and development. In so doing we are steadily gaining in our appreciation of several types of interrelationships that are important to those concerned with water resources.

First, through training of current employees and in new hiring, we are equipping our own organization with personnel who encompass the wide range of disciplines needed to work out solutions to water problems. Our organization will include engineers who will try to solve water quality problems, and also biologists, economists, lawyers, and others needed to assimiliate the complex considerations involved in modern water resource development plans.

Secondly, we are trying to work out appropriate and effective arrangements for coordination and distribution of effort among all agencies who can and should contribute to solution of water problems. Insofar as water quality considerations are concerned, we are looking to the Department of Health, Education, and Welfare for both day-to-day advice and continuing, concurrent consideration of long-range studies.

Finally, we are convinced that exchanges of information and ideas such as at this Symposium are becoming more and more necessary for effective action on water problems. We know that our personnel who are participating will benefit and we plan to make the proceedings widely available to our field offices. We hope that the program of the Corps of Engineers can contribute significantly to maintaining and improving water quality as well as to meeting other needs for use of water, and we appreciate this opportunity to join in efforts towards that end.

RELATION OF REGULATION FOR QUALITY CONTROL TO ACTIVITIES OF THE BUREAU OF RECLAMATION

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Bureau of Reclamation activities in the realm of water quality control have followed a path of ever-increasing complexities over the years. Initial projects were concerned primarily with getting the water to the lands for irrigation purposes with no particular thought as to the quality of the waters so provided. We were concerned with quantity. Our projects were essentially single-purpose operations. As alkalinity developed, we became increasingly aware of quality standards of soils and the attendant relation of the quality of waters to be applied, and later of the quality of waste and return flow waters as they would affect downstream water uses. We were interested in the effects of water quality on structures. Quality considerations were centered on salt loads and transport quality such as turbidity, silt loads, and sedimentation. As multiple-purpose projects were introduced, the awareness of quality considerations increased. Bureau of Reclamation projects are now concerned with water supplies for irrigation, power, flood control, municipal and industrial uses, fish and wildlife conservation, recreation, navigation, and maintenance of streamflow. We are now vitally concerned with the physical, chemical, and biological quality of our project water supplies. We are concerned with these aspects of water as it enters a project area, as it proceeds through the project, and after it leaves the project. As these needs arose, they were recognized by the Congress, and additional authority was given to the Department of the Interior and to the Bureau of Reclamation.

The Bureau of Reclamation derives its authority from the Secretary of the Interior. By the provisions of the Reclamation Act of 1902, the Reclamation Project Act of 1939, and by numerous amendments and extensions to these acts, the Secretary of the Interior is authorized to investigate, construct, and operate projects to provide water for irrigation and other purposes in the 17 contiguous Western States. This necessarily includes authority for water quality investigations as required.

By the Act of August 9, 1955, the Secretary is authorized to make investigations of projects for the conservation, development, and utilization of the water resources of Alaska.

Although the Reclamation law provided authority for development of municipal and industrial water projects in the Reclamation

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* Mr. Burnett's paper was presented by Mr. C. B. Jacobson, U. S. Bureau of Reclamation, Salt Lake City, Utah.

States, the Water Supply Act of 1958 provided additional authority for construction of storage capacity for deferred use for this purpose.

The Federal Water Pollution Control Act of 1961 provides that in the survey and planning of any reservoir by the Corps of Engineers, Bureau of Reclamation, or other Federal agency consideration shall be given to inclusion of storage for regulation of streamflow for the purpose of water quality control. It also provides that storage and releases therefrom for water quality control shall not be provided as a substitute for adequate treatment or other methods of controlling wastes at their source.

There are numerous specific project authorizations for construction and operation of Reclamation projects, some of which include works specifically for water quality control.

The Bureau is making continuous studies of irrigation water requirements, which include consideration of water quality. We have learned by some 60 years of experience that adequate consideration must be given to both the chemical quality and the suspended sediment content of the water as well as to the chemical and physical characteristics of the soils.

In some instances where the quality of a certain water supply is not suitable for the proposed use, as for example if the saline content is unduly high for irrigation use, the poor quality water can be diluted with water of a better quality from another source, thus making it suitable for the required use.

The concentration of dissolved constituents in irrigation water retained by soils generally increases as the water is evaporated and utilized by plants. The concentration of these constituents also generally increases in drainage waters, and the quality may be adversely affected for further use. In the planning of projects, it is therefore essential that the quality of the potential water supply be carefully investigated with respect to: (1) the nature and concentration of the various constituents, (2) its probable effects, if any, on the crops and soils of the project under varying rates of application and conditions of precipitation; (3) character of the return flow from project lands and its influence on the quality of downstream water supplies for other uses; and (4) methods and costs of alleviating adverse effects, if any, on downstream water supplies.

In the design of a Reclamation project, water quality analyses are essential in determinations of the possible effects of corrosion on project structures.

In the release of water from reservoirs, it may be necessary to adjust the outflow to control the temperature and/or oxygen content of the water downstream to preserve fish life or maintain a suitable water quality for stream pollution abatement or for other purposes. For example, the outflow from Shasta Dam of the Bureau's Central Valley Project in California is regulated for temperature control for preservation of fish. The Bureau is studying the effects of operation of

control structures on the oxygen content of the water to develop methods of creating and maintaining a favorable oxygen content.

Many Reclamation projects supply municipal and industrial water. The Bureau delivers raw water to the user, and although the Bureau does not provide final treatment to make the water potable, it does add chlorine, when necessary, to prevent the growth of algae in the conduits. The Cachuma Project in southern California is an example of a project where chlorination is provided.

Sedimentation problems in connection with Reclamation projects include loss of reservoir storage space as a result of sediment deposition, aggradation, and formation of deltas at the heads of reservoirs; degradation of stream channels below reservoirs as the clear water picks up its natural sediment load; and deposit of silt behind diversion dams, and in canals, siphons, and other water control structures. These problems are under continuous study, as are those of stability of both natural and artificial channels required to transport water.

Studies of sedimentation as a special subject are relatively new in the field of engineering. Evaluation of many of the sedimentation problems on early projects was based solely on judgment. As the Bureau and other governmental agencies have gained experience in operating projects and have accumulated data on sedimentation, the practical operating knowledge acquired has made it possible to improve the techniques for evaluating the sedimentation aspects in project planning and development. Two outstanding accomplishments of the Bureau in this continuing work include the desilting works of the Imperial Dam on the Colorado and the recent programing of the complicated Modified Einstein Procedure for computing the total sediment transport of a stream.

Most Reclamation reservoirs are used for recreational purposes, and the regulation of this use requires consideration of water quality. The waters must meet quality standards to support such uses as boating, swimming, fishing, picknicking (drinking and cooking), wildfowl nesting, and various other uses.

The Bureau is conducting research on the use of monomolecular films to reduce evaporation losses from reservoir surfaces. A number of other agencies are cooperating. These studies, especially on new materials, include consideration of possible toxicity to fish, migratory waterfowl, aquatic plants, and the various animals inhabiting reservoir areas. Any undesirable change in physical or chemical characteristics, such as taste, odor, or color, is not permissible in water for consumption by humans or livestock; but studies to date have failed to indicate any harmful effects.

It would be well, at this point, to mention several of the specific problems now under study in certain areas as they relate to the Bureau.

The Bureau is constructing the Spring Creek Debris Dam in California to control polluted mine waters during periods of low flow in

the Sacramento River. These polluted waters will be released only when sufficient dilution is available, to preserve the salmon runs in the river.

The Bureau is constructing a project in the Malaga Bend section of the Pecos River in New Mexico to intercept and divert flows of salty spring water to an impervious offstream reservoir. There the water will be evaporated. Interruption and diversion of the saline water will improve the quality of the water in the main stream. A similar situation exists at the potential site of the Dixie Project on the Virgin River in Utah. Since no suitable storage site has been found, the Bureau is tentatively planning to investigate treatment of contaminating water by salt water conversion processes.

The investigation of the Delta Division of the Central Valley Project in California includes practically the entire gamut of water uses and controls — municipal and industrial water uses, irrigation, drainage, navigation, stream pollution abatement, salinity repulsion, fish and wildlife conservation, recreation, and even limited flood control. The purpose of this investigation is to develop plans and establish what facilities are needed to improve the quality of water available in the delta area, to sustain and enhance existing development, and to provide for continued economic growth. Water quality control has not only been one of the controlling guidelines in the planning of the Central Valley Project, but is a control on project operations. This work is being carried out cooperatively with other Federal agencies, State agencies, and local people. Studies involve protection and enhancement of local fisheries and wildlife, as well as the necessary studies to determine desirable levels of pollution control as related to public health, recreation, and control of nuisance conditions.

Reservoir operations at Folsom Dam have been modified and remedial construction measures taken involving the modification of the river outlet to provide suitable water temperatures in the interests of the American River fishery. The Central Valley Project, in providing supplemental water, also has assisted with improvement of the water quality in many ground water pumping areas.

In our work in the field of water quality, our experiences working with the Fish and Wildlife Service, the Public Health Service, and the National Park Service have been of paramount benefit. These agencies have contacts and sources of information not readily available to the Bureau. They also have biological knowledge outside the normal experience of our Reclamation personnel. The use of these sources by our planners has allowed us to progress in water quality control work at an accelerated pace.

The Bureau is conducting extensive water quality studies in the Colorado River Basin, in cooperation with the Geological Survey. In addition, the Imperial Irrigation District collects water quality data on the All-American Canal; and the Salt River Water Users Association and the city of Phoenix are collecting water quality data on the

Verde River and the canals and wells of the Salt River Project. The Bureau is collecting water quality data from wells of the Gila Project and from Lake Mead.

Work is also proceeding on special studies, such as the one in the Eden area of Wyoming, where samples are being taken every 10 days at inflow and outflow points to characterize the effects of irrigation on return flows. There is another study underway in the river reach between Wanship Reservoir and below Echo Reservoir to characterize the effect of storage on quality of water. Although this area is out of the Upper Colorado River Basin, data obtained here are expected to be useful in the Upper Basin water quality studies. Samples are being obtained at all sites where possible transmountain diversions might be made out of the Upper Colorado River Basin.

In connection with the development of the Colorado River Storage Projects of the Bureau, a cooperative study is underway with the Geological Survey to evaluate the effect of storage and consumptive use of water in the Upper Colorado River Basin on the quality of waters of the Colorado River.

Colorado River studies include determinations of discharge, total salt concentration, and ion concentration relationships at key sites within the Upper Basin in addition to a quality of water operation study involving the four storage units and the eleven participating projects. The operations will be extended downstream to determine the quality of the releases from Glen Canyon Reservoir. As additional projects or units are authorized, they will be incorporated into the quality of water operations study.

Corollary studies will be conducted for the purpose of developing data in support of the assumptions used in the operation study. These will include: (1) determination of salt balance conditions on presently irrigated areas in the basin; (2) study of equilibrium conditions of the soils and irrigation water in presently irrigated areas; and (3) study of leaching or salt accumulation in various irrigated areas of the basin.

Reports scheduled from 1962 through 1975 will present the current status of chemical quality of water and predict future effects of developments in the Upper Basin.

No subject is of greater interest or importance to the people of the West than conservation of water. The Nation's water problem cannot be one of total quantity because we withdraw only about one-third of the total manageable supply and then actually consume less than one-tenth of that. Therefore, the national problem stands forth as one of management. Management of water involves getting the desired amount of water of the required quality to the point of use at the right time. Water use in most of the watersheds of the West exceeds the total supply; the same waters are used for irrigation, industrial supply, recreation, power, navigation, and many of the other multiple-purpose uses. Each use has its effect on water quality, and regulation of such waters must include evaluation of quality at each

point of demand, with proper consideration given to the later demands to be placed upon the waste and return flow waters from that point of demand. The Bureau of Reclamation, in cooperation with other interested State and Federal agencies, as well as local entities, continues to give such consideration in the planning, construction, and operation of its many projects. As we look to the future, we can foresee additional demands for increasing studies of water quality, such as provisions for the disposal of radioactive wastes, increased radioactivity in surface and ground waters from the effects of fallout, disposal of waste byproducts of new processes and materials, and the development of new management techniques resulting from more sophisticated computer analyses of water quality studies.

All Bureau of Reclamation projects now being planned give prime consideration to water quality control as a potential project purpose under the provisions of the Federal Water Pollution Control Act.

THE INFLUENCE OF CONSERVATION PRACTICES AND MEASURES ON WATER QUALITY

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The Soil Conservation Service (SCS) is responsible for developing and carrying out a national program for the conservation of the Nation's soil and water. Its primary objective is the establishment of conservation treatment measures and patterns of land and water use that are compatible with the capabilities of our land and water resources.

To accomplish this objective, the Service employs scientists and technologists from numerous disciplines. The knowledge and skills of agronomists, biologists, engineers, geologists, hydrologists, economists, soil scientists, and others are pooled to diagnose problems and develop plans for the use and treatment of our Nation's farms, ranches, watersheds, and river basins.

From its inception, the SCS recognized the necessity of local participation and control in carrying out action programs. Therefore, whether farms or watersheds are to be planned, the SCS provides assistance to individuals and local groups that want to develop and apply conservation programs.

FARMS AND RANCHES

The types of measures applied to the individual farm or ranch vary widely, depending on such factors as climate, topography, and soils, and on the desires or interests of the farmers or ranchers. There are over 100 items listed in the "National Catalog of Practices and Measures used in Soil and Water Conservation." Most of these practices and measures will directly or indirectly influence the quality or quantity of the water yield of an area. Although a practice may be designed for the primary purpose of controlling erosion, it may produce other benefits of significant value. For example, it is well known that soil particles are detached by the energy of falling rain drops. When vegetative cover protects the soil from the impact of rainfall, erosion is reduced. But there are other effects of establishing good vegetative cover, such as improving the condition of the soil. An improved soil allows more water to infiltrate the soil surface. It makes more water available for plant growth and contributes to the underground supplies that feed our springs. It takes a little longer for the water to reach a river by percolating through the soil, but normally this is desirable.

Runoff from bare fields or bare watersheds occurs quickly and may result in a flash flood of muddy water. Runoff from well-vegetated fields and watersheds occurs more slowly and is not heavily ladened with silt. Therefore, a simple measure such as the establish-

ment of vegetation for erosion control also tends to regulate streamflow. The installation of only a few acres of vegetation does not produce a significant effect in a watershed. But, if the vegetative cover is improved on all of the farms within a watershed and if additional practices and measures such as strip-cropping, terracing, contour tillage, etc., are installed, the effects of all these practices and measures acting together do have some influence not only on the rate of runoff but also in reducing the sediment content and improving the quality of the water produced by the watershed.

WATERSHEDS

In addition to the measures on individual farms and ranches, the SCS assists local groups in developing project plans for upstream watersheds. Each watershed is different and each plan is developed to solve the local problems. A project may be designed to reduce upstream floodwater damage or to provide for agricultural water management. It may include measures to provide a water supply for industrial, municipal, agricultural, or recreational use. Some degree of flood prevention has been included in most of the watershed projects planned to date. This usually involves the construction of earth dams that temporarily store flood runoff and release it at a relatively low uniform rate. These structures have a major influence in regulating the flow below the dam. But in addition to land treatment practices and measures, there are usually some other benefits that result from the construction of floodwater retarding structures. For example, even though these structures are not designed to trap the sediment load, it is impossible to store the floodwaters even temporarily without reducing the sediment load of the discharge water to some extent. Since some of the sediment will be trapped by the reservoir, additional storage is provided to permit the reservoir to operate at full capacity for a period of 50 to 100 years. Often structures are designed for storage of water for irrigation, municipal or industrial water supply, or recreation, in addition to the temporary storage provided for flood prevention. When permanent storage is provided in a structure, it becomes even more effective in removing some of the sediment being transported downstream.

Not all measures installed in watershed projects produce the same kind of benefits. It may be necessary to reduce flood damages by improving the existing channel. This could result in faster flowing streams and greater flood peaks downstream. If small streams are involved which outlet into lakes or major rivers, the flood effect may not be significant; but channel improvements often must be limited in scope or the effects of increased peaks must be offset by providing structural storage in the watershed. This is pointed out to make clear that all measures recommended by the SCS do not produce the same kind of effect on streamflow.

Just as each farm is different and needs a conservation plan prepared specifically for that farm, each watershed is different and needs a watershed program prepared specifically for that watershed.

There are exceptions, therefore, to almost anything that is said about the effect of watershed programs. It is safe, however, to say that overall a complete watershed program will reduce the rate of runoff, i.e., reduce flood peaks and the volume of sediment produced by the watershed. Reducing the peak flow normally permits a greater use of the total water yield of the watershed. Improving the quality of water by reducing the sediment content, of course, produces a range of benefits, depending on the use of the water supply.

RIVER BASINS

There is one other activity that should be considered in a discussion of the influence of conservation practices on water quality. This is the planning of large watersheds or river basins. As our population increases, it is necessary to expand the development of our natural resources to meet the increased demands for products of all kinds. Unfortunately, these resources are not distributed uniformly within major river basins nor does population expansion or urban development take place uniformly everywhere. In basins where our resources are limited or where there has been tremendous urban growth, we already have serious competition for our land and water resources. The SCS, therefore, participates with other Federal and State agencies in planning major river basins to solve specific problems. The SCS has participated in studies of numerous river basins to evaluate the effects of conservation practices and measures on flood peaks, flood volumes, sediment loads, etc., but the recent Potomac River Basin study is the first to emphasize the needs of upstream storage for water quality control. It is interesting to note that preliminary estimates of the cost of upstream storage were assigned as follows: recreation, 2 percent; water supply, 8 percent; water quality control, 40 percent; and flood prevention, 50 percent. In the Potomac study, therefore, a very significant portion of the upstream storage was recommended solely for the purpose of water quality control.

Let me summarize the activities of the SCS in this way. First, the Service cooperates with soil conservation districts to assist individual land owners and operators. Practices and measures are installed on their land primarily to conserve soil and water on the farm. Therefore, measures such as terraces are designed to produce a benefit to the farm unit, although it is recognized that these practices and measures may produce some very desirable effects downstream.

Second, the SCS cooperates with local organizations in planning and applying conservation measures on a watershed basis. This work encompasses all of the measures recommended for conservation purposes on individaul farms, and in addition, includes measures required to solve the problems of the watershed organization. Such additional measures might include a multiple-purpose structure to provide irrigation water and flood prevention or it might consist of a system of ditches to provide improved drainage. These measures are designed to provide "on-farm" and "community" benefits, although it is also recognized that many benefits will accrue to downstream interests.

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Third, the SCS cooperates with State and Federal agencies in planning the development of the natural resources of major river basins. A comprehensive plan for a river basin would include the practices and measures to be installed on individual farms and ranches and the system of structures, channels, or other works required in specific watersheds. It would also include the additional on-farm or small watershed practices and measures that need to be installed upstream to provide the level of protection or produce the desired benefit in the downstream areas of major river basins.

PRESENT AND FUTURE BENEFITS

Since the effect of each farm or watershed program is different, let me review some results and examine some expectations.

On two Texas watersheds that are farm-sized — that is, about 150 acres in size — it was found, by application of flow duration curves to sediment yield data, that the untreated watershed had nearly nine times more sediment moving past its streamflow station than did the conservation treated watershed(*1*). This can be considered a typical comparison for watersheds of this size, although, of course, the proportion of sediment yield varies somewhat across the country.

On larger watersheds such as those above the Loch Raven and Prettyboy Reservoirs, which are water supply sources for the City of Baltimore, the sediment yield is also reduced when conservation measures are applied in significant amounts. Installation dates and sediment surveys in these two reservoirs show that for Loch Raven Reservoir there has been a 70 percent reduction in reservoir sediment deposits during recent years, while for Prettyboy Reservoir, which is 12 miles upstream from Loch Raven, there has been a reduction of 44 percent(*2, 3*).

In Georgia, records from five of the larger waterworks show a steady downward trend in turbidity of the water being pumped from the rivers for treatment at the filter plants. For the Chattahoochee River at Atlanta, for example, average turbidity has decreased from over 300 ppm in the early 1930's to less than 100 in the early 1950's. The decreases in turbidity are very plainly attributable to the increases of conservation measures on these river watersheds(*4*).

Let me turn now from results on a watershed basis to what can be done on a large river basin basis. Studies of watershed protection projects indicate that results shown in Table 1(5) can be achieved in major basins. In the New England area, for example, where present sediment concentration is very low, a reduction of only 6 percent can be expected by 1980. In the Lower Mississippi, however, where the present sediment concentration is very high, a reduction of 30 percent can be expected by 1980. How are these benefits going to be produced nationally? Here are some ideas.

In river basin projects where the SCS has investigated and recommended storage for water quality control to meet the requirements

TABLE 1. FACTORS INFLUENCING SEDIMENT CONCENTRATION IN MAJOR DRAINAGE BASINS

Basin	Predominant physical characteristics				Sediment concentration		
	Climatic type	Land form	Relative erodibility of soils	Major erosion source of sediment	Present relative rate	Estimated reduction, By 1980	By 2000
New England	Humid	Rolling	Low	Sheet	Very low	6	10
Delaware-Hudson	Humid	Rolling	Low	Sheet	Low	6	10
Chesapeake Bay	Humid	Rolling to dissected	Low	Sheet	Medium	21	35
Southeast	Humid	Dissected to low rolling	High	Sheet, channel	High	36	60
Eastern Great Lakes	Humid	Rolling	Low	Sheet	Low	6	10
Western Great Lakes	Humid	Rolling	Low	Sheet	Low	6	10
Ohio	Humid	Rolling	Medium	Sheet	Medium	12	20
Cumberland	Humid	Dissected	High	Sheet	Low	6	10
Tennessee	Humid	Dissected	High	Sheet	Low	6	10
Upper Mississippi	Humid to subhumid	Low rolling to dissected	High to low	Sheet	High	21	35
Lower Mississippi	Humid	Dissected to low rolling	High	Sheet, channel	Very high	30	50
Lower Missouri	Humid	Dissected to low rolling	High	Sheet	Very high	24	40
Lower Arkansas, White, Red	Humid	Dissected to low rolling	Medium	Sheet	High	33	55
Upper Missouri	Subhumid to semi-arid	Low rolling to mountainous	High to low	Sheet, channel	High to low	33	55
Upper Arkansas, White, Red	Subhumid	Rolling	High	Sheet, channel	High	45	75
Western Gulf	Subhumid to semi-arid	Rolling	High	Sheet	High	30	50
Rio Grande-Pecos	Semiarid to arid	Dissected	Medium	Channel	High	21	35
Colorado	Semiarid to arid	Dissected to mountainous	High to low	Channel	High	18	30
Great Basin	Arid	Mountainous to plains	Medium	Channel, sheet	Medium	12	20
Pacific Northwest	Superhumid to arid	Mountainous	Low to high	Sheet, Channel	Low to high	9	15
Central Pacific	Superhumid to arid	Mountainous	Low to high	Channel, sheet	Medium	18	30
Southern Pacific	Subhumid to arid	Mountainous	Low to high	Channel, sheet	Medium	18	30

set forth by the Department of Health, Education, and Welfare, it is expected that funds will be made available to the SCS to construct the dams if the projects are approved by the Congress.

Under the watershed program the SCS can cooperate in the planning of reservoirs to provide storage for water quality control. At the present time, the SCS cannot provide funds for construction of such reservoirs. Amendments are being considered that would permit the Federal government to share with local agencies the cost of providing such storage.

It must be kept in mind that the work of the SCS does not include spectacular engineering structures. SCS dams are limited under PL-566 to 25,000 acre-feet of storage. But the volume of the work is an indication of the influence these dams can have on water quality control. As of January 1963, the SCS had received over 1800 applications for assistance in watershed planning; planning had been completed on over 800 watersheds; and programs had been authorized on about 450 watersheds. Work is currently underway on slightly under 300. Through fiscal year 1962, preliminary plans had been completed on somewhat over 2600 dams and construction had been completed on about 650. In one state alone the applications pending include the development of municipal water supplies for 53 towns and cities.

The Department of Agriculture's inventory of conservation needs indicates a need for watershed programs on 8300 watersheds in the United States. Work has been completed on less than 1 percent of this number. Construction has been started on about 3 percent, is authorized on over 5 percent, and planned on over 8 percent. These percentages may appear small when expressed in terms of the total job; however, progress has been good, if we consider the fact that the program was authorized in the fall of 1954, a certain amount of tooling up was required to handle the work, and, of course, the requests for assistance must be developed locally and cleared through State and Federal channels before actual field work can be started.

Much more conservation work needs to be done, but enough has been accomplished to prove the effectiveness of the various practices and measures in the conservation of our soil and water resources. This work is moving forward from approximately 3000 offices located throughout the United States. The effects of these efforts have been obvious on small areas such as farm units and small upstream watersheds. More and more evidence is being found to show that very significant benefits are also occurring on large watersheds.

The cooperative effort of Federal, State, and local agencies in the installation of conservation practices and measures on watersheds is an effective means of achieving flow regulation in upstream areas and silt pollution control. Water quality is being improved but primarily as a byproduct of work to accomplish other objectives. If an effort was made to determine upstream storage requirements for pollution abatement and to secure the necessary legislative amend-

ments to permit Federal-local sharing of construction costs, a much greater contribution could be made by the SCS to streamflow regulation and water quality improvement.

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RELATION OF REGULATION FOR QUALITY CONTROL TO THE ACTIVITIES OF THE FEDERAL POWER COMMISSION

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The Federal Power Commission is vitally concerned with the comprehensive planning of river basins. Under statutes dating back to 1920, the Commission has been given important responsibilities in such planning activities. In fact, an early milestone of importance in basin planning is the requirement of Section 10(a) of the Federal Power Act. This section requires that to be licensed a water power project must, in the judgment of the Commission, be best adapted to a comprehensive basin plan.

I am pleased, therefore, to be able to discuss with you the relationship of the Commission's activities to the increasingly important function of streamflow regulation for water quality control. The views expressed, however, are my own and are not necessarily those of the Commission.

Briefly, the Commission has two major activities relating to water resources planning and development. The oldest of these is its licensing function, under which the Commission issues licenses to individuals, corporations, states, and municipalities authorizing the construction, operation, and maintenance of water power projects on government lands and on streams over which the Congress has jurisdiction. It may also license these non-federal interests to utilize the surplus water or water power from a government dam.

At the end of fiscal year 1962 there were licenses in effect for 268 major projects with some 16 million kilowatts of existing installed capacity and 25 million kilowatts of ultimate capacity. The existing capacity under license represents 74 percent of all non-federal hydroelectric capacity in the United States. The ultimate installations under major licenses involve a claimed or estimated cost of about $5.5 billion.

The Commission's second major activity relating to water and related land resources planning is its comprehensive river basin studies carried on generally in cooperation with the federal constructing agencies. The principal role of the Commission in such cooperative investigations is to furnish advice on electric power matters. This involves estimates of the amount and value of hydroelectric power that can be developed in connection with proposed plans, estimates of the future market for such power, and recommendations of provisions for developing the power potential.

An important result of the Commission's river basin studies, made both in connection with the licensing function and in cooperation with the other federal agencies, is the nation-wide inventory of water

power resources. Data on individual developed and undeveloped hydroelectric power projects are compiled annually and published periodically. As of January 1, 1963, preliminary estimates of the total hydroelectric resources of the United States were 150 million kilowatts of generating capacity capable, with average flow in the streams and rivers, of producing 640 billion kilowatt-hours of electric energy a year. About 38 million kilowatts of the total capacity was in existing hydroelectric developments that generate an average of about 200 billion kilowatt-hours annually. It may be noted that the 38 million kilowatts of developed hydroelectric capacity accounted for about 18 percent of the total electric-generating capacity in the United States.

Although the Commission makes studies of water resources projects and keeps abreast of new developments in the fields of power generation, transmission, and distribution, it does not carry on research as such. This, of course, stems partly from the fact that the Commission is not a constructing agency.

In our consideration of streamflow regulation for water quality control, it should be noted that such regulation may have important effects on hydroelectric power development. Storage included in a reservoir for water quality control may provide head usable for power development at the reservoir site. The streamflow regulation may also increase the firm power output at the site and at hydroelectric power plants downstream.

Although storage for water quality control may have important effects on hydroelectric power development, the Federal Power Commission is more often concerned with the effects the construction of hydroelectric projects may have on water quality control. Storage reservoirs at hydroelectric projects are usually operated to supplement natural flows during low flow periods and thus increase the production of firm power. Such streamflow regulation may contribute to water quality control by increasing natural minimum flows; however, whether such benefits are in fact provided depends upon how the hydroelectric power plant is operated. A hydroelectric plant at a storage reservoir usually is most valuable when operated as a peaking plant. In a hydroelectric plant so operated, maximum water discharges are made at times of peak power requirements. Optimum operation of the plant in the interest of power would probably dictate that no water be released during off-peak periods of power demands. Obviously such operation might be detrimental to water quality control. In some cases, in order to make the peaking power operations compatible with water quality control, a re-regulation reservoir is constructed downstream from the power plant. The re-regulation reservoir permits unlimited daily or weekly peaking operations of the upstream power plant and makes possible uniform water releases in the interest of water quality. In other cases minimum water releases from the storage reservoir are prescribed. Sometimes, in such cases, a small generating unit is installed to utilize and discharge the required minimum flows during periods when the main generating units are not operating.

In issuing licenses for hydroelectric projects, the Commission, acting under the authority of the Federal Power Act and other acts, takes a number of actions to ensure proper consideration of the viewpoints of various affected interests and of the needs for such purposes as navigation, flood control, irrigation, fish and wildlife conservation, recreation, public health, and water quality control.

The Commission notifies interested members of the Congress; Governors; and Federal, State, and local agencies of applications for preliminary permits and licenses for hydroelectric projects and gives them an opportunity to submit comments. Notices of filings of applications are published in local newspapers and in the Federal Register. In addition, before acting on an application, the Commission requests comments from the Secretaries of the Army, Agriculture, Interior, and Health, Education, and Welfare on the project as it affects their interests, and if other departments or agencies of the government are involved, their views are likewise requested. Any party who believes that his interests may be affected by a proposed project may submit suggestions or protests to the Commission; and hearings in connection with an application may be ordered by the Commission, either upon its own motion or upon the motion of any party to the proceeding.

Plans submitted as part of an application for license are reviewed critically by the Commission's engineering staff to make sure that the design will result in project works that are safe and are adequate to develop properly the resources involved. Field supervision to ensure compliance with license conditions, both during construction and after a project is in operation, is assigned to one of the Commission's five regional offices or to another authorized government agency, specified in the license.

Several licenses include provisions for minimum flow releases or other operating requirements in the interest of water quality control. A few specific examples will illustrate such requirements.

The license for Project No. 2009, in Virginia and North Carolina, issued to the Virginia Electric and Power Company, covers the Gaston development now under construction and the downstream Roanoke Rapids development now in operation. Both developments are on the Roanoke River downstream from the federally constructed John H. Kerr reservoir and power project. Immediately downstream from the Roanoke Rapids development the river is polluted by discharges of industrial wastes from the plant of the Halifax Paper Company and sewage from the towns of Weldon and Roanoke Rapids. Article 25 of the license for Project No. 2009 prescribes minimum flow releases from the Roanoke Rapids pond in the interests of the preservation of fishery resources and stream sanitation. It also prescribes the minimum daily dissolved oxygen content to be included in the flow releases. These provisions were determined after a public hearing was held, particularly on the issue respecting the effect, if any, of the construction and operation of the proposed Gaston project on the quality of water in the Roanoke

River. The licensee has constructed submerged weirs above the power intakes of the Gaston and Roanoke Rapids developments in order to skim the higher quality water, particularly with respect to the oxygen content, from the upper layers of the respective pools. It had been found that the oxygen content of water released during certain times of the year from the upstream John H. Kerr reservoir was less than that required for sustaining fish life, and it was not anticipated that the water quality would improve with normal passage of water through the Gaston and Roanoke Rapids ponds and power outlets.

The license for Project No. 2232, issued to the Duke Power Company, covers 10 existing developments and one development, Cowans Ford, under construction on the Catawba and Wateree Rivers in North Carolina and South Carolina. This series of developments occupies a 215-mile stretch of river except for two undeveloped reaches aggregating about 40 miles. Pursuant to an agreement between the licensee and North Carolina State interests, the licensee has constructed a submerged weir at the Cowans Ford development in order to skim the higher quality water from the upper layers of the reservoir. It has been found that in a series of dams and reservoirs without intervening stretches of free flowing stream the quality of water in releases from each succeeding reservoir becomes lower, particularly with regard to the oxygen content. The agreement also provides for the licensee to make minimum water releases at the six developments in North Carolina in the interests of stream sanitation, fish and wildlife conservation, and other beneficial purposes. These minimum stream flows are prescribed in Article 31 of the license. Minimum average daily releases from the five developments in South Carolina are covered in Article 32. This article provides that the licensee shall cooperate with the South Carolina Water Pollution Control Authority to establish a mutually agreeable schedule of minimum daily flow releases from the five developments in South Carolina. During construction of the Cowans Ford dam, the licensee received Commission approval to install an intake structure that could be used to take condenser cooling water from the reservoir for a future steam-powered electric-generating plant with ultimate installation of 2,000,000 kilowatts. The water would be returned to the reservoir above the dam. The effect of this future use on water quality is not known at present.

The Turlock and Modesto Irrigation Districts have filed an application for license for the New Don Pedro Project No. 2299 on the Tuolumne River in California. The purposes of the project are irrigation, flood control, power, and exchange storage for the City of San Francisco. The California Department of Fish and Game has recommended inclusion of a provision in the license that the project shall be constructed and operated in a manner that provides water temperatures below 56°, as measured at the La Grange bridge, during the period of October through March. This is the period for spawning and incubation of chinook salmon in the Tuolumne River. At a hearing held in October 1962, testimony was presented on temperatures necessary for the preservation of fishlife and on the temperature of

the water that would be discharged from the reservoir during the critical and average water years. A decision on this matter has not yet been reached.

When appropriate, other types of special conditions are included in licenses in the interests of various water resources development purposes or for the protection of the public. For example, several licenses have required clearing of certain zones in the reservoirs in the interest of public health. Licenses for a number of projects require that the licensees take such measures for the effective prevention of the breeding of malarial mosquitoes in the reservoirs as may be required by the Commission, by the Commission and the affected State health agencies, or by the United States Public Health Service. In one case, the licensee is specifically required to place oil or other materials, as recommended or approved by the U. S. Public Health Service, in the shallow reaches of the reservoir to prevent the propagation of mosquitoes.

Licenses have been issued for several projects that also include storage for municipal water supply. Other licenses cover projects that provide storage or other facilities for irrigation, in addition to the power development. In one case a licensed project is operated to re-regulate the flows from an upstream Federal reservoir in order to ensure sufficient streamflow downstream for proper disposal of municipal sewage plant effluent. In two cases the licenses specifically permit the diversion of water from the reservoirs for condensing purposes in steam-electric plants.

In addition to the relationship of hydroelectric power development to water quality problems, there is also an important relationship between thermal-electric plants and water quality. This, of course, is the matter of thermal pollution of streams as the result of using stream flows for condensing purposes. With the construction of increasingly larger amounts of thermal-electric capacity, including nuclear units, this problem will become increasingly important.

An indication of the significance of this problem is shown by a recent Commission survey of the water requirements of the electric-utility steam-electric plants in the United States. This survey, made at the request of the Department of Commerce, showed that 29 trillion gallons of water were used by such plants in 1959, or about 23 percent of the total United States water withdrawals for all purposes that year, according to information given in the January 1961 report of the Senate Select Committee on National Water Resources.

Of the water withdrawn by electric-utility steam-electric plants in 1959, 20.6 trillion gallons was fresh and 8.4 trillion gallons brackish, primarily from the ocean. Of the fresh water, 15.4 trillion gallons was withdrawn from rivers, 1.9 trillion gallons from the Great Lakes, and 3.3 trillion from other lakes and surface sources.

Since a portion of the 29 trillion gallons withdrawn was recirculated after passage through cooling towers or spray ponds, the

total equivalent use of water amounted to 34 trillion gallons. This is equal to 61.7 gallons per kilowatt-hour generated.

Cooling towers and spray ponds reduce the amount of water required for steam-electric plants, but they increase the consumptive use of water. They are not used where water supplies are adequate because they involve additional expense. In the 1959 survey, plants with cooling towers or spray ponds accounted for 16 percent of the power generation of all plants. Fresh water withdrawals at these plants amounted to about 15 percent of what they would have been without cooling towers and spray ponds. This gives a rough indication of the potential for reducing fresh water withdrawals in the future if it should become necessary to limit the water supply to steam-electric plants.

Only about 0.3 percent of the 29 trillion gallons of water used was actually consumed. The rest was discharged, generally to the source from which the water was supplied. The temperature of the returned water was raised some 12° to 13°F, but the water was otherwise unaltered.

The importance of these factors is apparent when it is recognized that the annual power generation in utility thermal-electric plants is expected to increase from 568 billion kilowatt-hours in 1959 to more than 2,000 billion in 1980. This estimate was made by the Commission in connection with its National Power Survey now under way.

FLOW REGULATION FOR WATER QUALITY CONTROL AND WATER RIGHTS

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When I started preparing these remarks on the relation of water rights to flow regulation for quality control, I had hoped that I could continue the euphoria of opening session speeches. This paper would not write that way, however. Water rights is a rather sticky subject — a nasty one in many respects. The path we will be taking may be very difficult and tortuous.

We should set the stage by referring to the basic law. Section 2(b), added by the 1961 amendments to the Federal Water Pollution Control Act, provides that "storage for regulation of streamflow for the purpose of water quality control" shall be considered in the planning of Federal water resources projects. This is the key to my topic — *"for the purpose of water quality control."*

No one appreciates more than I the difficulties incumbent upon this task. The problem of releases from impoundments for water quality control is the most difficult problem we have in the water quality field. In the long run this may be the key to whether water quality is controlled in this country or not. Flow regulation may very well be the most important aspect of water quality control.

Let us assume for the purposes of this discussion that we have secured adequate treatment of wastes at their source as required by the law. Let us assume also that the hydrological problems are solved, that the mathematical problems are solved, and that all the other technical problems of releasing water at the right time to achieve water quality control are solved. And here I recognize that this is the subject of this Symposium and will no doubt take many years to achieve — but let us suppose that these problems are solved, that the water has been impounded, and that it now is being released from the reservoir. After the water is released and flows down the stream, it presumably becomes a part of the waters of the State, just like any other waters.

Let us take an outrageous case first.

A farmer wants to irrigate downstream, so he pumps the water from the river, puts it on his land, and the water does not get back into the stream. Here, all the work, all the theory, all the operating plans, all the Congressional objectives, all the interstate and interagency agreements — all these things — go right down the drain because the water is withdrawn. I think that this is the prototype of the problem that we have to deal with and that we can have many, many variations of the same thing.

Then there is the case of a water user who, though he does not

withdraw water for a consumptive use, pollutes the water so that stream quality is not improved by the flow regulation provided.

Another variant may be — and this is why water quality control cannot be over-generalized or over-simplified — that of a public water supply that is excessively mineralized. This was the case in Dallas during the drought of the fifties. The water supply had such high chlorides that it turned lawns brown and many people simply could not drink the water. Water of low chloride content was brought in and sold in milk cartons at $0.40 per gallon, which is more than the price of gasoline. Would release of water to alleviate a situation in a domestic water supply like that at Dallas be water quality control?

These points are brought out to illustrate that case by case we can have a complete spectrum of uses for quality control water and that we certainly cannot provide answers to every question today that may arise in the future. We can only dream of the answers.

The key point for this discussion, I think, is the first case cited, that of someone such as the man engaging in irrigation farming. He takes the water out of the stream, uses it to irrigate his crops, and thereby thwarts the purpose of the Act to provide flows for water quality control.

SYSTEMS OF WATER LAW IN THE UNITED STATES

In the field of water rights there has been a considerable amount of controversy, as most of you know. We even have our own cliché — that in the field of State and Federal water rights there is more heat than light. Even in trying to give a dispassionate review of the situation — because of many people's legitimate bias — I may create more heat than light. But even at this risk, I think we have to examine the situation to determine what the facts are — what the background is — before we can determine whether we can handle the water rights problem in water quality control. I say this because in large measure we are governed by history; as Justice Holmes said at one time in a particular case, "In this case a page of history is worth more than a volume of life." We have a tremendous history of conflict or of alleged conflict between Federal and State water rights behind us, and we cannot divorce ourselves from it. Where we go in this field may, however, very well be determined by legislation or decisions outside the field of water quality.

This material is no doubt old hat to some, but to avoid the risk of leaving unanswered questions for others, I will start by analyzing the systems of water law in the United States. This is essential because, it seems to me, the critical conflict between State water rights and Federal water quality control is going to emerge in the western States.

In the 17 western States where water is not so plentiful, we have only to compare the value of land with water rights with the value

of land without water rights to learn the value of water and to understand its critical importance. Because water was found only in certain places and shortages were encountered almost from the time of settling, in the western States the unique system of water law known as the prior appropriation doctrine has developed.

Under the prior appropriation doctrine, priority of application of water to a beneficial use gives one the right to use the water so appropriated so long as the use is maintained. This system is often characterized by the catch phrase, "First in time, first in right." To illustrate, a junior appropriator located upstream cannot divert water for his own use to the detriment of a senior appropriator downstream. The doctrine of prior appropriation is written into several State constitutions and defined by State laws. Generally, its administration results in specific allocation of streamflow to water users under the jurisdiction of a State administrator.

In the western States where the prior appropriation doctrine has developed, the average annual rainfall is relatively low compared to the humid East and the major appropriative use is agricultural irrigation, which is a highly consumptive use. It is estimated that two-thirds of the water applied to crops does not return to the water source. On the other hand, municipal and industrial use, which is the large use in the East and is becoming increasingly more important in the West, is generally nonconsumptive and more than 90 percent of the water withdrawn is returned to the surface waters. In the 17 western States it is estimated that over 90 percent of the available water is used for irrigation; in the 31 eastern States it is estimated that less than 5 percent is used for irrigation.

The western States have embraced the prior appropriation doctrine, but laws vary considerably from State to State. Only seven — Arizona, Colorado, Idaho, Nevada, New Mexico, Utah, and Wyoming — have no elements of the riparian, or reasonable use, doctrine that is prevalent in the East. Since the prior appropriation doctrine of water rights deals with a commodity that is very precious in the western States, it has been the subject of much litigation. In any particular jurisdiction there are apt to be numerous judicial benchmarks that delineate the rights, duties, and privileges of water users.

The riparian use doctrine, on the other hand, has been adopted by the eastern and midwestern States. The riparian use doctrine was embodied in the common law of England; it was practiced in the early colonies and is presently applicable in modified form in all but one or two of the eastern jurisdictions. The riparian doctrine is based on the premise that running water is not susceptible to unqualified ownership and that the right to use such water is incidental to property ownership. Thus only riparian owners, that is, people who have land abutting a watercourse or who have a watercourse running through their land, are entitled to use of surface waters, or have riparian rights. Under the riparian doctrine such persons have a right to the use of the streamflow passing through their land in its natural state, i.e., undiminished in quantity or quality.

In the development of the riparian doctrine and in the resolution of conflicting riparian rights, it soon became evident that the riparian's right to receive the stream undiminished in quantity and, especially, in quality is not unlimited. His right to the enjoyment of the stream is subject to similar rights of all other riparian owners in their reasonable enjoyment of the stream. Therefore, it is against the unreasonable use of this common benefit that legal action can be taken. This modification of the riparian doctrine, enunciated in 1874 by Justice Cooley of Michigan as the reasonable use doctrine, is the form used by the midwestern and eastern States.

A corollary of the reasonable use doctrine is the right of the riparian owner to be free of unreasonable interference in the use of water. Reasonable use is the only measure of riparian rights and the question of reasonableness is a question of facts. A characteristic of the eastern system of water rights is the absence of frequent litigation. Water users have generally achieved an accommodation of their needs through private arrangements and surprisingly few cases have come before the courts. Although this has the advantage of providing a flexible system of operation, without the guidelines provided by numerous judicial decisions, it has left large areas of uncertainty. Increasing and often conflicting demands of municipalities, industries, and agriculture for water are making eastern water users acutely aware of the lack of certainty of their water rights.

I would expect that in dealing with augmented flows provided through flow regulation for water quality control we will continue to have this uncertainty in the East. I would also expect that with its tradition an accommodation will be reached in the East based on negotiation rather than on legal action. In the 17 western States, however, we are more likely to run into situations that will involve legal actions. It boils down to the fact that there is more water in the East and therefore more room for accommodation. In the West water rights are essential to property rights and are therefore a matter of life and death; every man is fighting for every acre-foot of water he can get.

FEDERAL INTEREST IN WATER RIGHTS

Along with this understanding of where water rights conflicts are likely to arise, we have to recognize that the Federal Government is now in the business of water pollution control. The Federal interest in water pollution control set forth in the Federal Water Pollution Control Act, as amended, indicates that the clock is not going to be turned back and that the Federal Government is in the water pollution control field to stay. The Federal interest arises for several reasons. From the following list I think the cogency of the Federal interest becomes apparent:

1. The relatively fixed fresh water supply. Give or take a wet or dry cycle, the nation's fresh water supply is just about the same now as it was when Columbus discovered the Americas.

2. The uneven natural distribution of water geographically and seasonally. There are 17 major river basins in the coterminous United States. The 48 coterminous States certainly do not coincide with the 17 major basins nor with the subbasins. Handling water pollution problems on a river basin basis, therefore, naturally brings in a national interest.

3. The rapid growth of population, industry, and agriculture — often where water is not plentiful. The tremendous growth of southern California where more than 10 million people depend on an adjacent basin — the Colorado River — for their water supply is an outstanding example.

4. The concentration of population and industry in urban communities and development of metropolitan complexes. The enormous increases in water use by the rapidly growing population, expanding industry, and intensified agriculture and the very large increases in waste discharges resulting from population and industrial growth, new technologies, and changing land use practices are seriously jeopardizing the suitability of the nation's water resources for needed use and reuse.

5. The failure to construct sewage and industrial waste treatment facilities as fast as they are needed to provide adequate water pollution control.

6. Lastly, the failure to develop means for dealing with new and complex water pollution problems as they have emerged.

I think that the national legislature has recognized all of these points in placing the Federal Government in the business of water quality control.

COOPERATION IN QUALITY CONTROL

On many of these points, dealing with the States with regard to water quality control has been *relatively* — and I emphasize that word "relatively" — simple. Right now, for example, we have a large water quality study going on in the Colorado River Basin. California and Arizona are meeting amicably with five other States and the Federal Government. California and Arizona are both interested in water quality control, despite their differences in the quantity dispute. As a matter of fact, I can illustrate the difference in feeling. During a meeting in Phoenix we needed a map of a particular portion of the basin. A map was secured from the State files, but when it was put up, a murmur arose throughout the room and would not subside. On investigation we found that on the map there were numbers relating to the distribution of water between Arizona and California. Even though it was pointed out that the map was displayed only to indicate where the river flowed, the people could not get their minds off the numbers, and not until the map was removed could we proceed with the discussion.

Regardless of conflicting interests in quantity of water, I think

that in the field of water quality we have reached an area of accommodation where all the States can work together, because whoever gets the water in whatever quantity wants the water in the best possible condition.

SOURCES OF FEDERAL-STATE WATER RIGHTS CONTROVERSY

We might outline, now, as candidly as we can, the sources of Federal-State controversy in water rights.

Many Federal statutes dating from the latter part of the nineteenth century led people to suppose that the United States had permanently transferred control of water rights to the States in the patents that authorized the acquisition of water rights under State law along with the acquisition of land in the West. In addition, in legislation admitting several of the western States to the Union, Congress accepted State constitutions with provisions that included the recognition and confirmation of existing water rights. This also led to the notion that the Federal Government was relinquishing control of water rights to the States.

Then there are the acts under which the Federal Government entered water resource development activity. So that there are no hidden skeletons in the closet on this issue, I think it is useful to review the acts.

The Federal Reclamation Act of 1902 included a provision that Federal activities should not interfere with State laws relating to the control, appropriation, use, or distribution of water used for irrigation or any vested right acquired thereunder. This provision is typical of subsequent reclamation laws.

The Federal Power Act of 1920 provided that the Act was not to be construed as affecting or intending to affect, or in any way to interfere with State laws relating to the control, appropriation, use, or distribution of water used for irrigation, for municipal purposes, or for other uses or in any other vested right acquired thereunder.

In the Flood Control Act of 1936, for the first time, it was declared to be a national policy for the Federal Government to engage in flood control activities because of the adverse effects of floods on commerce between the States and on the national welfare. This created quite a storm, and in the Flood Control Act of 1944, it was declared to be the policy of Congress to recognize the interests and rights of the States in determining the development of watersheds within their borders and to limit the use of works authorized for navigation to those purposes that do not conflict with any beneficial consumptive use of water in the 17 western States. These statements of policy have been repeated in the Omnibus Rivers and Harbors Bills each year to give the notion of States' rights in this area.

Essentially the same declarations are included in the Watershed Protection and Flood Prevention Act of 1954. Section 4 of the Act

establishes as one of the prerequisites for Federal assistance in watershed development the requirement that a local organization or the land owners acquire such water rights pursuant to State law as may be needed in the installation and operation of the works of improvement.

Finally, in the Federal Water Pollution Control Act, as many of you know, it is ". . . declared to be the policy of Congress to recognize, preserve, and protect the primary responsibilities and rights of the States in preventing and controlling water pollution , . . ." Section 1(b) further provides that ". . . nothing in this Act shall be construed as impairing or in any manner affecting any right or jurisdiction of the States with respect to the waters (including boundary waters) of such States."

This series of acts has been taken by many people to mean that the Federal Government has relinquished its primary rights in water, or water rights, to the States. On the other hand, if the United States had relinquished its rights, why was it necessary to repeatedly acknowledge State authority in these statutes? In other words, the primacy of Federal rights in water was implicitly acknowledged in each of these statutes. The fact is that Federal rights and responsibilities in water could not be relinquished under the Constitution.

On the other hand, it should be noted that no change has been made in the provisions of the Constitution dealing with the control of water under the commerce clause, the general welfare clause, the national defense clause, or the treaty-making clause. The Federal sovereignty with respect to navigation has been generally affirmed.

As has often happened in American history, while the statutes repeatedly have recognized State authority, Federal court decisions have almost uniformly upheld Federal sovereignty against claimants of water rights under State law. That is, the courts have generally held for the Federal Government. So, while the Congress has continued to enact this series of laws recognizing States' rights, a series of Federal court decisions have pretty uniformly upheld Federal rights whenever they have conflicted (or apparently conflicted) with States' rights.

I think it is appropriate to call attention to some of these cases. The most famous cases — United States vs. Rio Grande Irrigation Company in 1899 (174 U.S. 690) and Winters vs. United States (207 U.S. 564) — generally have made it clear that the sovereignty of the United States over waters coming under the commerce and treaty-making clauses of the Constitution has not been broadly relinquished by any statutory enactments.

Among other court decisions along this same line, the classic case is the United States vs. Appalachian Power Company (311 U.S. 377) decided by the Supreme Court in 1940. Although this case dealt with structures, the scope of the language of the decision is instructive. In it the Supreme Court stated:

"This power of Congress to regulate commerce is so unfettered that its judgment as to whether a structure is or is not a hindrance is conclusive. Its determination is legislative in character."

The Court went on to say:

"In our view it cannot be properly said that the constitutional power of the United States over its waters is limited to control for navigation. By navigation respondent means no more than the operation of boats and improvement of the waterway itself. In truth, the authority of the United States is the regulation of commerce in its waters. Navigability, in the sense just stated, is but a part of this whole. Flood protection, watershed development, recovery of the course of improvements for utilization of power are likewise parts of commerce control. That authority is as broad as the needs of the Congress."

One of the cases that created — at least in my opinion — the most heat and the least light was the famous case of the Federal Power Commission vs. Oregon (349 U.S. 435), the case more familiarly known as the Pelton Dam Case. In deciding this case in 1955, the Supreme Court affirmed the supremacy of Federal jurisdiction over unappropriated non-navigable water arising or flowing over reserved lands of the United States, and in the western States the Federal Government has quite a bit of reserved lands.

One case that is creating a lot of controversy but is still before the courts is the United States vs. Falbrook Public Utility District (165 Fed. Supp. 806). Although I do not believe it proper to talk too much about this case, I do want to quote from the lower court opinion to give the flavor of what is happening. The lower court cited the decision of the Supreme Court in the case of the city of Tacoma vs. Taxpayers of Tacoma (357 U.S. 320) and stated:

"It is no longer open to question that the Federal Government under the Commerce Clause of the Constitution (Art. 1, Sec. 8, Cl. 3) has dominion, to the exclusion of the States, over navigable waters of the United States."

The District Court then continued:

"It is our conclusion that as to the use of water for power projects, the Supreme Court has made it clear that Congress has acted to endow the projects with such a public interest that State action shall not be permitted to interfere with the functioning of the projects."

From these citations you can see that the situation is a relatively critical one. It is relatively easy to say, "We can solve Federal-State water rights questions on a case-by-case basis," and this method will continue unless we arrive at a conclusion acceptable to both the States and the Federal Government. When water rights questions are solved on a case-by-case basis before the courts, however, the Federal Government has generally won.

EFFECT OF EXERCISE OF FEDERAL WATER RIGHTS

We may be dealing with a theoretical issue. With all the controversy over Federal and State water rights, perhaps we should ask, "Who has been hurt?" Aside from the theoretical question of States rights and State privileges versus the supremacy of the Federal Constitution, *who has really been hurt?*

First I would like to quote Assistant Attorney General Ramsay Clark, who heads the Lands Division, which handles water questions in the Department of Justice. He said:

> "For all the hue and cry arising from this controversy, not one state, not one county, not one municipality, not one irrigation district, not one corporation, not one individual has come forward to plead and prove that the United States, exercising alleged proprietary rights in the unapproved waters of public domain, has destroyed any govermental power or property right. Why? because it has not happened."*

Now a view from another spokesman, Senator Frank Moss of Utah, who I think may fairly be said to represent the western States' point of view in this issue. He said recently:

> "I must confess that a rather detailed perusal of many articles on the subject of Federal-State conflict in water rights has failed to turn up many cases where actual damages can be shown. The few cases I have uncovered where actual damages due to loss of water seems to be demonstrated appear to be based on disputes over water rights acquired by the Federal Government by purchase or in other manner under State law."**

I think these positions are not very far apart.

Especially in dealing with water quality under the Federal Water Pollution Control Act, we have a situation where there need be no conflict between the States and the Federal Government. Although the potential for conflict is certainly there and it would be expecting the millenium to expect that none will develop, it will be the result of baseless discord, both State and Federal, rather than principles, if conflict does develop. All too often conflict has revolved around the development of potential water rights that have never actually been exercised.

REDUCTION OF CONFLICT

What can be done to prevent conflict over water quality control? First the Federal agencies must reach an accord on how water quality control will be handled, decide when water will be released for

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*Speech, National Association of Counties, Grazing, Water, and Revenue Conference, December 1962, Las Vegas, Nevada.

**Speech, Annual Midwinter Conference of the National District Attorneys' Association, Los Angeles, California, March 11, 1963.

quality control, who is to be responsible for releasing the water, and on what criteria.

Agreement among the Federal agencies is certainly an essential first step, but it is only a part of the solution. The Federal agencies and the States must also be in agreement as to the purposes for which water is released for water quality control. If the State governments and all the agencies of the Federal Government can agree on methods of operation — that waste control measures must be effectively enforced and that water released for quality control should remain in the stream to do its intended job — we will have the problem more than half licked.

I do not think that we should go beyond this. As in any water pollution control case, once Federal and State Governments see eye to eye, if anyone — individual, industry, or municipality — believes that he is being deprived of property without due process, then by all means he should have access to remedy through the courts. This is quite analogous to the condemnation procedure used in the building of Federal highways or the interstate system.

In the building of a road, taking of land or a building obviously involves compensation and the question is, "How much?" In the water field we are going to have two questions, "Is this man entitled to compensation?" and "If so, how much?" If the Federal agencies and the States can establish mutually acceptable guidelines and act together, water rights questions can be handled normally just as a private right or private compensation suit would be handled in a State court.

Another question that is going to arise — and I think that this has already come up on at least one river in the United States — is that of the withdrawal of released water from a stream before it has served its intended purpose. Who has the power to police these withdrawals? As I have tried to point out, I believe that the ultimate power and responsibility rests with the Federal Government. Water quality control is also in the State interest, however, and to avoid diversity of interest between the State and Federal Government, an agreement should be reached on how much water should be left in a streambed at any time for water quality control.

If on the other hand, a State joins with an adverse water appropriator in the name of State rights when one of these private water users takes water from a stream, thwarting the purposes for which a project was built and for which the water is released, we may all be in for a very, very difficult time.

In conclusion, let me come back to the Federal Water Pollution Control Act. The statute provides that storage may be included in Federal water resources projects "for regulation of streamflow for the purpose of water quality control." Once the Public Health Service has made a report on a project; once the needed storage has been included in a project by the Corps of Engineers or the Bureau of Reclamation; and once monies have been voted by the Congress,

contracts have been let, the project put in operation, and releases made for water quality control, I think that whoever tries to thwart the purpose of the Act by exercising supposed rights to the water made available is going to be reversed, if necessary, by the courts. This is not to say, let me make clear, that in specific cases someone may not have been deprived of a property right for which he is entitled to compensation.

As a last word, let me say that we in the Public Health Service recognize that we are facing a new problem and we are asking you to join with us in thinking it through. I am sure that we cannot leave it at, "You go your way and we'll go ours." We are extending a hand to you in the other Federal agencies and you in the State agencies and asking you to join with us in the recognition that we are going to have some most difficult technical problems to solve before we can properly incorporate water quality control in water resource development projects. I hope we will not make it more difficult by introducing unnecessary legal problems.

Session 2

EFFECTS OF IMPOUNDMENTS ON WATER QUALITY IN RESERVOIRS

Moderator: **B. B. Berger**
U. S. Public Health Service

This session is concerned with the quality changes associated with the conversion of a free-flowing stream into an impoundment. Specifically, we can ask these questions:

What is the phenomenon of stratification and how does it affect water quality?

What is the phenomenon of eutrophication and how do we associate it with stored water?

What are the particular chemical reactions that take place in stored water that we associate with the usefulness of this water?

Each of these questions is treated in this session.

GPO 821-740-3

THERMAL STRATIFICATION IN RESERVOIRS

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The principal purpose of this discussion is to provide a general background for some of the more detailed presentations that are to follow. This background is desirable for those who have not had occasion to examine the phenomena of thermal stratification of water in natural lakes or manmade reservoirs. It is hoped that a brief review of some of the factors involved will be of value even to those who have had reason to investigate the subject in the past, but may not have retained all of the knowledge gained at that time.

The first man who ventured into a small pond on a calm, sunny afternoon in prehistoric times probably noted one of the effects of thermal stratification. Those who have enjoyed the pleasures of swimming in the old mill pond have made the same observation. When a swimmer stays on the surface, the water feels warm; but when he lowers his feet to tread water, the deeper water feels cold. The sun has warmed the surface layer of water and caused a reduction in density. The reduced density produces a resistance to mixing of the warmer, lighter water with the colder, heavier water, and the warm water floats on top as a thermal density layer or stratum. This type of stratification usually is temporary and is soon destroyed, either by surface cooling at night, or by mixing resulting from wind-induced wave action.

Among the physical characteristics of water, its change in density with change in temperature is one of the most important in the behavior of water and its constituents in lakes and reservoirs. Quantitatively this change is small, being only 4.3 milligrams per cubic centimeter, or less than 0.5 percent, between the maximum density of 1.0 gram per centimeter at 4°C and that of 0.995673 gram per cubic centimeter at 30°C, which is about the upper limit of temperature for most surface waters.

Density changes of water with changes in temperature exhibit two unique characteristics that exert important influences on the characteristics of stratification in lakes and reservoirs. These characteristics are illustrated in Figure 1. The figure does not present actual densities, but rather differences in densities for 1°C for water temperatures of 0° to 30°C.

The sharp break in the curve at 4°C illustrates one of the characteristics. This shows that the minimum effect of temperature changes on densities occurs at 4°C, and increases on either side of this value. This coincides with the well-known fact that the maximum density occurs at 4°C, and is an important factor in the winter stratification of water.

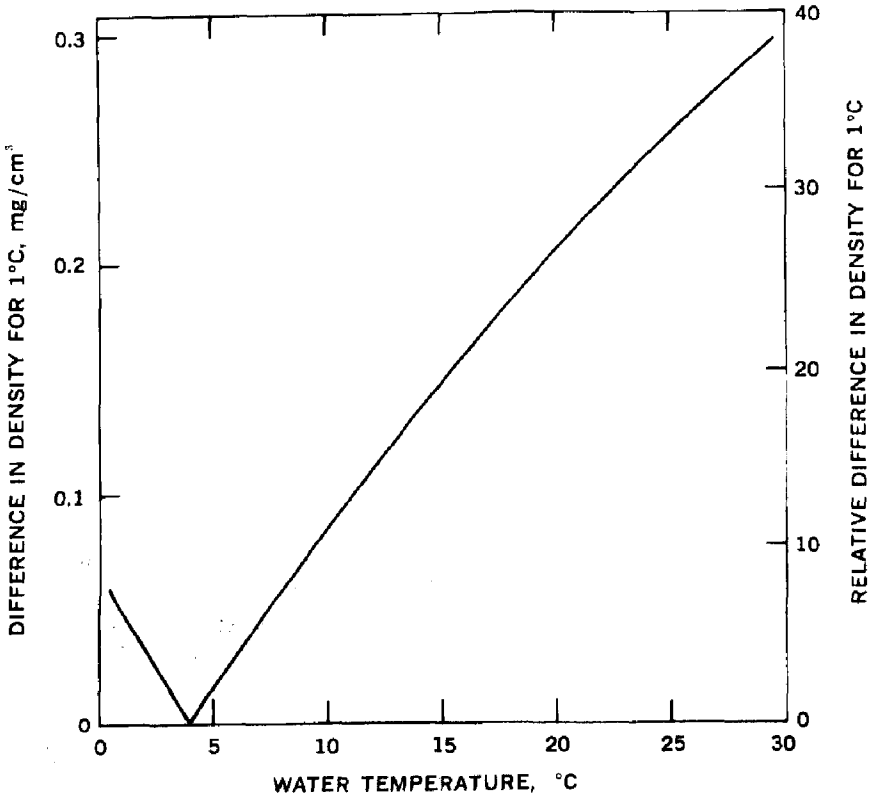

Figure 1 — Difference in water densities for various temperatures.

The other peculiarity is the very large density differences for 1°C temperature changes at the higher temperatures, compared to those at lower temperatures. Reference to the left vertical scale shows that there is a density difference of only about 0.008 milligram per cubic centimeter for 1°C change in temperature in the vicinity of 4°C, whereas there is a difference of nearly 0.3 milligram per cubic centimeter, or nearly 40 times as great, at 30°C. The relationships throughout the temperature range are shown by the right vertical scale. The resistance to mixing, or conversely the amount of work required to accomplish mixing, of water exhibits quantitatively identical relationships to temperature. For example, a column of water with a given height and cross section and a temperature of 22°C at the bottom and 23°C at the top would consume 30 times as much energy in mixing as would a similar column of water 4°C at the bottom and 5°C at the top. This fact explains why stable stratification may persist late into the fall with temperature differences as little as 2°C, whereas winter stratification may not occur in the absence of ice cover, and summer stratification does not start until the water mass has warmed and substantial differences in temperature from top to bottom have been established.

Knowledge of stratification in reservoirs has its origin in limnological studies involving natural lakes. A manmade reservoir may be considered as the upstream half of a natural lake, with a dam

taking the place of the downstream half. Obviously, many of the characteristics of lakes are reproduced in reservoirs. There are two important exceptions, however, which may lead to certain water quality problems downstream from reservoirs.

One exception involves the facilities for control of discharge from reservoirs, which may be operated to reduce downstream discharges below natural minimum flows.

The other exception involves the depths from which water is withdrawn from reservoirs. Water generally passes through natural lakes either by essentially complete displacement in the absence of stratification, or by flowage through the surface stratum when stratification exists. In both cases, water leaving the lakes has been subjected to normal aerobic processes of natural purification for extended periods of time and quality of the water usually is good. On the other hand, water discharged below reservoirs frequently is withdrawn from deep in the reservoir. In the absence of stratification this presents no problem. When stratification exists the water in the depths of the reservoirs may have been subjected to anaerobic processes of natural purification. These processes may produce undesirable water quality characteristics, such as low dissolved oxygen and excessive hydrogen sulfide, color, iron, and manganese, in the water downstream from the dams.

Thermal stratification may assume many patterns, dependent on geographical location, climatological conditions, depth, surface area, and other physical configurations of the lake or reservoir. This discussion is limited to description of only a few of the most typical patterns in reservoirs that are important to this symposium.

The simplest type of thermal stratification occurs in reservoirs that may be designated as run-of-the-river, or main stream, impoundments. Such a reservoir typically is impounded by a relatively low dam, and the impounded waters do not extend far beyond the limits of the natural river channel. Fluctuations in water level are limited to a few feet. Detention in the reservoir is only a few days or at most a few weeks. Although flow velocities are low, they usually are appreciable and in a positive downstream direction. Passage of water through the reservoir is by total displacement. If power production is involved the top of the penstock intake may extend from near the bottom to within 15 to 20 feet of the water surface.

Thermal stratification in this type of reservoir, which occurs most frequently in warm weather and is somewhat similar to that described in the old mill pond, is illustrated in Figure 2. The parallel horizontal temperature lines indicate a gradual temperature gradient decreasing from top to bottom through a moderate range of 25° to 20°C.

The temperature differences are caused by the manner in which the sun warms bodies of water. The upper layers of water absorb the larger portions of the sun's energy with only minor portions reaching the lower depths. As the depth increases arithmetically the

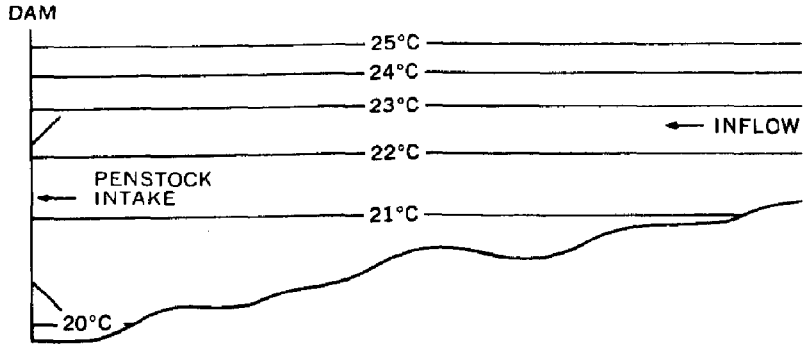

Figure 2 — Main stream reservoir — summer stratification.

energy absorption decreases geometrically, following the law of constant proportionality. Although the rates of absorption differ greatly among various bodies of water, it appears that a reasonable average for clear natural water may be about 30 percent of the entering energy in each 3-foot layer of water. Thus, roughly 70 percent of the surface energy may remain at 3 feet, 5 percent at 15 feet, and 1 percent at 30 feet. The depth relationship to energy absorption is reflected by the logarithmic spacing of the temperature lines in Figure 2.

The warmest water, at the surface, has the lowest density and therefore tends to remain at the surface, with the coolest and most dense water on the bottom. This stratification does not occur if stream velocities are sufficient to provide the energy necessary to overcome the resistance to mixing inherent in the different water densities. The velocities may be those of either the downstream flow of the water or currents induced by wind. Many main stream reservoirs have neither the necessary flow velocities nor long, unbroken surface reaches that would permit the wind to induce mixing velocities.

The effects of this type of stratification on water quality have not been found to be nearly so important as are the effects of the classical three-layer pattern of stratification, which occurs in many storage reservoirs. The principal adverse effect of the temperature gradient is the reduction in reaeration that results from the reduction in vertical circulation of the water. Dissolved oxygen concentrations as low as 5 milligrams per liter have been found in a number of main stream reservoirs at locations far from significant sources of pollution.

The classical three-layer stratification pattern that occurs in many storage reservoirs is much more complex than the simple thermal gradient pattern found in main stream reservoirs. The differences between the two types of reservoirs in physical configuration, dam design, and reservoir operation contribute to the differences in stratification patterns.

The typical storage reservoir usually is located on a tributary

rather than on a main stream. The stream is impounded by a relatively high dam of 100 to 125 feet or more. The impounded waters extend far beyond the natural river channel and into many embayments to form long unbroken reaches of surface on which wind may act to induce currents, waves, and mixing of the waters. Fluctuations in water level of as much as 70 to 80 feet or more throughout the year are common. The storage capacity in relation to drainage area is large, and detention is several months. Flow velocities in much of the reservoir are negligible and may be influenced more by wind-induced currents than by downstream movement of the water. Passage of water through the reservoir is discontinuous, and quantities of the water may remain in storage for nearly a year. Drawdown of the reservoir dictates that the discharge intakes be located deep in the reservoir, below the minimum level to which water will be drawn.

Figure 3 shows the thermal pattern that occurs in late winter or early spring. The reservoir water is cold, and at 6°C has a low resistance to mixing. The water is easily mixed by wind action and has a uniform temperature from top to bottom.

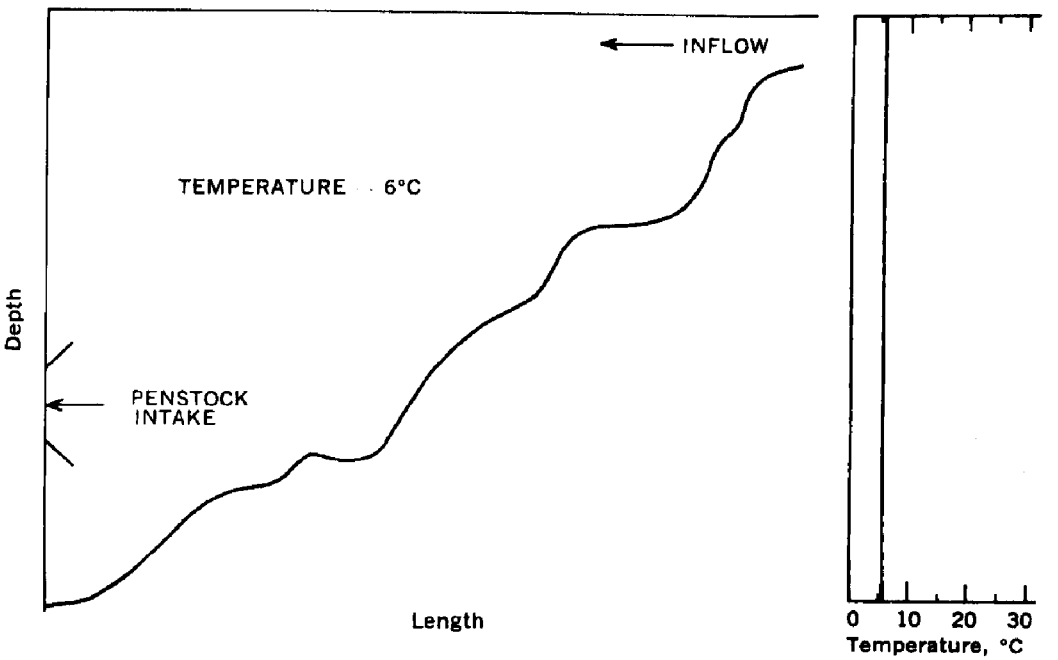

Figure 3 — Storage reservoir — spring temperature pattern.

As the season advances and atmospheric temperatures become higher, both the inflowing tributary water and the surface water in the reservoir warm up more and more rapidly, and become more and more resistant to mixing. Finally, the resistance to mixing becomes great enough to overbalance the ability of the wind to accomplish circulation to the bottom of the reservoir, and stable stratification is established. This may occur as early as April in the southern portion of the country, and a month to 6 weeks later in the northern portion.

The resulting summer stratification is illustrated in Figure 4. This figure shows the classical three-layer stratification to which limnologists have devoted so much study in natural lakes.

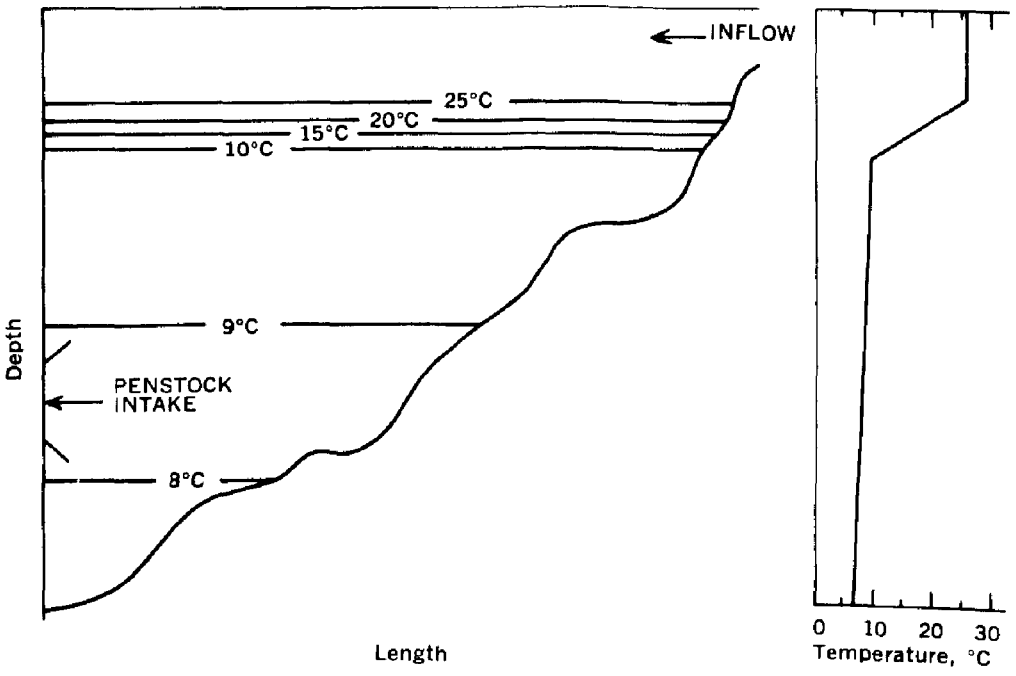

Figure 4 — Storage reservoir — summer stratification.

The upper stratum, or epilimnion, may be 30 to 50 feet deep. The reservoir is mixed to this depth by wind-induced currents, and has a uniform temperature, which in this instance is 26°C.

The quality of water in the epilimnion usually is quite good. Prolonged storage and reaeration permit the forces of natural purification to accomplish maximum benefit. Organic wastes are stabilized, and dissolved oxygen usually is near saturation. Bacterial contamination is reduced to a minimum. Silt is practically eliminated and color is decreased. Wide variations in water quality are reduced and relatively constant quality is achieved. The only adverse effect may be excessive growth, or blooms, of algae, with attendant taste and odor production.

Below the epilimnion is the thermocline, which may be 10 to 20 feet deep. As its name implies, the thermocline is a stratum in which temperature decreases rapidly as depth increases. The thermocline has been defined for convenience, though on a strictly arbitrary basis, as a stratum of water in which the temperature decreases 1°C or more in a depth of 1 meter, or 0.55°F in 1 foot. The decrease in temperature is accompanied by an increase in density, with a corresponding increase in resistance to mixing. In Figure 4 the temperature of the thermocline decreases from 26°C at the top of the stratum to 10°C at the bottom.

A well-established thermocline is quite stable and has a strong

resistance to mixing. It serves, in a manner similar to a flexible diaphragm, to separate the top and bottom strata of water. Figure 5 illustrates the stability of the thermocline. Here the wind has been blowing strongly from left to right across the reservoir. The water of the epilimnion has been driven toward and piled up on the right side of the lake, forcing the thermocline on that side deep into the reservoir. Correspondingly, the left side of thermocline has risen toward and actually intercepted the surface of the reservoir. As a result, a portion of the cold water of the thermocline is exposed at the left bank of the reservoir. Despite this displacement, when the wind stops blowing, the thermocline returns to its former horizontal position without breaking up. This return is accomplished by a series of oscillations during which the opposite sides of the thermocline alternately rise above and fall below the normal horizontal level until finally the normal position is resumed. The series of oscillations is known as a seiche.

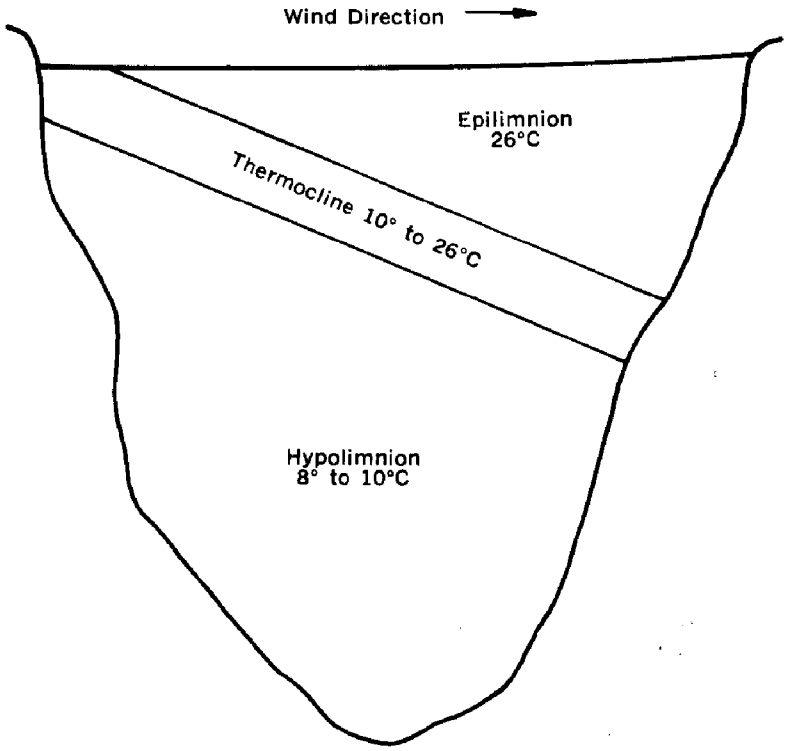

Figure 5 — Storage reservoir — summer stratification wind tilted thermocline.

The bottom stratum of the reservoir, below the thermocline, is the hypolimnion. Here the water is excluded from the atmosphere by the overlying thermocline and epilimnion. Very little light and heat from the sun penetrate to these depths, and very little increase in temperature occurs after stratification is established. Most of the increase takes place in the upper portion of the hypolimnion, which produces a slight temperature gradient from top to bottom. In Figure 4 the temperature of the hypolimnion is 10°C at the top and 8°C at the bottom.

Summer stratification may persist until late October or early November in the southern portion of the country, and may terminate a month or so earlier in the northern portion. During the 4 to 6 months of summer stratification, the hypolimnion is unable to replenish its dissolved oxygen, and decomposition of organic matter present in the water, in bottom deposits, and in dead plankton, which settle from the top strata continuously, depletes the available oxygen. In the hypolimnions of many reservoirs, even though man-made pollution may not be involved, total depletion of dissolved oxygen occurs. During the period of anaerobic, or septic, decomposition that follows, hydrogen sulfide may be produced, color may increase, and the iron and manganese contents of the water may reach objectionable levels. Water withdrawn from such a hypolimnion and discharged to the stream below the dam contains the objectionable constituents and is deficient in dissolved oxygen.

Some storage reservoirs do not exhibit this classical type of stratification. Those reservoirs that do not store substantial volumes of water at winter temperatures or that discharge such water before warm weather occurs do not develop thermoclines. Some reservoirs that are relatively shallow and have broad expanses of surface areas exposed to strong winds may not develop thermoclines. These types of reservoirs may, however, exhibit temperature gradients like those in main stream impoundments.

Total oxygen depletion does not occur in the hypolimnions of some reservoirs. There is some evidence that water poor in the nutrients that support aquatic life may not develop sufficient organic material to exhaust the dissolved oxygen through decomposition.

As atmospheric temperatures drop in the fall, inflowing tributary streams and surface water in the reservoir become cooler. This cooler water is mixed throughout the epilimnion and the upper portion of the thermocline by convection and wind action. Cooling continues until the temperatures and densities of the epilimnion and thermocline approach those of the hypolimnion. Finally, the resistance to mixing is reduced to the extent that wind action can mix the water to the bottom of the reservoir, and the temperature becomes uniform from top to bottom as illustrated in Figure 6. This occurrence is known as the fall overturn.

In the southern portion of the country, where surface water temperatures rarely drop below 4°C, no stratification occurs in winter, and temperatures remain uniform throughout impoundments. In northern areas, where temperatures drop as low as 0°C, and especially where ice cover forms, winter stratification occurs.

The temperature pattern of winter stratification is the reverse of that in summer, as shown in Figure 7. The colder, but in this case lighter, water at 0°C is at the surface, below the ice cover. The warmer water, with its maximum density at 4°C, is on the bottom. The temperature increases sharply from 0° to 4°C in the surface stratum, and resembles a thermocline, though it is not commonly designated as such. The temperature of most of the water is 4°C.

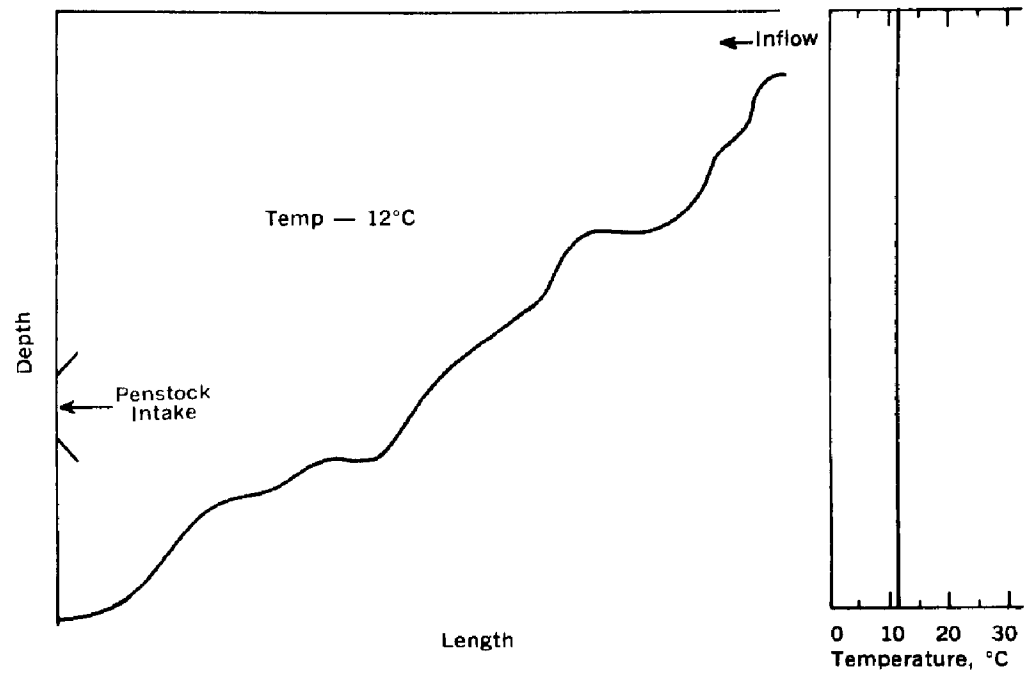

Figure 6 — Storage reservoir — fall temperature pattern.

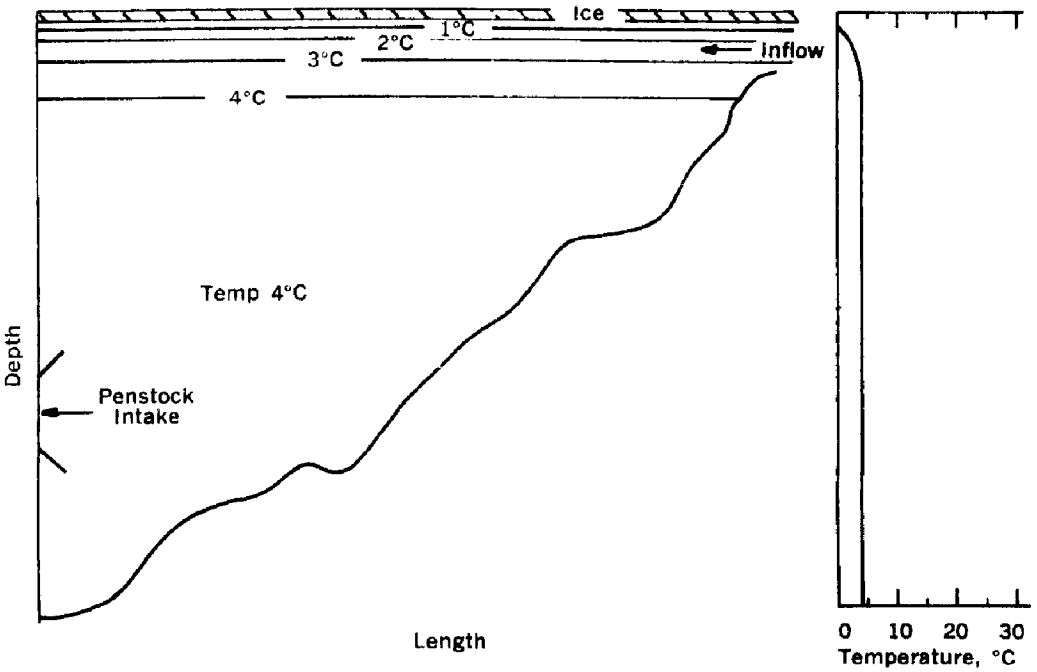

Figure 7 — Storage reservoir — winter stratification.

Total depletion of dissolved oxygen during winter stratification may occur near the bottom of the reservoir, as a result of decomposition of bottom deposits. Total depletion throughout the entire depth is rare and apparently occurs only in shallow lakes under somewhat abnormal conditions. At the start of stratification, the dissolved oxygen concentration is greater in winter than in summer. At winter temperatures, rates of organic decomposition are low, and reduced plankton productivity yields less dead plankton than in summer to deplete the oxygen.

The quality of water withdrawn from the lower levels of reservoirs in winter generally should be better than that in summer.

As atmospheric temperatures increase in spring, reservoirs that have been stratified during winter pass through the spring overturn and return to the uniform temperature distribution illustrated in Figure 3.

A type of stratification that has been observed in reservoirs but has no known counterpart in natural lakes deserves mention. This has been found only in main stream reservoirs that receive cool water from upstream storage impoundments. It is produced only when the water flows through a reservoir at appreciable velocities and requires large portions of the cross sectional areas of the reservoir for passage. The resulting stratification is illustrated in Figure 8. The incoming water at 20°C is about 6°C colder than normal surface water during midsummer. The flowing water occupies the entire cross sectional areas of the upper end of the reservoir. From about the middle of the reservoir on downstream, only portions of the larger cross sectional areas are required. The portions not required by the flowing water, above the top of the penstock intake, are occupied by a wedge-shaped body of warmer water, consisting of a thermocline and an epilimnion. The thermocline is not horizontal, but is approximately parallel to the bottom slope of the reservoir and is held in this position by the cooler water flowing beneath it. The stability of the thermocline is revealed by the fact that its upstream end, which intersects the water surface, moves upstream when streamflow is reduced and downstream when streamflow is increased, but is not destroyed unless streamflow becomes extremely high.

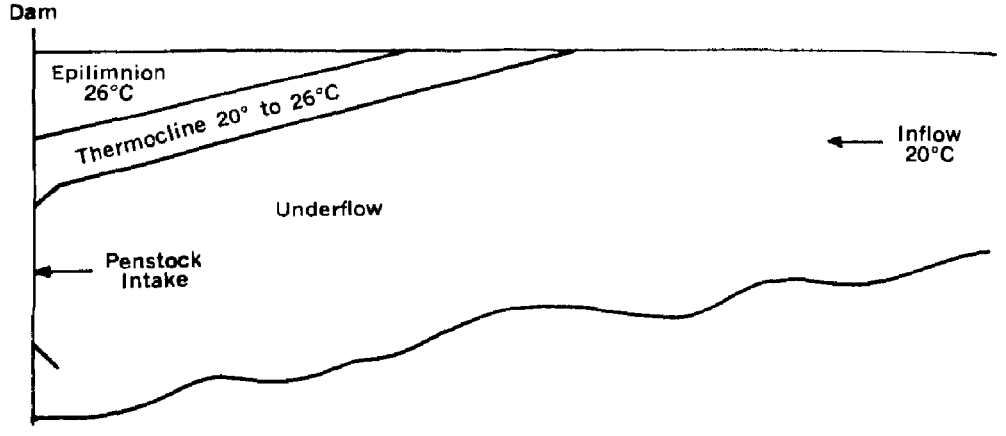

Figure 8 — Main stream reservoir — current tilted thermocline.

This type of stratification is not common at present, but will become more prevalent as river systems are developed more completely, with storage reservoirs pouring cold water into downstream reservoirs.

The principal effect of such stratification on water quality results from the elimination of reaeration of the water flowing beneath the thermocline. If the flowing water has a significant oxygen demand and if it requires several days to pass through the lower end of the reservoir, excessive depletion of dissolved oxygen may result.

DISCUSSION

Dr. Donald R. F. Harleman*

California Institute of Technology, Pasadena

Mr. Kittrell has described clearly the phenomena of thermal stratification in reservoirs. The purpose of this discussion is to show quantitatively how thermal stratification in a reservoir affects the quality of the water released.

We are concerned with a complex fluid-mechanics problem involving the interrelationship between the vertical density distribution resulting from the thermal structure and the vertical velocity distribution induced in such a fluid by the inflow to the reservoir at the upstream end and by the withdrawal of water by a turbine intake at the downstream end.

To simplify the problem somewhat, let us consider a large reservoir in which the flow pattern is primarily controlled by the discharge at the turbine intakes on the face of the dam. This is an especially good example if water is stored in the reservoir during spring runoff, and during the summer season of thermal stratification the rate of water release is appreciably greater than the rate of inflow. We can further visualize a rectangular box in one end of which the wall represents the dam and a horizontal slot represents the turbine intake, or reservoir outlet.

If the fluid in the box is of constant temperature and density, vertically, the streamline pattern a short distance upstream of the outlet is a series of equally spaced parallel lines as shown in Figure 1. Thus the percentage of the total flow from all depths is the same regardless of the elevation of the outlet slot. Hence the vertical position of the outlet has no effect on the quality of water released, it being a simple average of the vertical distribution of any constituent such as iron content or dissolved oxygen within the reservoir.

As a second case, we will consider a similar box in which the fluid has a vertical temperature distribution such that the fluid density increases linearly with depth. This is actually a more com-

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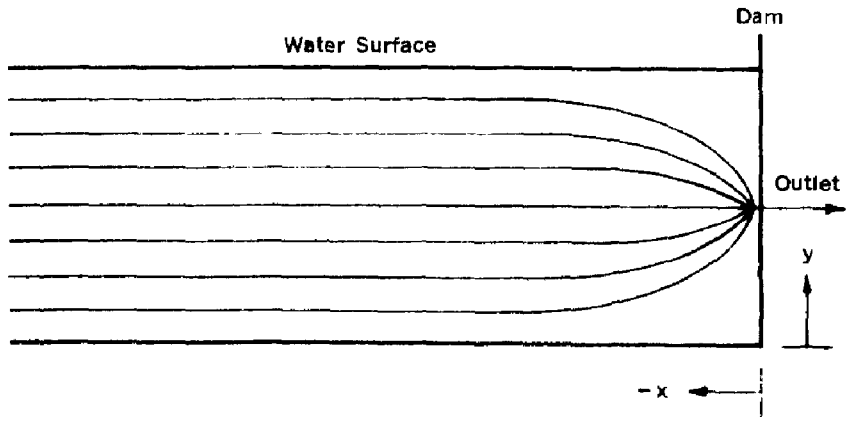

Figure 1 — Stream lines in a reservoir of uniform density.

plicated problem from the fluid-mechanics viewpoint than the three-layer system described by Kittrell. The three-layer system of epilimnion, thermocline, and hypolimnion (with turbine intakes deep in the hypolimnion) is rather simple, fluid-mechanically, since all the water is drawn from the hypolimnion. There are many reservoirs, especially the deep ones that store during the spring and then release during the summer, in which the distribution of temperature is perhaps better approximated by a linear gradient rather than by the sharp thermocline previously discussed. Theoretically and experimentally we can show that, under conditions of a density gradient, internal velocity concentrations will occur; that is, there will be a strong peak in the vertical distribution of horizontal velocity in the vicinity of the elevation of the intake and, therefore, the quality of the water discharged will be strongly influenced by the concentration of constituents at the elevation of the intake. The velocity concentration is due to the fact that the vertical density gradient tends to stiffen the fluid against vertical motion and relax it to horizontal motion.

Several interesting and analogous situations occur that are familiar. One is in the atmosphere where a vertical temperature gradient is always present. If horizontal pressure gradients exist, as they almost always do because of high and low pressure areas, the phenomenon known as the jet stream develops. Furthermore, this phenomenon also exists in the ocean where there are always temperature gradients. The main currents of the ocean — the gulf stream, and so on — are manifestations of these velocity concentrations.

Theoretically, there are two methods of analyzing the problem of velocity concentrations in a stratified fluid with a linear distribution of density. Although the basic assumptions are quite different both methods point to the existence of selective withdrawal.

The first method of analysis(*1*) neglects viscosity and heat conduction and considers only the dynamics of an incompressible fluid under gravity whose density increases linearly with depth. The solu-

tion for the flow pattern in a reservoir, or in the hypothetical box, due to the withdrawal of water as from a turbine intake can be found in terms of a single dimensionless parameter known as the densimetric Froude number

$$F_1 = \frac{Q}{W z_0^2} \sqrt{\frac{\rho z_0}{g\beta}}$$

Where: Q = turbine discharge in cubic feet per second at the time of temperature measurement.

W = width of the reservoir in feet at place where the temperature measurement was made and at the elevation of the centerline of the turbine intakes.

z_0 = vertical distance in feet between the water surface and the centerline of the turbine intakes.

ρz_0 = density of water at the center line of the turbine intake in slugs per cubic foot.

g = acceleration of gravity (32.14 feet per second per second).

β = slope of the linear density curve for the underflowing layer of water, b, computed in slugs per cubic foot per vertical foot.

This parameter incorporates the characteristic dimensions of the system such as depth of the intake, the flow rate, and the vertical density gradient. For values of this parameter of the order of magnitude of unity the streamline pattern is essentially the same as for a homogeneous fluid. At a densimetric Froude number of $1/\pi$, or roughly one-third, however, the solution becomes mathematically imaginary and the physical interpretation is that the process of internal velocity concentrations or selective withdrawal must begin at this point.

Within the range of reservoir dimensions, flow rates, and temperature gradients of interest in actual practice, the value of the densimetric Froude number is of the order of 0.01. This means that under conditions of even the smallest vertical temperature gradient, a selective withdrawal can be expected to occur. This theoretical approach is therefore of little value in quantitative prediction of the flow mechanics, but it has proven the existence of the effect we are seeking. More importantly, it indicates that in the range of interest the inertial forces are very small compared to the gravitational effects of the density gradient since the densimetric Froude number expresses physically the ratio of the two forces.

This has led to the development of a second theoretical approach, which we are now analyzing and experimenting with at the California Institute of Technology.

The second theory(2) considers both viscosity and heat conduction in an incompressible fluid having a vertical density gradient.

To solve the equations of motion, the inertial forces, which were shown to be small, are neglected The analysis indicates a strong velocity concentration in the reservoir at the elevation of the outlet. In addition, it indicates a reverse flow over a significant portion of the velocity distribution in a vertical section. The shape of the velocity distribution is a function of a single dimensionless parameter incorporating the gravity constant, the density (or temperature) gradient, the coefficient of heat conduction, and the viscosity of the fluid.

The objective of this research program, which is supported by the Division of Water Supply and Pollution Control of the Public Health Service, is to obtain a method for determining the characteristics of the water released through an outlet from an impounding reservoir. If we know the vertical distribution of any constituent of interest, such as DO for example, we want to be able to predict the concentration in the water released. Furthermore, we want to predict the change in the concentration of the constituent as a function of the elevation of the outlet.

Figures 2 to 5, which deal with a study in which I cooperated with the Walla Walla District of the Corps of Engineers and the Tennessee Valley Authority (3), illustrate some of the points I have made.

Figure 2 shows a typical series of vertical temperature profiles taken 700 feet upstream from Fontana Dam. The profiles indicate that the stratification during the summer months is not of the classical three-layer pattern, but rather show a gradual increase of temperature with depth.

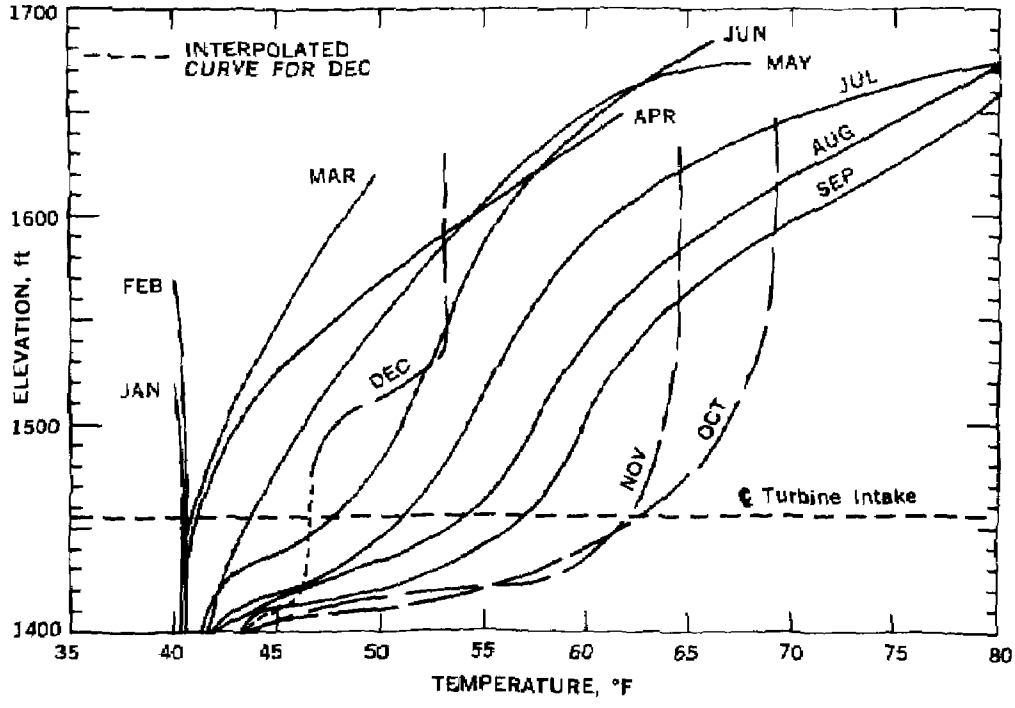

Figure 2 — Typical temperature profiles, Fontana Reservoir. Data for 1945.

Figure 3 shows typical temperature and density curves for Fontana Reservoir. The data available were observations of temperature at regular intervals about 700 feet above the dam. From this the vertical distribution of density was calculated. This showed that over an appreciable region the distribution of density was essentially linear.

Figure 4 is a schematic of an internal density current. It was assumed that the bottom of the moving layer was established at the break in the density curve. The thickness was estimated as the vertical depth, b, necessary to give the observed discharge temperature, based on the assumption that velocity was uniform over the depth of the density flow.

The correlation of the vertical thickness of the moving layer with the densimetric Froude number was only moderately successful as shown by the scatter on Figure 5; it indicated, however, that further research and perhaps laboratory experiments would be fruitful.

Figure 6 shows the experimental apparatus used in laboratory experiments at the California Institute of Technology.

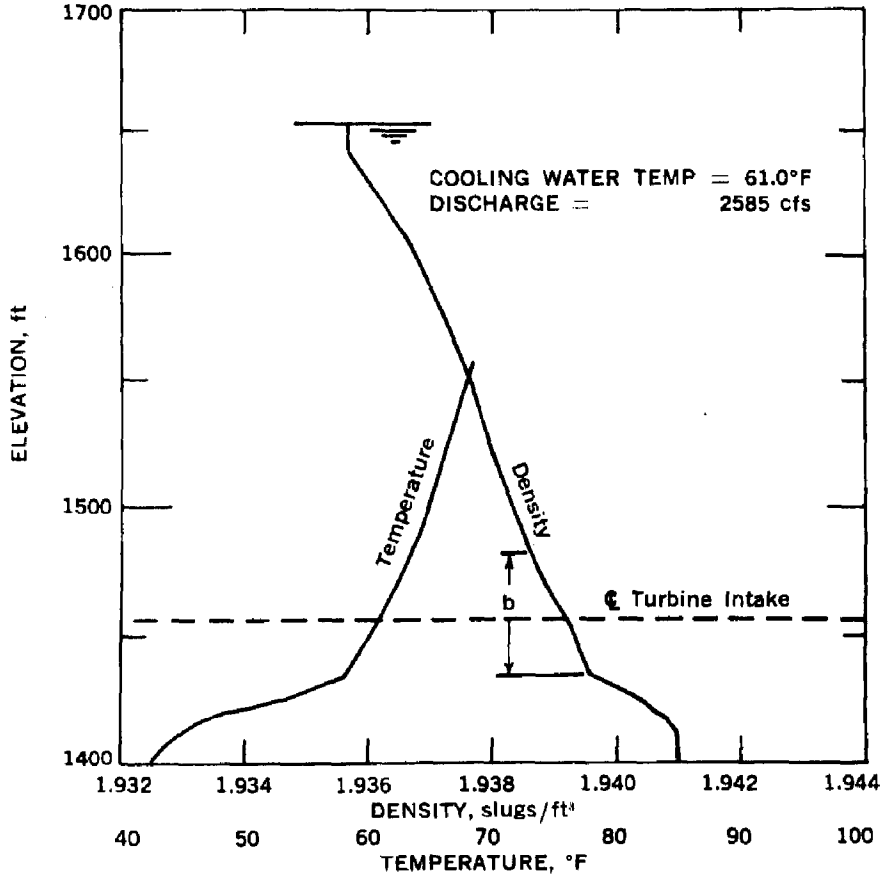

Figure 3 — Typical temperature and density profiles in Fontana Reservoir. Data for October 3, 1945.

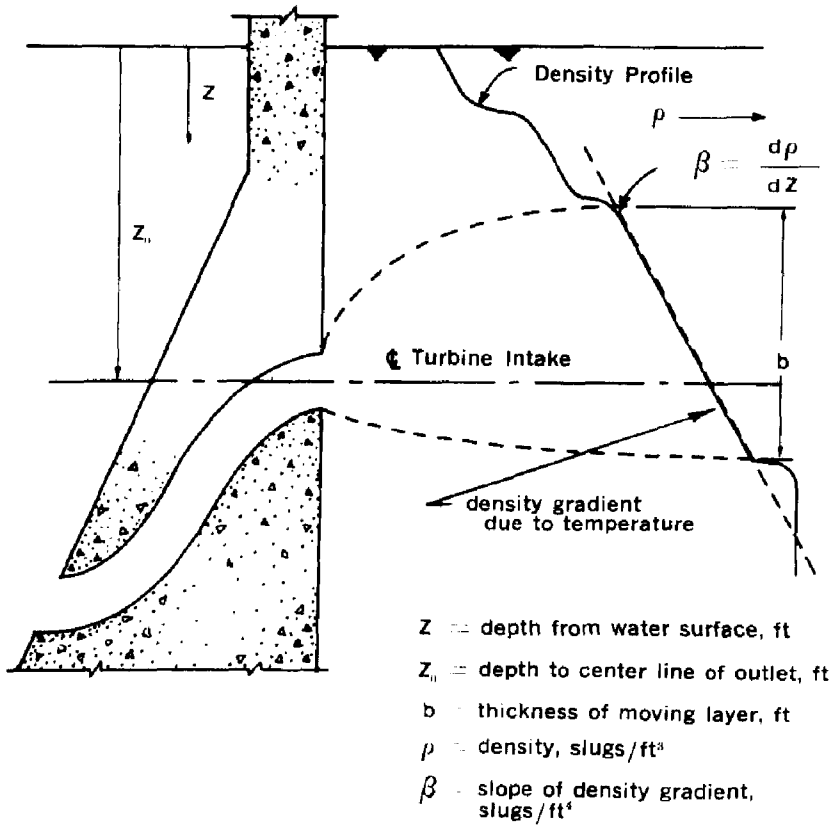

Figure 4 — Schematic diagram of internal current due to vertical temperature gradient.

At the end of the box is the horizontal slot, which simulates the reservoir outlet or turbine intake. The vertical density gradient was obtained by the rather tedious procedure of putting 1-inch layers of water of different densities in the box until the desired depth of about 12 inches was reached. Molecular diffusion would then iron out the stair steps. It is possible to get a very nice linear gradient, but it takes about 1½ days to prepare for each test.

As soon as flow is started a velocity concentration is induced at the level of the slot. Figure 7 is a plot of the velocity distribution some distance upstream of the slot. Note the strong concentration of velocity in the downstream direction at the level of the outlet. Observations show that the thickness of the moving layer tends to increase in the upstream direction. This growth in thickness of the moving layer probably is responsible for observations of the type Mr. Kittrell described as a tilted thermocline.

Obviously, even if the thickness of the moving layer should ultimately equal the reservoir depth (as it might in a very long reservoir) there will still be a strong selective withdrawal of water along the elevation of the outlet and water quality will be primarily dependent upon the water quality at that depth.

The most significant conclusion of these studies is the need for providing flexibility and variability of outlet elevations in impound-

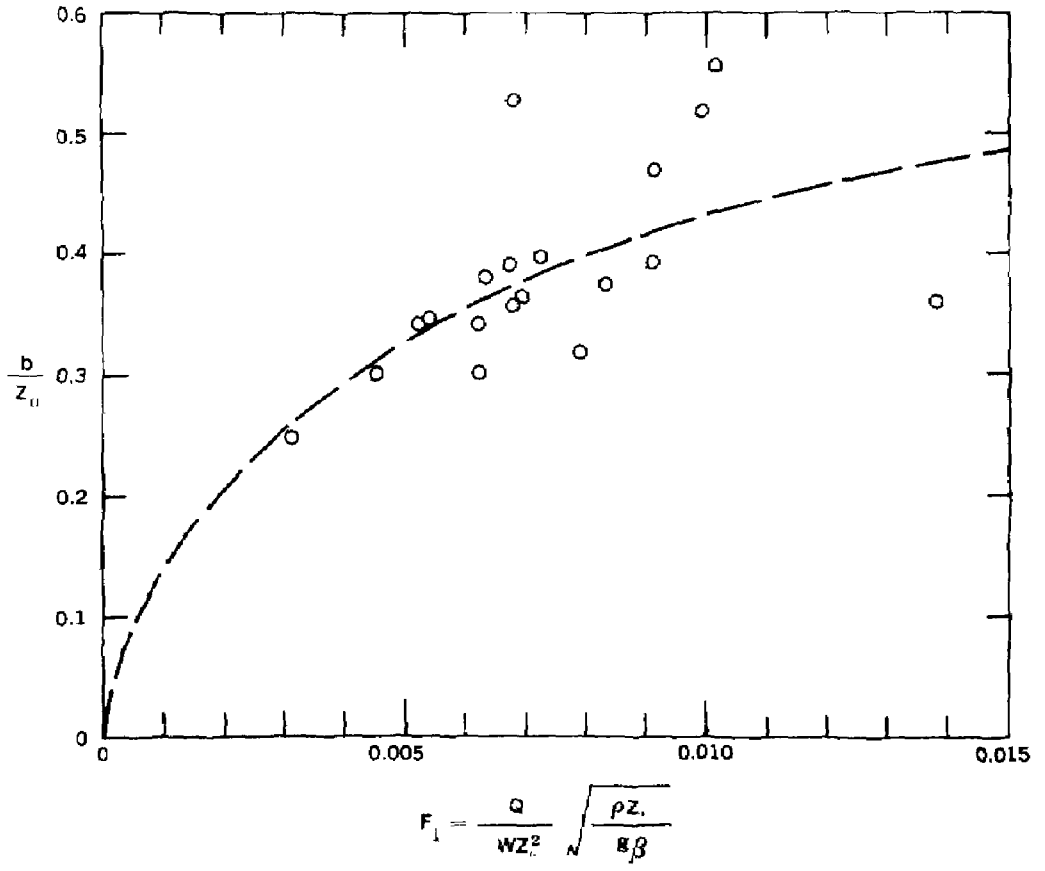

Figure 5 — Vertical thickness of internal current vs. densimetric froude number.

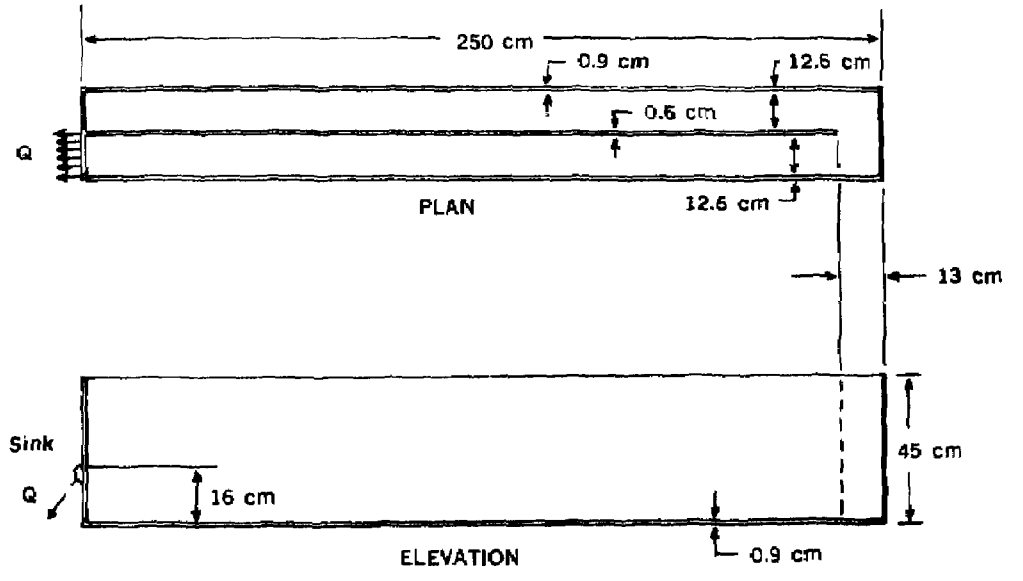

Figure 6 — Schematic diagram of experimental apparatus.

ments in which the quality of water discharged is an important consideration. The increased cost of such outlet structures should be more than compensated by the benefits of improved water quality in most cases.

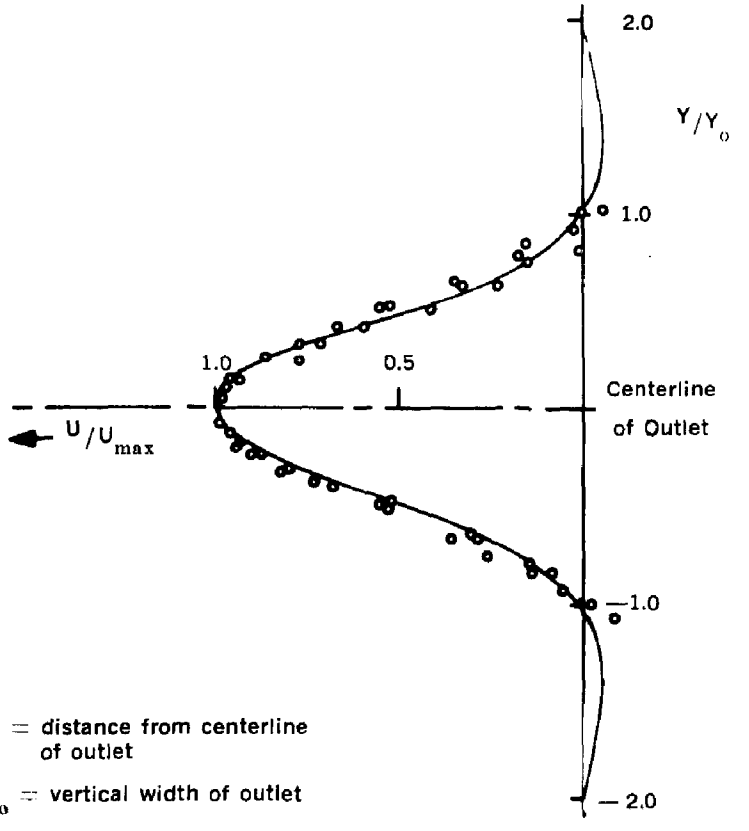

Figure 7 — Velocity concentration upstream of an outlet (sink).

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DISCUSSION FROM THE FLOOR

Mr. Sidio, U. S. Public Health Service: Mr. Kittrell, what work is actually necessary in determining the existence of thermal stratification in reservoirs?

Mr. Kittrell: Such a determination can cover a wide range of degrees of work. Probably the simplest attack would be to determine the temperature at the surface of the reservoir and, if intakes are located deep in the reservoir, the temperature of the water discharged through the penstock. It is desirable, of course, to determine the dissolved oxygen at the surface and in the water flowing through the penstock at the same time. If temperatures and dissolved oxygen values are much lower in the penstock water than at the reservoir surface, the chances are very good that the classical thermal stratification does exist.

Of course, one can go much beyond this and actually determine the temperature gradient from top to bottom with a thermocouple-type instrument. Such an instrument — which costs only about a hundred dollars, incidentally — can have a cable of almost any length necessary to reach the bottom of the reservoir and is very simple to drop over the side of a boat or along the upstream face of the dam. Temperature would be measured at various intervals of depth — 10 feet is a fairly standard depth interval over which temperatures are taken.

The same thing can be done with dissolved oxygen, which is one of the principal things of interest. There is a probe-type instrument, which I believe costs as much as 400 or 500 dollars, that can be used to determine dissolved oxygen. When I was with the Tennessee Valley Authority, we became interested in determining which reservoirs discharged water low in dissolved oxygen, and we developed a simple method for determining dissolved oxygen, which at one time was in Standard Methods. I do not believe it is included now. I believe the name was the amidol method. We prepared capsules of two reagents; I believe one was citric acid or some citrate salt that acted as a buffer and the other, amidol. This produced a yellow color in the presence of dissolved oxygen. We prepared permanent color standards from various mixtures of chromate and dichromate. We sent these to the operators of all the dams with instructions as to how to use them and asked them to run dissolved oxygen tests every week on water discharged through the penstock. Although this was a rather gross measurement, it did indicate whether there was significant oxygen depletion in the water discharged from the penstocks. We were very well satisfied with the results, although later on, I believe, Churchill went to titration right at the reservoir sites. Any agency responsible for a number of reservoirs might well consider determining which reservoirs are discharging waters deficient in oxygen.

Mr. O'Connor, Manhattan College: Dr. Harleman, in the laboratory experiments you described, were there any turbulence fluctuations in that stream that approached the intake?

Dr. Harleman: No, the scale of the experiment was not large enough to get turbulence fluctuations.

Mr. O'Connor: Is that generally true in the water that approaches the intake in reservoirs, too?

Dr. Harleman: One of my Figures shows the vertical distribution of velocity up to the center line of the intake. The theoretical curve is shown by a solid line, and the experiments we have done for low Reynolds number flows are indicated by points. In the Fontana data, the magnitude of these internal currents is still of the order of a tenth of a foot per second, even at the maximum value. Therefore, I would not expect turbulent mixing to be a very serious consideration. The thicknesses of the currents in Fontana, we think, are of the order of 70 feet in a depth of about 400 feet.

Growth of the internal current thickness may well explain the tilted thermocline Mr. Kittrell showed in his Figure 8, because if you follow a line of constant temperature back from the dam during this type of flow it would exhibit an upward slope.

PHOTOSYNTHESIS AS A FACTOR IN THE OXYGEN BALANCE OF RESERVOIRS

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Research Associate, School of Engineering
Baltimore, Maryland

INTRODUCTION

Since September 1957, there has been under way at The Johns Hopkins University an investigation of low-flow augmentation for stream-pollution abatement. This study has involved the legal, economic, and technical aspects of the use of water stored in wet seasons for the control of stream water quality during dry seasons.

The evaluation of the need for and benefits of flow regulation generally requires consideration of the oxygen balance as related to stream-flow rates and waste-assimilative capacity.

A factor long recognized as generally significant in controlling the oxygen concentration of natural water bodies is the photosynthesis of aquatic plants, including microscopic algae that make up the phytoplankton. In spite of this general recognition, however, this factor has been frequently neglected in oxygen-balance studies. The following statement is quoted from a translation of a Russian-language paper by Vinberg(*1*):

> "Until recently little attention was paid to photosynthetic re-aeration during the investigation of the capacity of polluted waters for self-purification. Soviet research workers(*2, 3, 4*) have already admitted the urgent necessity of taking photosynthetic re-aeration into account, but methods for investigating this question are only beginning to be developed and have not yet been introduced in practice in sanitary-hygienic and sanitary-hydrobiological researches. Quantitative methods for the investigation of photosynthetic re-aeration are needed firstly, for understanding the frequently-underestimated significance of green organisms as agents in self-purification; and secondly, they are essential for the investigation of the oxygen balance of polluted waters."

This paper describes techniques that have been used in studies of photosynthetic oxygenation in streams, estuaries, and impoundments, and discusses the general significance of this factor in controlling the oxygen balance of impoundments and regulated streams.

BALTIMORE HARBOR STUDY, 1949

In 1947, The Johns Hopkins University began a 3-year study of water quality in Baltimore Harbor, an arm of Chesapeake Bay. Observations of diurnal fluctuations of dissolved-oxygen concentrations in the near-surface water levels indicated a strong photosynthetic effect, and therefore, attempts were made to measure

oxygen production by phytoplankton. This phase of the investigation took place in 1949. Although Garland(5) summarized the results, the study has only recently been reported in detail(6).

The technique used in the study — the only one reported in the English-language literature up to that time — was that employed by Gaarder and Gran(7) in their 1916 study of Oslo Fjord, the now-familiar light- and dark-bottle oxygen technique.

The objective of the light-dark test is to expose paired samples of water to conditions that are as nearly natural as possible, except that light is excluded from one of the samples. In this "dark" bottle, photosynthesis cannot take place, whereas in the "light" bottle, depending upon the depth of exposure and upon the presence of autotrophic organisms and nutrients, photosynthetic production of organic matter and the release of oxygen can occur. Respiration consumes oxygen in both bottles of course. One of the assumptions of the test is that respiration is equal in the two bottles. This assumption becomes less valid as the duration of the exposure period increases, because of diverging populations in the two bottles. This is one reason for the frequent precaution of limiting the test period to the shortest time that will produce a significant difference between the oxygen concentrations of the light and dark bottles.

Figure 1 shows one method of suspending the samples at the various depths tested.

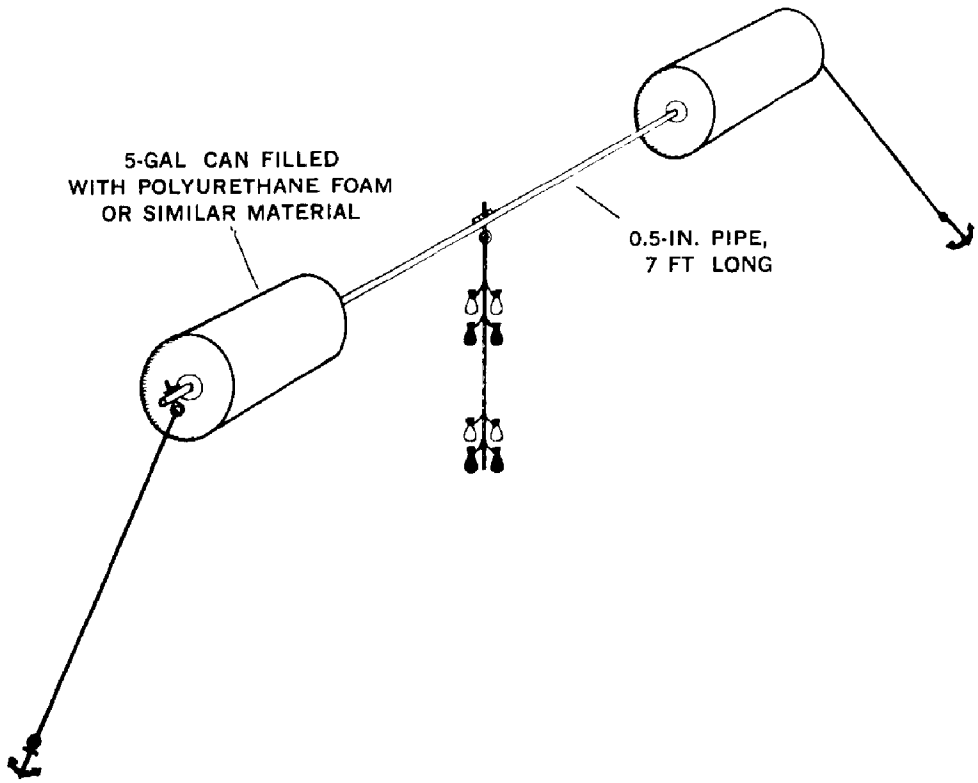

Figure 1 — Float for measuring the effect of photosynthesis by the light- and dark-bottle technique.

After exposure, the difference in oxygen concentrations between the two bottles is a measure of oxygen production at the depth of exposure. Figure 2 shows the variation of gross oxygen production with depth below the water surface for a typical 1949 test in Baltimore Harbor. The upward concavity of the curve near the surface reflects the inhibiting effect on photosynthesis of supra-optimal light, as observed by Marshall and Orr(*8*), who found maximum production well below the surface, with lesser production at shallower as well as deeper layers. This condition was not observed in Baltimore Harbor, probably because of the relatively high turbidity that limited supra-optimal light intensities to a very shallow layer near the surface, too shallow to be detected with the size of bottles and the vertical spacing used.

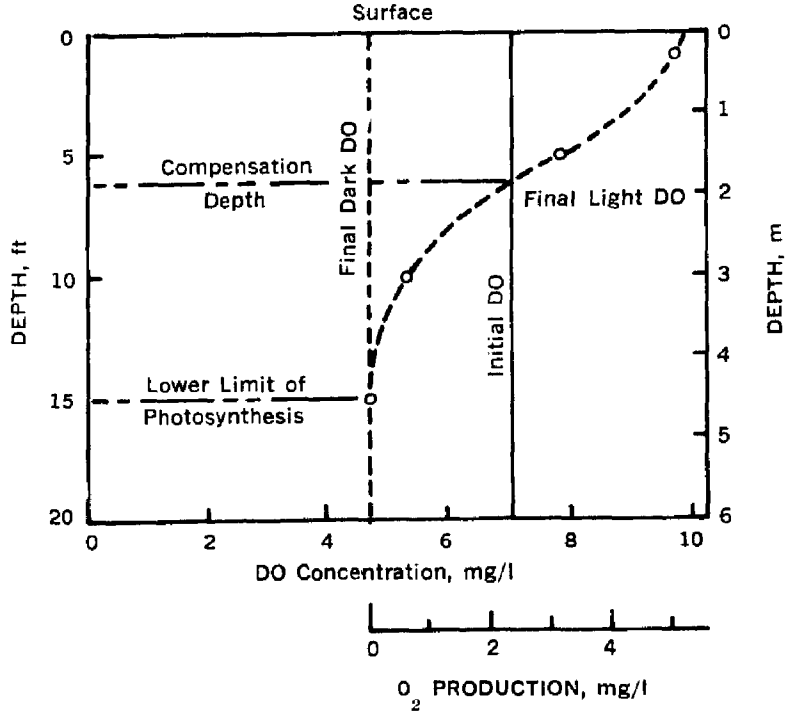

Figure 2 — Results of light- and dark-bottle test for photosynthetic oxygen production, Baltimore Harbor, Station B, August 19 to 23, 1949. (Ref. 6).

The solid vertical line in Figure 2 represents the initial dissolved-oxygen concentration in both light and dark bottles at all depths tested. The broken vertical line shows the final oxygen values in the dark bottles at all depths. These two lines are not necessarily vertical; in waters that are stratified within the depths to be tested, samples collected and exposed at different depths would be expected to have different initial oxygen concentrations and different respiration rates. Since Baltimore Harbor was found to be generally well mixed down to the natural bottom(5), a simplifying procedure was used in which a sample taken from a single depth was exposed at all depths tested.

The horizontal distance between the "final light DO" curve and

the "initial DO" curve (or line) is a measure of the net production at any depth. The distance between the initial DO line and the "final dark DO" line represents the respiration at any depth. The distance between the final light and final dark curves at any depth shows the gross production at that depth. The intersection of the final light and initial DO curves is the "compensation point," the point at which photosynthesis just balances respiration. The depth of this point is called the compensation depth. The intersection (or point of tangency) of the final light and final dark DO curves gives the lower limit of the productive or euphotic zone. The vertical distance from the surface to this latter intersection is the depth of the euphotic zone. This depth is determined by the transparency of the water to the wave lengths of solar radiation that support photosynthesis.

For a test in nonstratified water, if the origin of the horizontal scale is shifted to the right to coincide with the final dark DO line, the horizontal scale then shows the gross oxygen production directly.

The area enclosed by the "final light DO" curve, the "surface" line, and the "final dark DO" curve is a measure of the total oxygen production for the column of water, or

$$P_a = \int_o^e P_z dz \qquad (1)$$

in which P_a = gross photosynthetic oxygen production for the column of water, grams per square meter ($g \cdot m^{-2}$)

o = depth at the surface (zero)

e = depth of euphotic zone, meters

P_z = gross photosynthetic oxygen production at depth z, mg/l

P_a can be determined by planimetering the area under the curve of production versus depth. The area can also be determined with acceptable accuracy by approximate integration methods such as the trapezoidal rule or Simpson's rule.

During the summer of 1949, 12 light-and-dark tests in Baltimore Harbor showed an average gross oxygen production of 2.7 grams per square meter per day (24.0 pounds per acre per day). For the entire harbor area, this amounted to 605,000 pounds per day. When compared with the quantity of atmospheric oxygen absorbed by the harbor, 187,000 pounds per day as estimated by Garland(5), the contribution of photosynthetic oxygen is seen to be of major significance.

In 1961, a similar, but more intensive, study of photosynthetic oxygenation was carried out in the Delaware River estuary. Before starting this investigation, we reviewed the various newer techniques for analysis of photosynthesis and other factors of the oxygen balance,

which had been introduced into the literature since the 1949 Baltimore Harbor study(*9, 10, 11, 12*). These methods do not depend on bottle measurements and therefore eliminate the known and suspected errors related to bottle effects. (For a discussion of the bottle effects, see reference *13*.) A modification of Odum's method based on slack-water sampling(*14*) was also considered. As explained elsewhere (*15*), these various techniques were not attempted because they either did not account for some of the oxygen-controlling factors believed to be important in the Delaware estuary, or required an extensive sampling program far beyond the resources of personnel and equipment available. With full recognition of the potential sources of error in bottle methods, we decided to use one of the available bottle methods because their limitations appeared less invalidating than those of any feasible open-water technique.

In 1952, Steemann Nielsen(*16*) introduced the light- and dark-bottle carbon-14 method of measuring primary production. Because of its greater precision, the carbon-14 method has been widely accepted as an improvement over the oxygen method. However, an apparently unsettled controversy over interpretation of the results of the carbon technique led us to reject this method also(*15*). This left us with the light- and dark-bottle oxygen method of Gaarder and Gran(7) as used in Baltimore Harbor in 1949, but with improved equipment and procedures.

In the 1961 investigation of the Delaware River estuary, 100 light and dark tests (oxygen method) were made from March through December 1961. A series of 24-hour tests in August and September, when oxygen levels in the estuary were at their annual minimums, indicated that phytoplankton were responsible for a gross oxygen production of well over 1 million pounds per day(*17*).

In this study, a concept was developed that should have some application in studies of reservoir oxygen balance. This concept employs a new yardstick of self-purification that we have called the compensated-zone depth, shortened for convenience to the "cozode." (The cozode should not be confused with the *compensation depth*.) The cozode is defined as the depth of the water column, measured from the surface, for which the total respiration of the planktonic community is balanced by the gross photosynthesis of the phytoplankton in the euphotic zone. In mathematical terms, the cozode is defined as that depth at which

$$\int_0^e P_z dz = \int_0^C R_z dz \qquad (2)$$

in which C = the cozode, meters

R_z = respiration at depth z, mg/l

and the other terms are as previously defined.

In a stratified reservoir, respiration would be expected to vary

with depth. In such a case, the simplest way to determine the cozode is by a graphical solution, in which the function

$$R_{o,z} = \int_{o}^{z} R_z dz$$

is determined for a series of values of z by planimetering the corresponding areas under the curve showing respiration as a function of depth. These areas are then plotted as a function of z as shown in Figure 3. Then the value of C is taken from the graph at the intersection of the curve with the horizontal line representing the value of P_a.

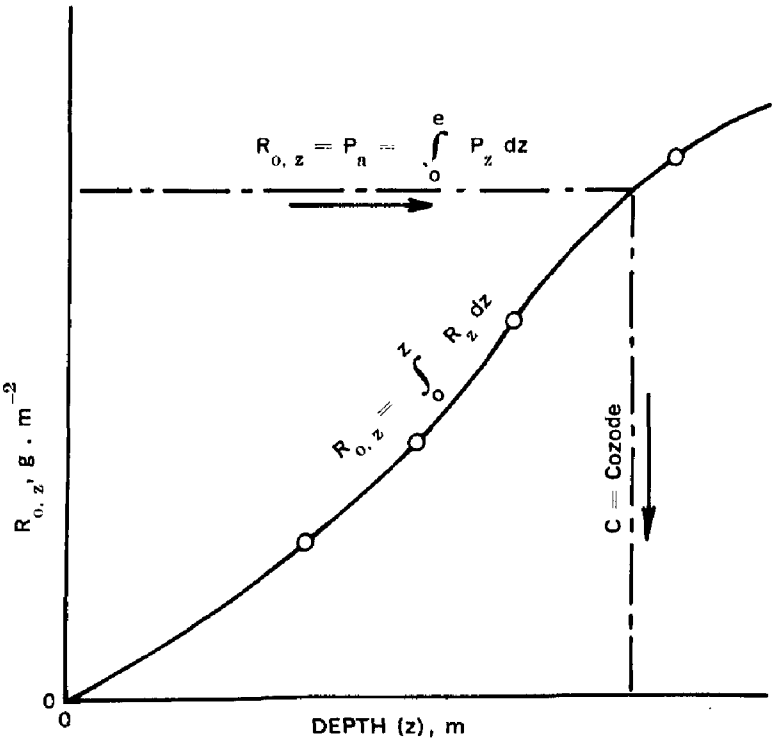

Figure 3 — Illustration of graphical determination of the cozode.

If one is dealing with a vertically non-stratified system, i.e., if respiration does not vary with depth, then the cozode can be determined simply by dividing the gross production per unit of surface area by the respiration per unit of volume or

$$C = \frac{\int_{o}^{e} P_z dz \ (g \cdot m^{-2})}{R_z \ (g \cdot m^{-3} \text{ or } mg/l)} \qquad (3)$$

Inasmuch as the cozode varies with the duration of time considered, the period should be specified. For many purposes, the 24-hour day is the most useful period. The 24-hour cozode can be deter-

mined by use of light and dark tests exposed for 24 hours. Greater accuracy will usually result from a series of shorter tests whose periods aggregate 24 hours.

In the study of the Delaware River, which is generally taken as a non-stratified estuary, equation 3 was used to determine the cozode. Figure 4 shows the frequency distribution of values of the cozode for two stations in June. Also shown are the mean depths of the river cross-sections at these stations. Comparison of the data for the two stations shows an advantage for the station at Eddystone over that at Kaighn Point. Not only is the cozode greater at Eddystone, but also the mean depth is less than at Kaighn Point. In fact, the cozode exceeded the mean depth of the river at Eddystone in two of the six 1-day tests. This indicates that about one-third of the time in June, the total oxygen demand of the river water in this area is more than balanced by the photosynthetically liberated oxygen. During such times, the excess photosynthetic oxygen, together with oxygen absorbed from the atmosphere, is available to balance the demand of bottom deposits and other oxygen-removing factors.

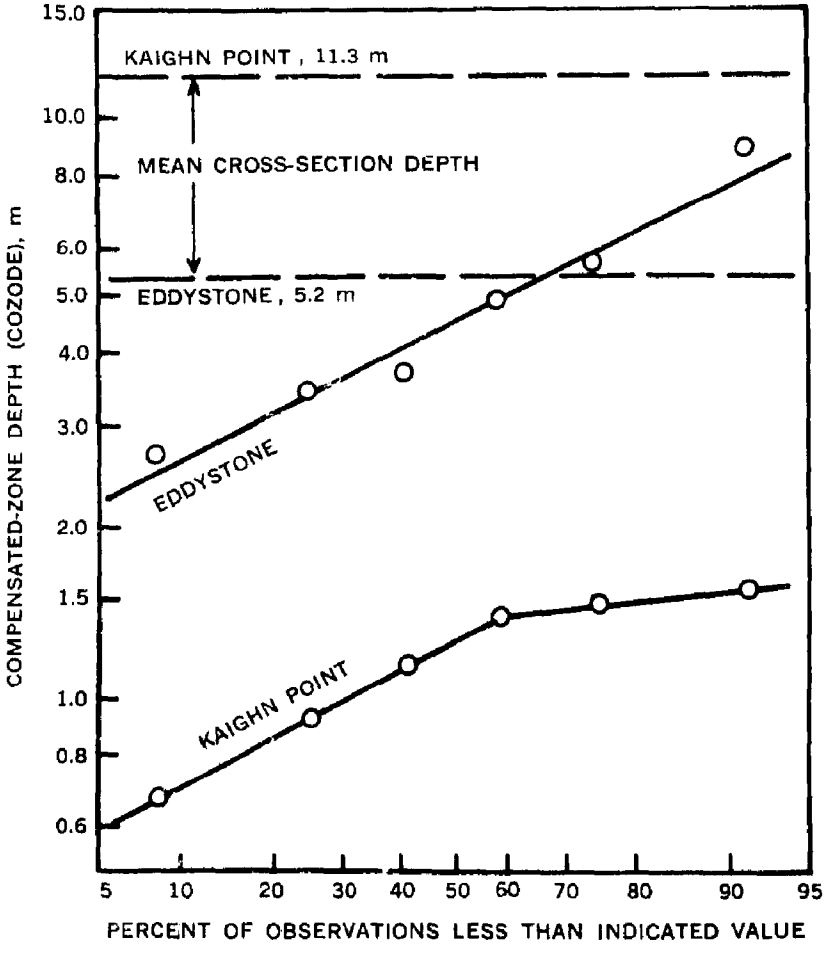

Figure 4 — Frequency distribution of compensated-zone depths (1-day tests only), Delaware River, June 1961.

Seasonal Variation of Photosynthesis

A search of the literature has revealed very little information on the seasonal variation of photosynthesis. In the 1949 study of Baltimore Harbor(*6*), the tests were not designed to investigate this question. In the 1961 study of the Delaware River estuary, however, tests were made in all seasons. The data appear to show a strong correlation between temperature and photosynthetic oxygen production, as indicated in Figure 5. This figure does not show the true relationship between temperature and photosynthesis, but only an empirical relationship between the two for a single station in the Delaware River. The consistency of the data is noteworthy, however, in view of the many factors that control photosynthesis. The apparent correlation indicates that many of these factors are strongly correlated seasonally with temperature. In discussing the relative importance of light and temperature as factors influencing algal periodicity, Prescott(*18*) observed that increases or decreases in plankton sometimes attributed to temperature changes are actually due to light variations. On the other hand, the Delaware River observations showed maximum photosynthetic rates in August and September, when temperatures were maximum but duration and intensity of sunlight were well below their maximum values at the time of summer solstice.

Whatever the explanation, the data for the Delaware River, presented in detail elsewhere(*17*), indicate that photosynthesis varies markedly with the time of year, ranging from negligible values in March to maximum values in late summer. The 1961 variation at Kaighn Point is described approximately by the equation

$$P_s = 0.04\ (1.218)^T \qquad (4)$$

in which P_s = daily oxygen production in the surface samples, mg/l/day

and T = water temperature, °C

This indicates that the rate of photosynthesis increases about 22 percent per degree rise in temperature in the Delaware River. It is emphasized that this is not the effect of temperature alone, but represents the combined effects of all factors controlling photosynthesis, many of which are apparently themselves strongly correlated with the annual temperature cycle.

Reservoir Studies

In 1957, a study was made to determine the effect of a submerged weir in the Roanoke Rapids Reservoir on water quality discharged through the penstocks at the dam(*19*). The submerged weir served to retain the deep waters of low oxygen concentration while allowing the shallow layers of water, with their relatively high oxygen concentrations, to be selectively withdrawn from the reservoir and passed downstream. The oxygen was needed downstream for the assimilation of wastes from several towns and industries.

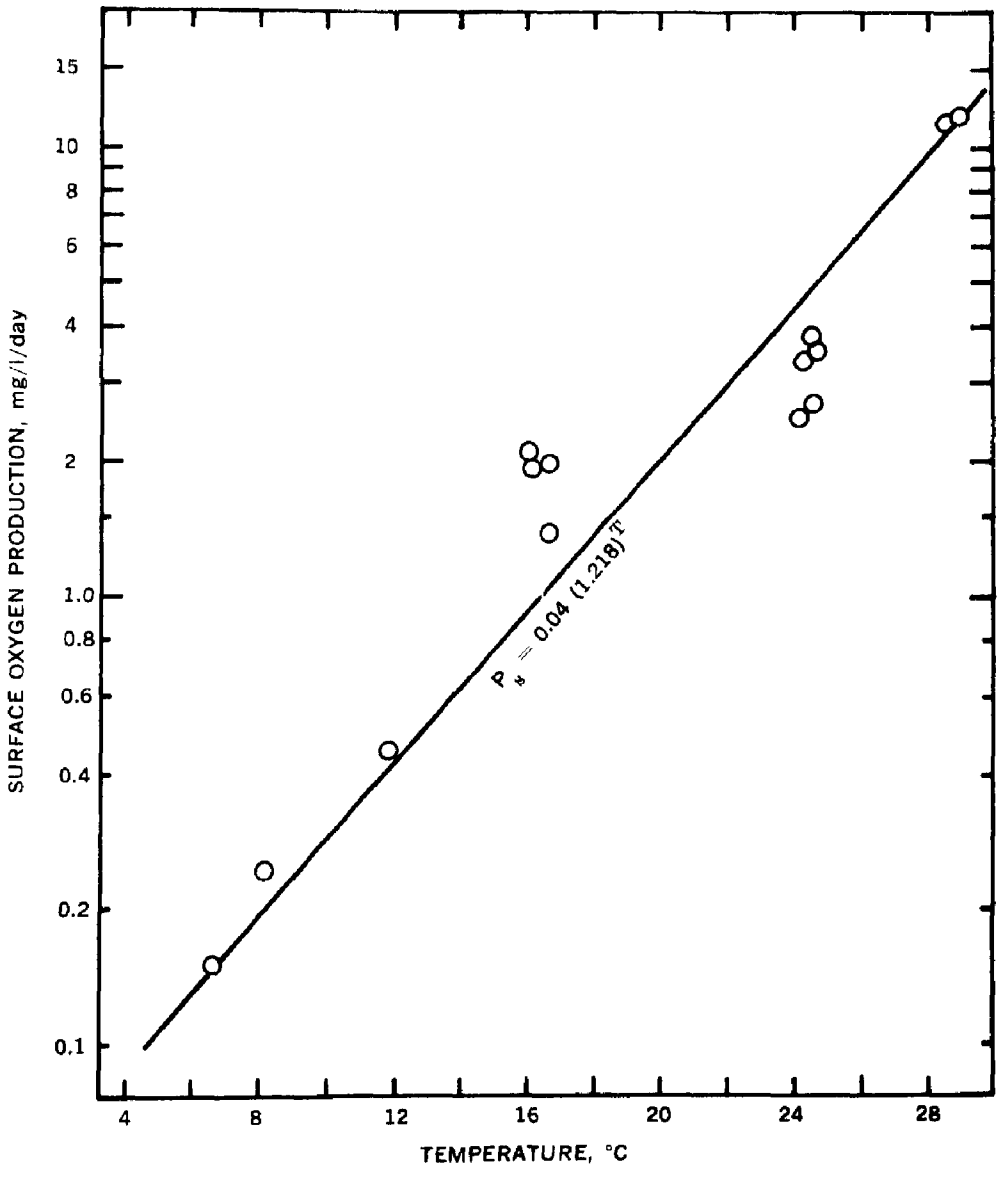

Figure 5 — Gross oxygen production at surface (depth = ½ foot) as a function of water temperature, Delaware River at Kaighn Point.

The successful hydraulic operation of the submerged weir raised a question concerning the ability of the system to replenish the oxygen so removed. For this reason, a study of the reoxygenating capacity of the reservoir was made. Although the writer was closely associated with all phases of the investigation of Roanoke Rapids Reservoir, the primary responsibility for this phase was in the hands of Dr. Donald W. Pritchard and Dr. James H. Carpenter, both of the Chesapeake Bay Institute of The Johns Hopkins University. Their analysis appears in an appendix in the unpublished report of the overall study compiled by Fish et al.(*19*).

Based on observations of diurnal changes in the DO concentrations of the surface layer of water, and using a modification of Odum's method of analysis (9), Pritchard and Carpenter estimated the mean rates of photosynthetic oxygen production, atmospheric oxygen exchange, and respiration for the reservoir. Briefly, their procedure was as described below.

The oxygen balance of a cubic-meter parcel of water in the surface layer 1 meter in depth was considered. Based on the absence of a vertical gradient in oxygen concentrations at the 1-meter depth and of any consistent horizontal gradients in the top 1-meter layer, exchange of oxygen between the parcel considered and adjacent waters was assumed to be negligible. The oxygen balance of the parcel was described by the equation

$$\frac{dC}{dt} = K_2 (C_s - C) + P - R \qquad (5)$$

in which C = concentration of dissolved oxygen at time, t, $g \cdot m^{-3}$

K_2 = atmospheric reaeration coefficient, hr^{-1}

C_s = saturation concentration of dissolved oxygen, $g \cdot m^{-3}$

P = rate of photosynthetic oxygen production, $g \cdot m^{-3}\ hr.^{-1}$

and R = rate of respiration, $g \cdot m^{-3}\ hr^{-1}$

For the condition of daily maximum dissolved-oxygen concentration in the surface layer, usually occurring about 3 p.m., the rate of change in concentration, dC/dt, was set equal to zero, which simplified equation 5 to

$$O = K_2 (C_s - C)_A + P_A - R \qquad (6)$$

Based on Odum's hypothesis that photosynthetic production varies directly with light intensity (9), it was assumed that maximum production occurs at noon and that the daylight diurnal variation is in the form of a sine curve. (Disagreement among various authorities on the type of variation was noted, but the use of other types of diurnal variation did not markedly affect the final results.) From Odum's hypothesis and based on the characteristics of sine curves, the average rate of photosynthesis between 9 a.m. and 3 p.m. was taken as

$$\overline{P_{M,A}} = 0.92\ P_{max} \qquad (7)$$

in which $\overline{P_{M,A}}$ = mean value of photosynthetic rate of production between the time of morning (M) and afternoon (A) observations

and $$P_A = 0.70\ P_{max} \qquad (8)$$

The respiration rate, R, was assumed to be a constant. Based on a finding by Ryther(*20*) that respiratory rates equalled 10 percent of the optimal photosynthetic rate for healthy laboratory cultures, it was assumed that

$$R = 0.1\ P_{max} \tag{9}$$

A mean value of equation 5 for the period between morning observations (about 9 a.m.) and afternoon observations (about 3 p.m.) was written as

$$(dC/dt)_{M,A} = K_2\ \overline{(C_s - C)_{M,A}} + \overline{P_{M,A}} - R \tag{10}$$

in which $(dC/dt)_{M,A}$ = difference in concentration between afternoon and morning observations divided by the time interval

$\overline{(C_s - C)_{M,A}}$ = average deficiency between morning and afternoon observations

and $\overline{P_{M,A}}$ = mean value of the photosynthetic rate of production between the time of morning and afternoon observations

Simultaneous solution of equations 6, 7, 8, 9, and 10 gives

$$K_2 = \frac{0.60\ (dC/dt)_{M,A}}{0.60\ \overline{(C_s - C)_{M,A}} - 0.82\ (C_s - C)_A} \tag{11}$$

and

$$P_{max} = \frac{-K_2\ (C_s - C)_A}{0.60} \tag{12}$$

By use of equations 11 and 12 and the observed oxygen concentrations at about 9 a.m. (M) and 3 p.m. (A), K_2 and P_{max} were found to be 0.157 per hour and 0.248 gram per cubic meter per hour, respectively. Because the parcel of water considered was 1 meter in depth, the surface exchange coefficient, K_s, was numerically equal to K_2, from the relationship

$$K_s = \frac{V}{A}\ K_2 = \frac{1 m^3}{1 m^2}\ (0.157\ hr^{-1}) \tag{13}$$

or

$$K_s = 0.157\ m \cdot hr^{-1}$$

From the value of P_{max}, the gross daily photosynthetic oxygen production for the upper meter, P_{day}, was computed to be 2.14 grams per cubic meter per day. The depth of the euphotic zone was taken to be 4.3 meters. Several methods of integrating the production over the entire depth of the euphotic zone gave values of the total production in a column of water under one square meter of surface, P_{total}, ranging from 4.19 to 5.98 grams per square meter per day.

The respiration rate was computed to be

$$R = 0.1\ P_{max} = 0.025\ g \cdot m^{-3}\ hr^{-1}$$
$$= 0.6\ mg/l/day$$

which agreed closely with an observed BOD value of 0.5 milligram per liter per day. The total respiration for the euphotic zone was therefore computed to be

$$R_{total} = 4.3 \times 0.025 \times 24 = 2.6 \text{ g} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$$

The net production of oxygen was then found to be

$$P_{net} = P_{total} - R_{total} = 4.2 - 2.6 = 1.6 \text{ g} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$$

The net exchange of oxygen was found to be negative, representing a loss of oxygen from the system of 1.0 gram per square meter per day.

The concept of the cozode used in the 1961 study of the Delaware River has been applied to the above results obtained by Pritchard and Carpenter. The cozode is

$$C = \frac{4.2 \text{ grams m}^{-2} \text{ day}^{-1}}{0.6 \text{ gram m}^{-3} \text{ day}^{-1}} = 7 \text{ meters}$$

This indicates that photosynthesis in the euphotic zone of Roanoke Rapids Reservoir is equivalent to the oxygen demand of the water down to a depth of 7 meters (23 feet). At a pool elevation of 133 feet, Roanoke Rapids has a volume of about 82,000 acre-feet and a surface area of about 4,800 acres. Thus, the mean depth is approximately 17 feet. Since the cozode exceeds the mean depth, the oxygen balance of the entire reservoir water volume must show an overall oxygen surplus, which is consistent with the finding of Pritchard and Carpenter that there was a net flux of oxygen from the reservoir surface into the atmosphere during the study period.

A need for study to find ways of capturing the oxygen lost to the atmosphere is apparent. Perhaps mechanical mixing of the reservoir water to prevent supersaturation at the surface is one method of retaining and using for waste decomposition the oxygen now lost to the atmosphere. If the average surface oxygen concentration can be reduced by this means to values significantly below saturation, the atmosphere will become an additional oxygen source instead of an oxygen sink.

Oxygen Demand of Photosynthetically Fixed Carbon

I am not unaware that most of the literature on the relationship between plants and the oxygen balance is concerned primarily with the detrimental effects of algae and higher plants. The oxygen demands of algae following "population explosions," or blooms, can be a serious problem, a problem that has focused attention upon this aspect of aquatic algae. These detrimental effects of blooms should not be allowed, however, to obscure the fact that aquatic plants, including the phytoplankton, can be credited in many cases with a net contribution to the critical-period oxygen balance of water bodies; this has been indicated in Roanoke Rapids Reservoir. It seems highly probable that much of the reoxygenating capacity, which has in the

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past been credited to atmospheric reaeration on the basis of the oxygen-sag equation of Streeter and Phelps(*21*) and other formulas, should really be credited to photosynthesis.

I have been frequently reminded that for every gram of oxygen released by photosynthesis a gram of biochemical oxygen demand is produced by the synthesis of organic matter, and therefore there can be no net gain of oxygen. This is a gross oversimplification — it must be qualified by consideration of the relative rates, periods, and locations of the oxygen liberation and subsequent oxygen demand. To support this, one need only point to the vast standing crop of fixed carbon on this earth in the form of petroleum, coal, plants, and animals, including several billions of human beings. All of this carbon was fixed by photosynthesis, but some of it has waited millions of years to be oxidized, before it will eventually take back the oxygen liberated at its birth.

Organic matter fixed photosynthetically in a reservoir may settle to the bottom where it may be oxidized anaerobically, or may remain until the fall turnover, when the critical period with respect to oxygen conditions is passed. Organic matter fixed in Roanoke Rapids Reservoir may show up still unoxidized in Albemarle Sound, where oxygen demand is not a problem.

In any event, oxygen-balance studies in any water body, whether a river, an estuary, or a reservoir, must take into account the effects of photosynthesis during the period and throughout the area of critical oxygen conditions.

ACKNOWLEDGMENTS

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DISCUSSION

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Hull's researches have a close parallel with much of the work that has interested me during the past 15 years. My motive was basically one of establishing aquatic ecologic relationships rather than making applications to sanitary engineering problems. Polluted waters have interested me only as one end of the aquatic habitat spectrum, but many of the data gathered can be drawn on for comparison with those of Hull. Our experience with clear and dark bottles has shown that photosynthetic yields under such conditions are lower than those that occur under completely natural conditions and that respiration rates in the dark bottles are higher than those in nature. Consequently, Hull's estimates of the oxygenation capacity of a phytoplankton community are conservative ones, and his estimates of the depth of the euphotic zone are conservative when they are based on enhanced respiration rates inside black bottles. Our studies under completely natural conditions have revealed photosynthetic yields amounting to 6 grams of carbon fixed per square meter of lake surface per day during the summer months. This work was repeated during several summers and represents the mean of many determina-

tions. Converted to oxygen production, it amounts to 16 grams of oxygen produced per square meter per day, which is similar to the highest values reported by Hull.

Another aspect of our studies has a bearing on this problem. We have observed that most ponds and lakes usually exhibit a fairly close balance between diurnal photosynthetic oxygen production and nocturnal respiration by the total community. If a sudden supply of organic matter is added, as for example by autumn leaf fall in a small pond, an excess of respiration over photosynthesis will develop with a consequent excess of CO_2 supply, as is most conveniently detected by reduced pH values. This enhanced CO_2 supply does, however, stimulate the autotrophic community to higher photosynthetic yields and a new balance is soon achieved in which the photosynthetic O_2 production by day matches the nocturnal O_2 consumption of the total community, including those components that feed on the added organic matter. Conversely, periods of photosynthetic excess may be observed. In Western Lake Erie, these are most evident in April when the spring phytoplankton pulse usually drives the pH values up to about 9.0. The CO_2 deficiency (and others as well, no doubt) resulting from this imbalance tends to reduce the photosynthetic capacity, and the enriched supply of organic matter tends to stimulate reducer components in the total community, resulting in a return to the balance described.

Hull's observation that there are autotrophs capable of photosynthesis at low light intensities also has been confirmed by our investigations. Some of the highest phytoplankton densities and oxygen concentrations we ever observed were found in January under a sheet of ice in Urschel's Quarry where a Chlamydomonas community flourished in light supplies that averaged less than 2 percent of full sunlight. Such high production in 0°C water casts some doubt on the widely held opinion that photosynthesis is inhibited by low temperatures. Because efficient phytoplankton crops develop wherever light and nutrient conditions are favorable, it seems one is justified in assuming that, within reasonable limits, CO_2 from any source in an aquatic environment will be converted to O_2 by the photosynthetic process. By reasonable limits, I mean that it is obviously possible to inject loads of organic matter into a pond that will overload the capacity of the autotrophic community to perform this conversion. But the eminent success of the sewage stabilization pond device (which confounded the expectations of many sanitary engineers) attests to the effectiveness of the process.

My personal reaction to the increase of impoundments and reservoirs in our civilization is most favorable. I would like to see the trend accelerated considerably. I am convinced that the best thing we can do with the millions of tons of water that cascade down our streams today is to create impoundments that will hold these waters quietly for a while, exposing them to the purifying action of the phytoplankton community, thus improving the water quality while providing numerous other well-known and beneficial byproducts. At Bowling Green, we are considering establishment of a shallow

pond to hold the effluent of the city sewage treatment plant for a few weeks before sending it down the Portage River. It is hoped that this pond can be excavated by judicious borrow-pit management during the construction of the bypass for highway 75. Such a pond will further improve the quality of the effluent (which is already well up to public health department standards as a result of recent remodelling of our treatment plant) and will serve as a safety factor in emergencies. Many other cities would be well advised to consider similar projects, especially where they can be designed as a byproduct of other construction. The resulting ponds should provide fishing for the young as well as improve the quality of water on the downstream side of the city.

TABLE 1. QUANTITIES DERIVED FROM INVESTIGATION OF PHOTOSYNTHESIS IN NATURAL PHYTOPLANKTON COMMUNITIES

Average phytoplankton density	1-6 microliters per liter
Photosynthetic yield	
CO_2 absorbed at optimal light	1-8 micromoles per microliter of phytoplankton per hour[a]
CO_2 gross absorbed, summer	500 millimoles per m^2 per day
Net CO_2 absorbed (in excess of diurnal respiration by total community), summer	250 millimoles per m^2 per day
Estimated CO_2 exchange with atmosphere, (O_2 exchange is likely to be of the same order of magnitude)	13 millimoles per m^2 per day
Rate coefficients	
CO_2 transfer across air-water interface in ponds	10^{-3} cm per sec[b] range is 10^{-2} to 10^{-5} cm per sec depending on degree of turbulence
O_2 transfer across air-water interface in rivers	4×10^{-3} cm per sec[b]

[a] Much lower values may be encountered in dense phytoplankton communities.

[b] This is $\frac{D}{L}$ in the Fickian equation: $\frac{Q}{AT} = \frac{D}{L} \Delta C$ where $\frac{Q}{AT}$ is transport per square centimeter per second and ΔC is the concentration difference between the water sample and the interface, which is assumed to be in equilibrium with the atmosphere. Hence, a liquid boundary layer of unkown thickness L is presumed to be the major transport barrier.

Rivers, as they exist in most of the United States, are too turbid to provide a favorable environment for photosynthetic processes. The average rate of oxygen transport into an O_2 deficient river (O_2 near zero) is about 30 grams per square meter of surface per day. This computation is based on an average transfer coefficient across the air-water boundary layers of 4 x 10^{-3} centimeters per second ($\frac{D}{L} = 4 \times 10^{-3}$ in the Fickian diffusion equation). This value was computed from data for several rivers in Tennessee, gathered by M. A. Churchill. Similar values have been obtained experimentally with Lake Erie water, mechanically stirred in a finger bowl. The O_2 content of rivers is, however, seldom near zero. Consequently, this maximal estimate must be reduced in proportion to the departure from atmospheric equilibrium. In O_2 deficient rivers, however, O_2 absorption from the air is frequently the dominant source of oxygen.

Table 1 gives the quantities derived from our years of investigations of the aquatic photosynthesis. These may aid in making first approximations of the O_2-producing capacity of natural phytoplankton communities.

DISCUSSION FROM THE FLOOR

Mr. O'Connor, Manhattan College: Dr. Hull, in your paper you indicated there may have been some vertical gradients in DO in the Roanoke Rapids Reservoir case. Could you give me an order of magnitude of what they were?

Dr. Hull: Pritchard and Carpenter's analysis of oxygen changes in Roanoke Rapids Reservoir was based on the top 1-meter layer of water. At the depth of 1 meter we could find no detectable oxygen gradient; we were well aware, however, that one could occur at times. Taking this into account by assuming a conservatively high oxygen gradient of 0.1 milligram per liter per meter of depth at the 1-meter depth, and going through the calculations again, Pritchard and Carpenter found that this added factor of a vertical flux across the bottom of the 1-meter layer of water tended to increase the photosynthetic production and decrease the atmospheric exchange coefficient. One-tenth of a milligram per liter per meter of depth was greater than we ever observed at the 1-meter depth.

Mr. O'Connor: You indicated that the BOD exertion was 0.5 milligram per liter per day. At what depth was that BOD sample taken and at what time of day?

Dr. Hull: The respiration value of 0.5 milligram per liter per day was obtained by observing the DO change in a dark bottle suspended near the surface for a 24-hour period. The sample was obtained near the water surface after dark.

Mr. O'Connor: Dr. Verduin, from my own readings in the limnological area, I suppose the assumption is usually made that the

respiration rate through the course of the daylight period is constant, as was assumed in the paper by Dr. Hull. Are there any data on diurnal variation in respiration rate, and if not, would you express an opinion as to how that rate might vary throughout the course of the daylight hours?

Dr. Verduin: I cannot give you the actual reference for the paper in which I have reported this, but I have done some work on the respiration rate in the afternoon as compared to midnight and morning. I did it by collecting samples; by exposing them for photosynthetic measurements; then putting these samples that had been exposed to light, in the dark; measuring their respiration after a 5-hour interval; and measuring again 8 hours later. I found that the respiration rate was nearly twice as high during the 5-hour period immediately after exposure to light as it was during the second period that would correspond, let us say, to from 10 o'clock at night to 6 the next morning.

I think this is a fairly good estimate of the kind of respiration increase that occurs under illuminated conditions. This has been reported by others working with cultures. In other words, when you expose phytoplankton to light, they build up a substrate that supports a higher rate of respiration, roughly about twice as much.

Mr. Churchill, Tennessee Valley Authority: I have a question along the same lines. Some of our English contemporaries maintain that respiration rates of phytoplankton are higher at high oxygen concentration than at low concentrations. Do either of you gentlemen, or anyone else in the room, have any data on this?

Dr. Hull: I have not had any personal experience with this problem, but information in the literature is a little contradictory. Zobel has reported that no relationship exists between respiration of bacteria and oxygen concentration between the limits of approximately 0.3 and 36 milligrams per liter. Only in one or two of our experiments on the Delaware River did oxygen concentrations approach either end of this range. We did get oxygen concentrations as high as 32 milligrams per liter at the end of a few, long-term, 5-day experiments.

Other literature (I cannot cite the references) indicates there is a relationship between the photoinhibition effect of supraoptimal light intensity and oxygen concentration.

Dr. Verduin: I do not know what kind of experiments you are referring to, Milo, but in my experiments the oxygen concentration was higher during the first 5 hours than it was later, so that a correlation might exist between the oxygen concentration and respiration rate. I did not, however, have such phytoplankton concentrations that the oxygen was seriously depleted, so I interpreted this as being due to changes in substrate rather than change in oxygen concentration.

Dr. Lewis, U. S. Public Health Service: One other point might be brought up here. We have been considering optimal conditions. If, however, there is a period in which good sunlight is available over

several days so that quite a large growth of phytoplankton organisms results, followed by a period of cloudy weather, the respiration requirement of the organisms will be greater. Changes in temperature and other conditions may cause considerable variation in respiration requirements.

How often a good increase in oxygen by these organisms could be expected during the day would be of interest to the engineers who are considering the use of these organisms in supplying oxygen.

Dr. Hull: We examined this factor in our work on both the Delaware River and the Roanoke Rapids Reservoir. Variations do occur, of course, and on cloudy days you get less production. A very widespread misconception, however, is that on cloudy days no photosynthesis occurs. My Figure 1 showing the variation of photosynthesis with depth showed measurable production in Baltimore Harbor down to depths of some 14 feet. Even on the brightest, sunny day it is pretty cloudy at a depth of 14 feet so all photosynthesis on cloudy days cannot be ruled out. In fact, on the Delaware River we found concentrations of 2 milligrams per liter or more in the surface samples even when it rained all day and we did not see the sun at all.

Dr. Heukelekian showed as early as 1931 that these organisms did not need direct light at all. They can liberate oxygen in very diffused light. The literature is full of information indicating that very low levels of surface light, less than 1 percent, support photosynthesis. So, although variability exists, as was pointed out, this factor must still be considered in the oxygen balance. It is a significant factor, especially at shallow depths.

Mr. Churchill: I would like to add a little fuel to what Jack just said. We have been working on a very deep and very sluggish river in our area, and we anticipated a net oxygen use by phytoplankton. But how wrong we were! In three separate 24-hour studies — one in July, one in August, and one in September — we actually found a net addition of oxygen to this very deep, very sluggish stream by the phytoplankton. So, for my money, phytoplankton are pretty good oxygen producers.

CONTROLS ON SOLUTION AND PRECIPITATION IN RESERVOIRS*

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INTRODUCTION

Reservoirs have many variable characteristics. Some are related to natural processes whereas others are related to management practices. It is the purpose of this paper to discuss both kinds of characteristics insofar as they have a bearing on the solution and precipitation of inorganic and organic substances in reservoirs.

The composition of water that flows into a reservoir is controlled by the interaction of climate, geology, topography, biota, and time, as shown by Gorham(*1*). When this water comes into contact with solids different from those with which it has been in contact or when unlike waters are mixed, chemical reactions may occur(2, p. 218) The environmental events that bring about encounters between water and new solid phases or between unlike water masses in reservoirs will be examined first, followed by a more detailed discussion of the chemical reactions that result.

THE RESERVOIR ENVIRONMENT

Reservoirs are designed for a variety of purposes, and both the type of construction and the management greatly influence water quality. Two principal kinds of impoundments were recognized by Kittrell(*3*): (1) storage reservoirs, characterized by high dams on streams with relatively steep gradients, large surface areas with many extensive embayments, low velocity as a consequence of slow passage of water through the impoundment, variable surface levels, deep location of intake penstocks, and typical thermal stratification, which commonly leads to a deficiency of dissolved oxygen in bottom waters; and (2) main stem reservoirs, characterized by low dams, small surface areas with much of the water confined to the original channel, more rapid flow and exchange of water, relatively constant surface levels, intake penstocks near the surface, small temperature gradients, and dissolved oxygen intermediate between that of unregulated rivers and storage reservoirs. The summer distribution of temperature in the two classes of reservoirs is shown in Figures 1 and 2.

The distribution of dissolved oxygen is of utmost importance in determining the composition of discharge water and is related to the cycles of nearly all of the important elements. Hutchinson(4, p. 701) suggested that the presence of an oxidized surface layer on sediments throughout the year in some lakes and its disappearance seasonally

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*Publication authorized by the Director, U. S. Geological Survey.

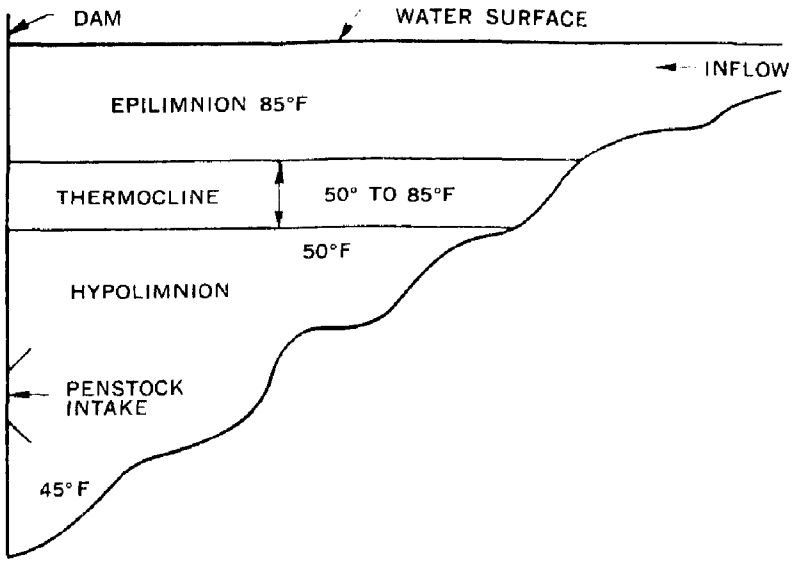

Figure 1 — Representative profile showing summer stratification in a typical storage reservoir. *(Ref. 3).*

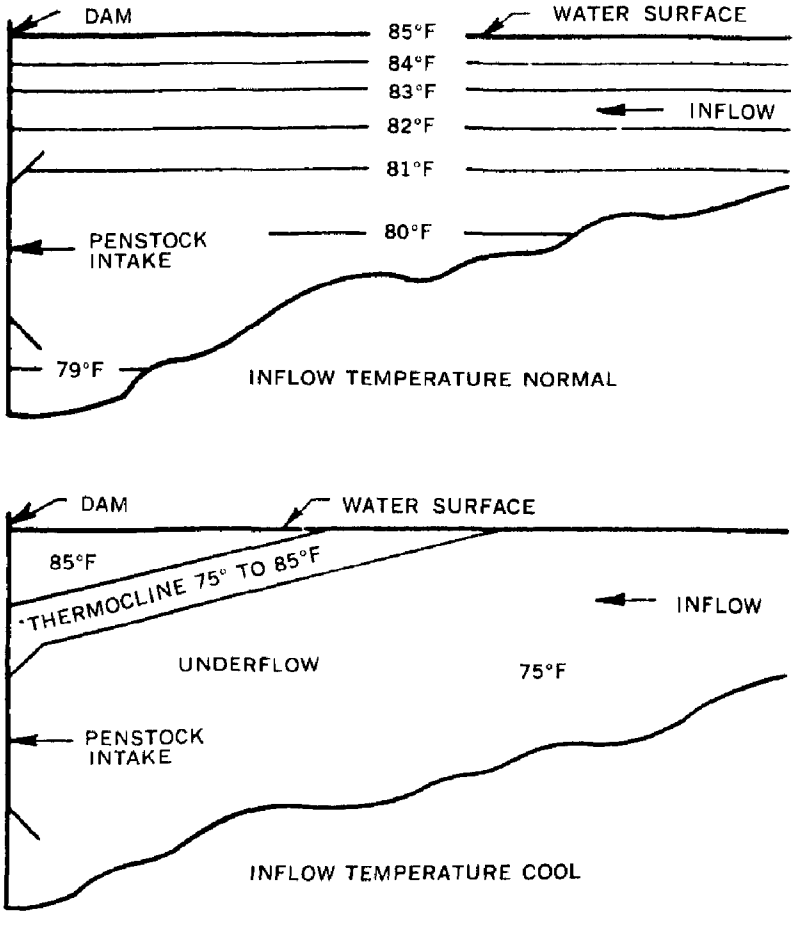

Figure 2 — Summer stratification in main stream reservoirs (Ref. 3).

in the deeper parts of the basin in others may be the most important phenomenon in the chemical classification of lakes. The occurrence or absence of this so-called oxidized microzone and the related concentration of iron is intimately involved in most of the chemical transformations with which we are concerned. This subject will be discussed in more detail in a later section.

CLIMATIC CONTROLS

The climatic variables that influence composition of reservoir water are precipitation, temperature, wind, evaporation, and solar radiation. Solar radiation is included because of its role in photosynthesis. The part played by climate in weathering, erosion, plant growth, and other processes outside of the impoundment will not be considered. The contributions of these sources to the chemical content of natural waters has been reviewed recently by Hutchinson(4) and Gorham(5). It is enough to note that the composition of inflow water reflects the conditions of its origin and that climate is one of the primary controls on the availability of substances for transportation by water.

The composition and temperature of inflow waters are particularly significant. If inflow water differs in composition or temperature from that of the water mass in the reservoir, chemical reactions may occur or density flows may result. In general, the dissolved solids concentration is lower during periods of high flow; however, concentrations of suspended solids usually are greater during high runoff.

Temperature

Both the concentration and proportion of ions in solution may be affected by such physical processes as freezing, dilution, and evaporation, all of which are manifestations of climate. The formation of an ice cover may be a regular event in northern areas. Freezing is initiated by sudden cooling of the reservoir surface during a calm, cold night, and a stratification of low stability in the top few meters results(4, p. 453). This inverse stratification is preserved under the ice. Size of a reservoir has an effect upon the probability of freezing. A deep basin loses heat more slowly than a shallow one, and a smaller surface is more likely to remain undisturbed during potential freezing conditions.

In his studies of English lakes, Mortimer(6) found that freezing removed 94 percent of the dissolved salts, all humus coloring matter, and a large part of the dissolved gas content. This led to increased concentrations in the water immediately under the ice. In Alaska, the increase in ice thickness on lakes was accompanied by an almost linear increase in mineral content of the unfrozen water just below(7). Highly mineralized waters of closed basins in Saskatchewan exhibited alternate freezing out and re-solution of sodium sulfate crystals during cold and warm periods(8, p. 149). It is unlikely that the freezing out of dissolved substances is a major control upon the composition of reservoir waters; however, stagnation resulting from an ice cover can produce significant changes in composition as was shown by

Mortimer(*6*). Kittrell(*3*) stated that winter stagnation in northern reservoirs does not result in total oxygen depletion in bottom waters, owing to the high initial dissolved oxygen concentration, the low rate of oxygen demand, and the shorter period of stratification.

Thermal stratification has a major influence on the water chemistry of reservoirs. The winter temperature pattern in a typical temperate zone lake is characteristically isothermal. There is complete vertical circulation as a consequence of the uniform density. In spring, solar heating warms the waters of the surface and tributaries until a density difference results sufficient to prevent mixing of the warm upper water with the colder, denser water below. As the surface becomes progressively warmer the density gradient steepens and the depth to which wind can mix the upper waters is diminished. The result is a separation of the reservoir into two isolated masses of water — a circulating surface volume floating upon a relatively stagnant volume below. This stratified condition typically persists until autumn, when cooling of the surface results in the diminution and eventual breakdown of thermal stability. At this time the reservoir "overturns" under the influence of wind, resulting in circulation to the bottom.

Wind keeps the water in circulation unless a persistent ice cover forms. In that event, an inverse type of stable thermal stratification persists until it is destroyed by warming and wind action. If winter stagnation occurs, it is followed by a spring overturn and a second period of circulation.

Although this generalized picture undoubtedly holds for many reservoirs, especially those having intakes at shallow depth, Churchill's(*9, 10*) reports on TVA impoundments clearly show wide departures from the ideal model when the intakes are deep. These departures are due primarily to the location of the intake penstocks through which water is discharged from the reservoir. The type of control exerted in this way may be considered as a special type of morphometric influence on water quality. The draft through the penstocks, of course, is an aspect of management control, since there is evidence that except for this factor a more typical thermal stratification would prevail.

The following generalized statements seem to apply to the seasonal thermal patterns of reservoirs as indicated by the references previously cited:

1. During cold months the water circulates freely (in absence of ice cover) and tends to be isothermal. Discharge is from the entire cross-section of the pool regardless of penstock depth. The flow pattern is diffuse.
2. Shortly after stratification occurs in early summer the flow from a deep intake is from the hypolimnion. Water at or above the level of the intakes is discharged first according to the density. Warm surface water descends to replace the withdrawn cold water. In reservoirs with a shallow intake, flow is confined to the mixed surface layers.

3. By late summer or early fall most of the cold winter water has been removed by discharge from deep intakes. Stratified withdrawal of warmer water then occurs.
4. In late fall inflow from tributaries is cooler (denser) than reservoir waters and tends to form density flows until such time as complete circulation develops.

Large variations in salinity, temperature, or suspended solids of inflowing waters may produce density flows. Anderson and Pritchard(*11*) identified four characteristic types of inflow water that accounted for the seasonal distribution of salinity and circulation patterns in Lake Mead (Figures 3 and 4). The first was a homogeneous winter water with a temperature of about 50°F and salinity near 700 ppm. Type two occurred during the spring high-flow period. The temperature was about 67°F and the salinity 275 ppm. The summer water had a temperature of about 76°F and a salinity of 800 ppm, reflecting the reduced inflow. The fourth type occurred during the fall when inflow was further reduced. Temperatures at this time were near 66°F and salinity about 900 ppm.

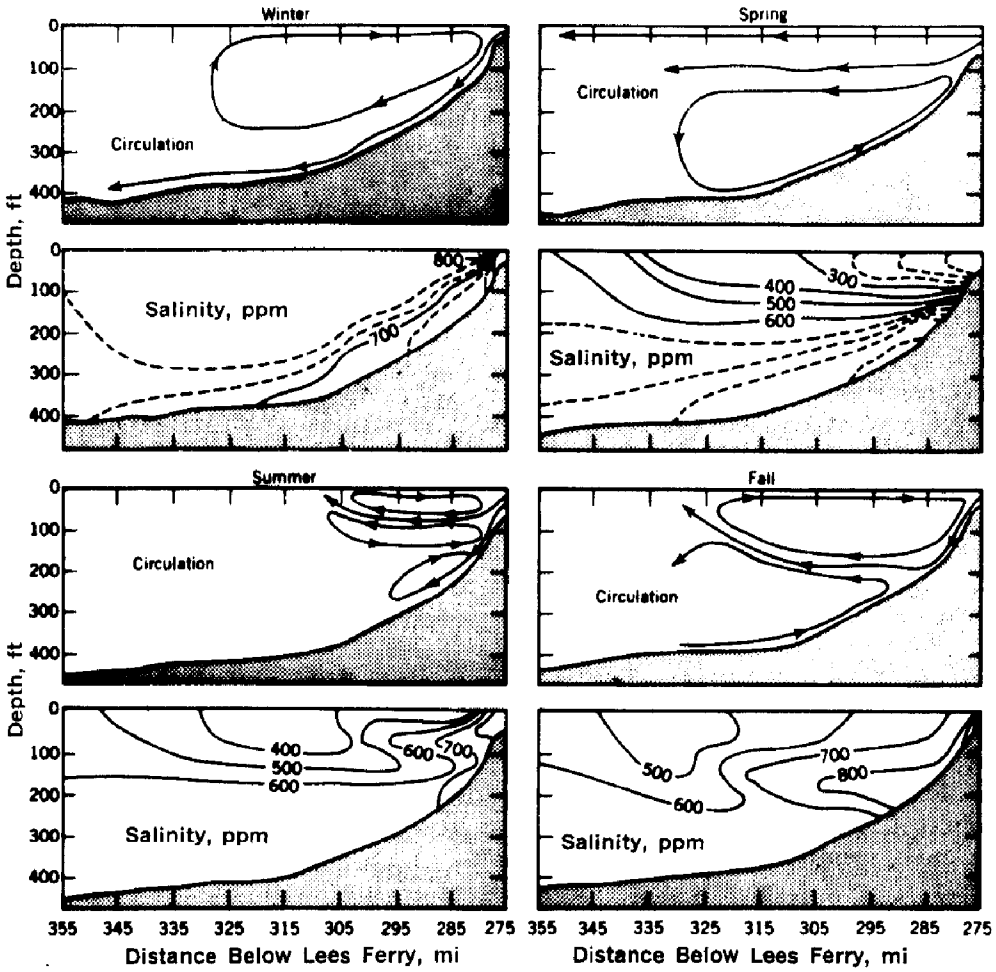

Figure 3 — Seasonal salinity distribution and circulation patterns, Lake Mead.

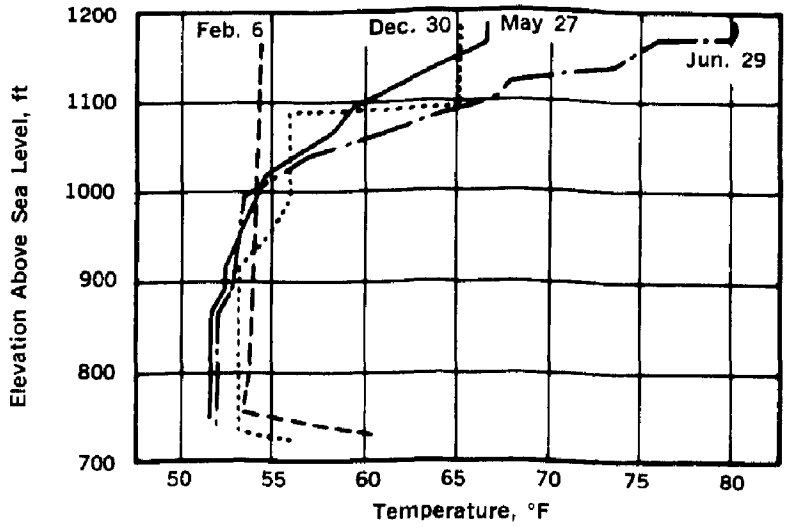

Figure 4 — Seasonal variations in temperature gradients, Lake Mead, 1948.

The influence of density currents on water quality has been described by Wiebe(*12*), Churchill(*13, 9, 10*), and Love(*14*). They described three types of density flows: overflows, interflows, and underflows. The significant point for our purpose is that water masses are brought into contact with solids or with waters of different composition, the results of which may produce chemical reactions.

One of the most significant aspects of density currents is their effect on dissolved oxygen. Wiebe(*12*) reported observations in TVA impoundments in which he related oxygen minima near the thermocline to density interflows rich in decomposable organic matter. The opposite effect was reported by Bryson and Suomi(*15*). They reported that oxygen increased in the hypolimnion of Lake Mendota as a result of a density flow following a heavy rain. Hutchinson(*4*, p. 297) believes there is evidence for the general occurrence of density currents running down the slope of the bottom of a lake, as dissolved material diffuses from mud into the water. These currents probably are best developed during summer stagnation when reduction processes liberate ionic material.

Wind

Wind influences ionic concentration by affecting evaporation(*16*) and by inducing water movements. Wind also delivers dust or dry fallout to the reservoir, some of which is soluble. Most of the wind-transported matter probably is of local origin and does not differ greatly from that supplied by runoff. In a similar way, material may be removed from the exposed margins of the basin by deflation during periods of low water, resulting either from evaporation or from regulated drawdown. Deflation has been shown to be important in natural lakes in semi-arid regions(*17*), but its importance in reservoirs in other climatic areas has not been reported.

Two types of currents are generally present in natural lakes: water movement from inlet to outlet and dominant wind-driven circulation(4, p. 363). There is reason to believe that the hydrographic slope current system dominates in many reservoirs, especially at certain periods of the year. They are, for example, responsible for density flows. Nevertheless, wind acting on an unfrozen water surface produces turbulent movement of water, resulting in transfer of material and heat. Winds are one of the main causal agents for seiches. The most important type of deep-water movement in stratified lakes is believed to result from internal seiches.

Evaporation

Evaporation combines the effects of wind and temperature to produce one of the major water losses in most reservoirs. For example, it has been estimated that approximately 12.3 million acre-feet of water is lost annually by evaporation from the principal reservoirs in the 17 western states(*18*). Most of the evaporation occurs during the warm months and in drainage basins with large reservoirs. It was concluded from this study that total water loss by evaporation is more closely related to the status of development in a river basin than to anything else.

Evaporation losses from Lake Mead are about 5 percent of the average inflow, or about 700,000 to 900,000 acre-feet per year. The effect of evaporation on water composition was investigated by Howard(*19*, p. 123) who found increasing concentration of soluble salts remaining in solution. Small increases in magnesium, potassium, and nitrate were observed in the outflow from the impoundment. These increases in ionic concentration were partly offset by decreases resulting from precipitation of dissolved materials. Howard estimated that during 14 years of storage Lake Mead water precipitated more than 1 million tons of silica and in excess of 9 million tons of calcium carbonate. It is doubtful whether evaporation or inorganic precipitation are the only controls in this case.

INORGANIC CHEMICAL REACTIONS

We have seen how climatic variables function in some of the compositional changes that occur in reservoir waters. We will examine now the chemical changes that result from the physical influences on distribution of water and materials.

Solution

When a liquid comes in contact with a solid, solution can occur only if atoms, ions, or molecules of the solid are strongly enough attracted by the liquid so that the strong forces that hold the particles in the solid are overcome. Most inorganic compounds go into solution as positive and negative ions rather than molecules. All inorganic ions are soluble unless combined with some other ion that prevents its going into solution. For example, silver nitrate and sodium chloride are both soluble, but silver chloride is only slightly soluble.

The quantity of a material that can go into solution in pure water at a given temperature is expressed by its solubility-product constant. This is a quantitative statement of the limit of solubility of any slightly soluble substance that forms ions. When the product of the concentrations of the ions in the solution exceeds the value of the solubility-product constant, either precipitation occurs or a supersaturated solution is formed. Supersaturated solutions tend to be unstable, and precipitation is the usual result of excess concentration of the ions.

The solubility of a gas is related to the ratio of concentration of gas in solution to that in the gas phase in contact with the solution. Such gases as oxygen, nitrogen, and carbon dioxide are usually present at or near atmospheric saturation levels during the period of the year when the water is in complete circulation. Under reducing conditions that prevail in the hypolimnion during stagnation, other gases are present, sometimes in sufficient concentration to form bubbles that rise to the surface. Methane is one of the products of anaerobic decomposition, but carbon dioxide, nitrogen, ammonia, hydrogen, and hydrogen sulfide may also be present.

Solution of pre-existing material within the land area of an impoundment is a familiar example of a solubility process. Trees, brush, and other obvious sources of organic matter are commonly burned or removed during construction. For example, TVA impoundments are cleared of trees and brush in the zone between full pool level and the normal level of maximum drawdown(*9*). The trees and brush remaining below the summer thermocline tend to deplete oxygen and produce hydrogen sulfide, although it is reported that little additional influence on water quality remains after a full annual cycle of operation. Some of the problems that can arise during site preparation are described by Benedetti and Roller(*20*) for the upper Green River, Washington. Hydrogen sulfide was leached by a small stream from hydrothermally altered rock of an extinct hot spring, slopes had to be stabilized with rip-rap, and a swamp deposit consisting of 600,000 cubic yards of organic material was encountered. A test covering of bank-run sand and gravel was tried as a means of sealing off this deposit, but methane gas was evolved from around its periphery. Investigation of this problem was being continued because of its possible effect on water stored.

Lake Mead provides a well-documented example of solution from an inundated reservoir area. Releases from this lake initially showed higher dissolved solids content than the average for the inflow(*19*). From records of dissolved solids inflow and outflow, it was estimated in 1948 that a total of 20 million tons of soluble salts had been dissolved from the bed, but that the concentration had only increased by half this amount because of precipitation of calcium carbonate and silica from the stored water. The leached material consisted largely of gypsum (calcium sulfate) and some halite (sodium chloride). As a result of this solution, sulfate concentration in the outflows increased more than 50 percent over that in the inflowing water

in several years. Calcium increased in the outflow despite the large amounts precipitated as calcium carbonate within the basin. Increased concentrations of sodium and chloride are attributed partly to solution of halite. Since 1951 the differences in concentration have been relatively small, salinity being sometimes higher in the inflow and sometimes higher in the outflow(*14*).

Many substances undergo an annual cycle of solution and precipitation correlated with the cycle of stratification. An example of this type of solubility cycle is provided by calcium carbonate, which precipitates from surface waters under certain conditions and redissolves at the bottom in the presence of carbon dioxide produced during decomposition.

Precipitation

Solids may be dispersed in water in one of three different forms, depending on the particle size. These are solutions, colloids, and suspensions. Particles in solution are single molecules or ions only a few angstrom units (A) in diameter. Colloidal particles are of the order of 10 to 2000 A in diameter and may consist of many molecules. They are of such small mass that they exhibit Brownian movement and do not settle under the influence of gravity. Colloids differ from suspensions only in size.

As mentioned earlier, a substance is precipitated when its solubility product is exceeded. All precipitations from natural waters are made from solutions that contain ions other than those of the precipitate, and some of these ions are frequently dragged down with the precipitate, a process known as coprecipitation. The amount of coprecipitation varies with the nature of the precipitate and the conditions of its formation. A precipitate first forms as particles of colloidal size before they become large enough to settle out. Coprecipitation usually occurs in the colloidal stage.

Under certain conditions of formation of ferric hydroxide precipitates, such as when solutions containing ferrous iron are raised in pH or redox potential, other ions may be removed from solution by coprecipitation(*21*). Hem and Skougstad studied the coprecipitation effects of ferrous, ferric, and cupric ions in laboratory solutions. They noted that the effects of ferric hydroxide precipitation on the content of other heavy metal ions in natural waters are approximately indicated by the behavior of copper. The results of these experiments suggest that the conditions most favorable for coprecipitation include a neutral or alkaline pH so that the normal positive charge on ferric hydroxide particles is neutralized. If precipitation occurs at low pH some anions may be adsorbed. Colloidal suspensions of ferric hydroxide in natural water probably do not carry any large amounts of other cations by adsorption on the hydroxide particles because of the small concentration of ferric hydroxide that can occur in stable suspensions; however, the behavior of some of the trace constituents in natural water may be affected by adsorption on colloidal ferric hydroxide.

It has been suggested that the scavenging effect of ferric hydroxide precipitates may explain the presence of certain rare metals in seawater in amounts much less than saturation(*22, 23, 21*, p. 96). This effect has apparently not been studied in inland waters. The work of Aarnio(*24*) on coprecipitation of humus and ferric hydroxide has been discussed by Hutchinson(*4*, p. 711). Since much smaller amounts of Al_2O_3 were needed to form a precipitate with humus material, it was suggested that in nature aluminum may be rapidly depleted, leaving the iron in solution.

Colloids occur in aqueous solutions as suspensoids and emulsoids. Suspensoids have low viscosity and little affinity for water. Because of their physical similarity to solutions they are known as sols, or in water, hydrosols. Dispersions of metals and salts in water are examples. Emulsoids have high viscosity and a high affinity for water. They are known as gels, or in water, hydrogels. Phenomena associated with surfaces are intimately involved with particles of colloidal size because of the very great surface area per unit mass.

The properties of surfaces are related to exposed atoms or ions lying on the surface. Within a crystal each ion is surrounded by oppositely charged ions except for those at the surface. These surface ions or atoms can attract and retain other ions or atoms by adsorption. Adsorption occurs at all surfaces, large or small, but the quantity per unit area is so small that it usually becomes significant only when the adsorbate is finely divided, as in the colloidal state.

Many substances function as adsorbents in nature. These include finely divided crystalloids, especially clay particles of the montmorillonite group, organic and inorganic colloids, gels of ferric hydroxide and silicic acid, humus colloids, polymorphic inorganic and organic complexes, and surfaces and integuments of living and dead organisms(*25*, p. 187). The role of ferric hydroxide in controlling phosphate has been described by Einsele(*26*). Hutchinson(*4*, p. 886) summarizes the effects of organic colloids on some physical properties of lakes.

Some of the ecological relationships of sorption reactions were studied by Carritt and Goodgal(*27*). They proposed a two-part mechanism, rapid adsorption followed by a slower diffusion-controlled process, to explain the observed uptake of phosphorous ions from solution. This process suggests that during desorption both the amount of phosphorus and the rate of its removal depends on the length of time that the complex has had to form. With long contact time the desorption is slow, and this stability of the phosphorus-solid complex is important because of the transport of suspended substances through regions of different pH, temperature, and salinity. It was further shown that many dissolved substances compete in sorption reactions. For example, phosphorus reduced the uptake of sulfate.

The initiation of crystallization from a supersaturated solution is not completely understood, but it is known that attainment of equilibrium may be very slow for some natural reactions. Sooner or later crystal nuclei appear; the greater the relative supersaturation of the solution, the more nuclei occur. Precipitation may proceed by co-

agulation of colloidal particles and by deposition of ions from solution to build up the crystal lattice of the nuclei. Both usually occur, and the domination of one process over the other depends on the conditions. In the laboratory it is found that keeping the degree of supersaturation low favors growth of original nuclei by deposition of ions from solution. Conversely, rapid mixing of reagents produces increased supersaturation and favors the formation of more nuclei. The importance of these relationships to natural systems in reservoirs is apparently unknown.

The formation of marl may be used as an example of natural chemical precipitation. Marl is deposited from a solution in which the solubility product of calcium carbonate is exceeded. The reversible reaction involved may be represented by

$$Ca(HCO_3)_2 = CO_2 + H_2O + CaCO_3 .$$

Removal of carbon dioxide by any of several means drives this reaction to the right. Welch(*28*) lists the following mechanisms that can result in the reduction of CO_2 concentration: activities of living organisms, agitation of water, a rise in temperature, evaporation, and incorporation of carbon dioxide in bubbles rising from bottom deposits.

In the sea large quantities of marl are thought to be deposited as a result of bacterial action, but no such relationship has been demonstrated in fresh waters. The process considered to be of prime importance in lakes is the utilization of carbon dioxide by plants for photosynthesis in accordance with the following reaction:

$$6\ H_2O + 6\ CO_2 = C_6H_{12}O_6 + 6\ O_2 .$$

Calcium carbonate that precipitates in the photosynthetic region settles into the decomposition zone where it may combine with carbon dioxide to increase the bicarbonate content. Ruttner(*25*) showed that in low calcium waters the calcium carbonate precipitated is insufficient to fix the available CO_2 and there is no accumulation of marl. In many lakes there is a net removal of precipitated carbonates by the subsequent deposition of inorganic sediment that forms an effective seal.

Ruttner(*25*) reported that 100 kilograms of fresh *Elodea canadensis* precipitated 2 kilograms of calcium carbonate in a day with 10 hours of sunlight. Howard(*19*, p. 123) estimated that 9 million tons of calcium carbonate were precipitated in Lake Mead. He calculated that the amount precipitated from the water accounts for only 0.45 percent of the 10.3 percent estimated to be present in the 2 billion tons (dry weight) of sediment accumulated in Lake Mead during the same 14-year period. Evidently large quantities of calcium carbonate are brought into the lake with the suspended load of the Colorado River.

Complex Formation

The term "complex" is applied to many natural substances of poorly defined composition, especially if the chemical species is partly

organic. The chemical definition of a complex is more specific and implies a definite structure consisting of a central atom or ion surrounded by atoms, ions, or molecules in a stable configuration. Complexes in solution may originate by direct solution of complex minerals from rocks or by reaction of dissolved substances with simple minerals to form complex ions.

Chelates are a special type of complexes between inorganic and organic structures. A chelate compound or ion is a ring structure containing a central atom, usually of a metal, tied by coordinate and polar valence bonds to an organic segment. Chelate ions or compounds generally behave very differently from the uncomplexed metallic ions. The term "chelation" is sometimes loosely applied as a general term for formation of any complex of a metal and an organic ligand. Organic complexes were reviewed by Bjerrum, Scharzenbach, and Sillen(*29*).

Complexes directly affect the composition of water by inducing or preventing precipitation. When complexing takes place, both redox potential and pH may be altered and the rate of oxidation or reduction may be slower than when complexing is absent(*30*).

Hem(*30*) noted that iron combines readily with many other ions to form complexes that generally have an ionic charge. In most cases the charge is positive, although neutral and negatively charged complexes exist. Among the iron complex formation reactions listed by Stumm and Lee(*31*) those of possible significance in reservoirs are the sulfato and phosphato complexes ($[Fe(SO_4)]^+$, $[Fe(HPO_4)]^+$, $[Fe(HPO_4)_2]^-$). These workers suggested that complex formation may be partially responsible for the high concentrations of humic acid and lignin derivatives often associated with high concentrations of soluble iron. Colloidal ferric hydroxide may be stabilized as a sol by organic compounds such as the yellow coloring matter studied by Shapiro(*32*). In his discussion of silica, Hutchinson(*4*, p. 799) wrote that he believes there is evidence for the existence of colloidal silica and possibly of complex aluminosilicate ions such as $Al(OH)(HSiO_3)^+$ or $Al(HSiO_3)^{++}$. Ingols and Wilroy(*33*) noted that the presence of natural tannins seems to induce precipitated manganese to dissolve, and it was suggested that organic complexing of trivalent manganese may keep this element in solution. Mortimer(*6*) suggested that cations adsorbed on sediments may be released into anaerobic bottom waters during summer stagnation by the breakdown of an iron-silica-humus adsorption complex. At the onset of autumn circulation this complex reforms and the cations again are adsorbed. Gorham(*5*) indicated, however, that he believes the marked fall in alkalinity of the bottom water at overturn, cited by Mortimer as evidence of base adsorption, may be due mainly to dilution of a very small volume of concentrated hypolimnion water with a large volume of more dilute epilimnion water.

Oxidation-Reduction Reactions

Oxidation is an increase in positive valence resulting from loss

of an electron by an atom, ion, or molecule. Reduction is the opposite process, a gain of electrons or loss of positive valence. In the reaction

$$4\ Fe^{+++} + 2\ S^{--} = 4\ Fe^{++} + S_2$$

sulfide ion is oxidized to sulfur, and ferric ion is reduced to ferrous ion.

Under ideal conditions all oxidation-reduction reactions are reversible and none ever goes entirely to completion. For example, the reaction

$$Fe^{++} = Fe^{+++} + \text{electron}$$

may go in either direction, depending on the presence of other substances that furnish or accept electrons. In general, ions with the greatest tendency to acquire electrons will do so at the expense of other ions present.

Oxidation-reduction has two aspects of importance: intensity, as expressed by the electrical potential with reference to an arbitrarily chosen standard, and the buffering, or poise of the system, i.e., the ability to carry on a given amount of oxidation or reduction without a significant change of potential(*34*, p. 195).

The theoretical aspects of redox potentials in natural waters have been summarized by Hutchinson(*4*) following Cooper's(*35*) treatment. In general, the potentials are insensitive to changes in the partial pressure of oxygen down to very low concentration. Reducing the oxygen concentration from 100 percent saturation to 1.0 percent lowers the potential only about 0.03 volt; however, a rise of one unit in pH decreases the potential 0.058 volt, a value that can be used to adjust potentials at different pH values to some arbitrary pH when an oxygen potential is involved.

The hypolimnions of some lakes exhibit a uniform redox potential, even with low oxygen concentrations. It is assumed that the mud surface remains oxidized under such conditions. More commonly the potential falls rapidly near the bottom and frequently the hypolimnion has potentials considerably lower than those in the epilimnion. The near-bottom decrease results from reducing substances derived from the mud, the most important of which is ferrous iron(*4*, p. 725). The most complete series of quantitative data showing chemical changes in the hypolimnion during stagnation are those of Mortimer(*5*) for English lakes. This work and that of Einsele(*26*) demonstrated that the redox potential is inseparably linked with the concentration of iron and that an understanding of these relationships is essential to an understanding of most other chemical cycles.

In deep water, reducing conditions probably always exist below the sediment surface at a potential of about 0.0 volt. When the sediment is in contact with oxygenated water, an oxidized microzone develops at the mud surface. This microzone has the brown color of hydrated ferric oxide, and when fully formed, exhibits a potential of about 500 millivolts. Because of a break in redox potential-depth curve below the sediment surface, Mortimer concluded that the oxi-

dized microzone was maintained by molecular diffusion of oxygen into the mud to a depth determined by the reducing power of the sediment. Thus the potential break represented the thickness of the winter oxidized layer. More recently Hayes and co-workers(*36*) and Gorham(*1*) presented evidence suggesting that the depth of the potential break represents the depth to which turbulence had stirred the sediment during circulation. In any case, as the oxygen concentration decreases at the beginning of stratification, the oxidized microzone becomes thinner and finally disappears when the potential in the surface layer of mud reaches above 200 millivolts. When present, the oxidized layer at the sediment-water interface serves as a barrier to diffusion from the mud to the water because of the greater adsorptive power of the oxidized phase. Also, if ferrous ions and phosphate ions diffuse into an oxygen-rich region, a precipitation of ferric phosphate occurs. Mortimer(*6*) showed that reduction was accompanied by the appearance in the water of ferrous, ammonium, manganous, silica, phosphate, and sulfide ions and soluble organic compounds.

Experimental evidence in support of this mechanism has recently been provided by artificially mixing a lake(*37*).

The natural restraints on redox potentials have been the subject of much study. It appears well established that living organisms exert a major control on oxidation-reduction systems in natural environments. Although the evidence cannot be presented here, the important paper by Baas Becking, Kaplan, and Moore(*38*) illustrates the point. It was concluded that the redox potential — pH characteristics of water are determined chiefly by photosynthesis, respiration, and oxido-reductive changes in the iron and sulfur systems.

MORPHOMETRIC CONTROLS

With regard to natural lakes, Hutchinson(*4*, p. 164) observed that the form of a lake basin and of the lake that occupies it depends partly on the forces that produced the basin and partly on the events that occur in the lake and its drainage after it has formed. The same statement can be made of impounded water bodies, if the special circumstances of their formation and subsequent management are considered.

The effect of reservoir size and shape on solution phenomena has been mentioned in connection with climatic controls. From the standpoint of water quality, the influence of morphometry on stratification is most important. Mortimer(*39*) recognized three consequences of stratification: (1) sufficient light for photosynthesis exists only in the epilimnion; (2) water movements in the hypolimnion are much reduced; and (3) dead organic matter rains down from the productive zone at a rate depending on the productivity. This gives rise to the oxygen demand typical of the hypolimnion. Thus, the oxygen is used up more rapidly in shallow lakes because of the smaller volume and smaller quantity of oxygen available at the beginning of stratifica-

tion. By similar reasoning, it is obvious that reduction products tend to reach high concentrations in the hypolimnions of shallow basins.

Morphometry sometimes acts directly to control chemical transformations. Hutchinson(*40*) explained the increase in bicarbonate in bottom waters of Linsley Pond by showing that more of the ion per unit volume could go into solution from precipitated carbonate in the sediment where the bottom slope was gentle than where it was steep. A more gradual slope provided more mud surface per unit volume. Shapiro(*41*) attributed a mid-water oxygen minimum in Lake Washington to a similar bed effect in which a submerged shelf with sediments of high oxygen demand was in contact with the water.

Reservoirs act as traps for sediment carried in by influent waters, with the result that the effective storage capacity and depth are reduced. The rate at which this process proceeds is extremely variable. Although the effect of reservoir sedimentation on water quality is probably minor compared to the serious loss of water storage space, other consequences of sediment accumulation have been reported. Gartska et al.(*42*) observed that most of the turbidity currents reaching Hoover Dam in Lake Mead occurred during the first 7 years of the impoundment when the original channel of the Colorado River was still well defined. Later, sediment deposited in the channel increased the area of the interface, resulting in reduced velocities and increased desilting of the inflowing water. The density currents spread into thinner layers and became increasingly less capable of reaching the dam. A similar observation was reported for Elephant Butte Reservoir(*43*). In discussing the chemical dissimilarity between small lakes and adjacent ground water, Hutchinson(*4*, p. 232) stated that lake water is separated from ground water by a seal of clay and fine silt deposited as an early lake sediment. This is not true for all lakes, however, and probably not for all reservoirs. This relationship needs further study.

In their studies of radioactive phosphorus in lakes, Hays and Phillips(*44*) found that the morphometric properties of a lake were one of the important controls on the final level of total exchangeable phosphorus. The volume determines the dilution, and the depth influences both thermal stratification and the relative size of the photosynthetic zone. They further concluded that rooted aquatic plants are probably unimportant in phosphorus uptake in large, deep lakes where the size of the littoral region is negligible compared to the total volume. In smaller and shallower lakes with minimal profundal zone, growth and bacterial decay of rooted aquatic plants probably dominates the phosphorus exchange.

BIOLOGICAL CONTROLS

The emphasis thus far has been on inorganic controls; however, the seasonal cycle of abundance of major and minor elements in water can only be interpreted with a knowledge of the ecological processes involved. Some of these effects have already been touched upon in previous sections.

Biological requirements for nitrogen and phosphorus have been stressed in water quality investigations because of their frequent occurrence in quantities too small to support plant growth. Other elements also are essential to organisms. Of these, potassium, calcium, sulfur, and magnesium are required in relatively large amounts. Hewitt(*45*) lists the following 10 trace elements, which are known to be essential to plants: iron, manganese, copper, zinc, boron, sodium, molybdenum, chlorine, vanadium, and cobalt. The abundance of these elements in water is controlled by the rates of supply and utilization by plants and animals, and by inorganic reactions.

Some organisms require still other elements. Thus, Hutchinson (*4*, p. 799) stated that the development of diatom blooms constitutes the most important mechanism by which silica is removed from lake waters. In reviewing the work of Vinogradov and Boichenko(*46*), Hutchinson concluded that the dissolution of aluminosilicate clay minerals by benthic diatoms greatly accelerates inorganic liberation of silica present in clay minerals of sediments.

Recent reports have emphasized the role of bacteria in controlling the redox potential of water and sediment and in the distribution of individual elements. Myers(*47*) and Ingols and Wilroy(*33*) found that bacteria are essential to the solution of manganese, although the mechanisms involved are not completely understood. Myers reported that manganese carbonate precipitates when carbon dioxide is removed from bicarbonate by bacterial action. Other bacteria are thought to utilize organic substrates that act as protective colloids, causing manganese to precipitate as the hydroxide. Under reducing conditions, this substance redissolves and may form high concentrations in bottom waters. Ingols and Wilroy(*33*) suggested that a bacterial byproduct rather than manganous ions may reduce manganic oxide by direct utilization of oxygen. The high concentrations of manganese reported in lakes with bottom temperatures of 23° to 28°C further suggest the importance of biological processes.

In a study of the transport of iron by clay minerals, Carroll(*48*) found that free iron oxide films could be removed from clay particles by lowering the redox potential through the metabolic processes of bacteria. Theil's(*49*) finding that bacteria can affect the solubility of alumina and silica was also substantiated by Carroll.

Products of biologic activity are important in the formation of complexes and in sorption reactions. Beauchamp(*50*) wrote that he believes diatom frustules have the capacity to adsorb sulfates and to prevent their reduction to sulfides. The accumulation of a partially decomposed organic layer on the bottom of a marsh was thought by Kadlec(*51*) to increase greatly the capacity of the sediment to adsorb ions. The role of dissolved organic substances in chelation of trace elements in natural waters was discussed by Saunders(*52*). During a study of the responses of a marl lake to additions of chelated iron and fertilizer, Schelske et al.(*53*) observed that a phytoplankton bloom removed iron from the water, leaving concentrations below the pretreatment level. Apparently the chelate molecule made avail-

able to the algae iron that had not been available previously. It was further noted by Schelske(54) that the same chelating agent, trisodium salt of N-hydroxyethylethylenediamine triacetic acid, was effective in bringing iron sediments into solution under aerobic conditions.

Although the subject of marl formation is still poorly understood in several respects, there is general agreement that photosynthesis by plants and shell formation by molluscs are two of the most important processes by which calcium carbonate (and to a lesser extent, magnesium carbonate) is removed from solution.

Nitrogen is intimately involved in organic cycles, since it is an essential constituent of protoplasm. Dugdale and Dugdale(55) presented evidence for nitrogen fixation by *Anabaena*, a blue-green alga, in Sanctuary Lake, Pennsylvania. Kadlec(51) studied conditions in soils exposed during drawdown. He found a decline in bases, probably as a result of leaching from the soil, but nitrogen increased throughout the system as a result of microbiological nitrification in the organic soil.

The dynamics of phosphorus in water-sediment systems has been the subject of continuing investigation since Einsele's(26) early work. As shown in an earlier section, inorganic phosphorus is inseparably involved with redox potential and the iron cycle. Nevertheless, Rigler(56) concluded that the turnover of phosphate under natural conditions appeared to be caused primarily by bacteria. Hays and Phillips(44) attributed to bacteria the decisive role in exchange of phosphorus between solid and aqueous phases, reversing the conclusions of Hays(57). A normal cycle was postulated as consisting of (1) uptake and synthesis of organic phosphorus in the water; (2) fallout to the sediment surfaces; (3) bacterial breakdown to inorganic phosphorus; and (4) restoration of phosphorus to the water. That the matter may not be so easily settled is shown by a recent study by Livingstone and Boykin(58) in which it was found that the most important factors in phosphorus release from mud are the exchange capacity of mud and the ionic activity of water.

In discussing biologically active elements, Lauff(59) wrote that cycling of mineral nutrients is most efficient when the zone of active plant growth is close to the zone of most active decomposition of organic matter. Shallow depths are particularly favorable for this type of regeneration cycle.

MANAGEMENT CONTROLS

In this category are included those factors manipulated by man in order to regulate conditions within the reservoir or downstream from it. These operations are not necessarily attempts to regulate the quality of impounded water, in fact they usually are not, but they are consequences of management of the reservoir for one or several purposes for which it was designed.

During the water loss investigations of Lake Mead, consideration

was given to the possibility of reducing evaporation loss by withdrawing warm water from the surface. Gartska and co-workers(42) concluded, on the basis of field and model studies, that once a steady state is attained withdrawals of water from a homogeneous reservoir consist of contributions from the entire reservoir. Upper-level withdrawals of water from a reservoir with stable stratification would contain a greater proportion from the layers nearer the surface than would be expected under idealized hydrodynamic conditions. Similarly, when withdrawals are made from the lower portions of the reservoir, they would include a greater proportion from the layers nearer the bottom than would be expected on theoretical grounds. Furthermore, withdrawal of warm surface water might have other undesirable consequences downstream, even if it were feasible from the engineering standpoint. Churchill's(*9, 10*) oxygen data for TVA reservoirs did, however, indicate that withdrawal of surface water is indeed feasible.

After finding that most deep-water reservoirs show increased manganese concentration near the bottom, Myers(47) concluded that the depth of withdrawal and the nature of circulation determined whether this substance would create a problem. In general, manganese can be avoided if water is withdrawn from the epilimnion. Ingols and Wilroy(*33*) suggested that small reservoirs should be kept in continual circulation, possibly by the method described by Riddick(*60*), as the best means of controlling the increased hardness and manganese concentration in the hypolimnion during stratification. Ford(*61*) described the benefits of circulation induced in a small reservoir by air injection. Stratification was eliminated with marked improvement in the quality of discharge water, notably because of the elimination of hydrogen sulfide.

Reduction of the volume of the epilimnion by surface withdrawal has been proposed for an entirely different purpose by Murphy(*62*). It was suggested that biological productivity might be enhanced by mixing deeper water, richer in nutrients, into the photosynthetic zone during the productive season. If this is true, then surface withdrawal may be detrimental in cases where it contributes to phytoplankton blooms.

Finally, attention may be drawn to two other aspects of reservoir management; these involve solution and precipitation. First, improved watershed practices that reduce the sediment load can be expected to benefit the reservoir, not only by extending the effective life, but also by substantially diminishing the amount of adsorbed substances carried into the basin. Second, factors affecting the exposed marginal areas of impoundments during drawdown may produce undesirable secondary effects when reflooded. Ingols(*63*) observed excessive organic loading following submergence of exposed lake bottoms on which plants had grown. Kadlec(*51*) studied the effects of drawdown on the productivity of a wildfowl marsh. Frequent and severe drying of the soil was the most effective inhibitors of release of plant nutrients after reflooding. The demonstration of the influence of nitrogen fixation by alder trees on lake productiv-

ity(64) and the possible leaching of manganese from oak trees of a forested watershed(47) suggest that vegetation control may be effective in the management of small impoundments.

CURRENT AND NEEDED RESEARCH

Much of what has been presented thus far is based upon studies of lakes, ponds, or laboratory tanks. With the increasing number and importance of impoundments in the development of water resources, more detailed knowledge of the reservoirs themselves is required if they are to be managed for optimum results in terms of water quality. The need is especially great for increased understanding of fundamental processes that may be applied in the early design stage for control or at least forecast of the ultimate water quality to be obtained.

A number of research projects in the Geological Survey are applicable to this type of study of the dynamic controls on water quality in reservoirs. The following areas of current research illustrate the scope of these investigations:

1. Occurrence and distribution of radioelements in water.
2. Exchange reactions of radioactive substances.
3. Mineralogy and exchange capacity of fluvial sediments.
4. Solute composition and minor element distribution in lacustrine closed basins.
5. Hydrosolic metals in natural water.
6. Organic substances in water.
7. Geochemical controls of water quality.
8. Analytical methods — water chemistry.

Specific Areas of Needed Research

1. Effects of reservoir aging on adsorption capacity of bottom sediments and on other physical, chemical, and biological processes.
2. Controls on bacterial activity in aerobic and anaerobic water and sediments with reference to the regeneration of chemical substances.
3. Role of organic matter in cycling of elements.
4. Improved sampling and analytical techniques for inorganic ions and complexes. (This is essential to a satisfactory understanding of chemical dynamics in reservoirs.)
5. Techniques for predicting the chemical and thermal conditions to be expected in new construction.
6. Improved management methods for optimum control of water quality.
7. Better understanding of the role of producer and decomposer organisms in controlling water composition.

8. Distribution and importance of organic and inorganic trace substances.

9. Fate and role of cultural additives, specifically the influence of these materials on natural processes. (This presupposes a knowledge of the uncontaminated environment.)

10. Nature of deep-water currents in thermally stratified basins and their effect on water composition.

11. Relative influence of bottom and suspended sediments (inorganic and organic) on adsorption processes.

12. Relationships between reservoir water and adjacent ground water under uniform and fluctuating levels.

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DISCUSSION

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The preceding presentation is based upon a review of literature, and a critique of the usual sort seems inappropriate, inasmuch as a large number of people other than the two authors are responsible for the data given. Mr. Love and Dr. Slack are to be congratulated for their exhaustive search for and selection of material, as well as their summation of pertinent information. It was impossible for them to enter into all related areas in the time allotted, and their omission of a number of phenomena is not assumed to reflect their unfamiliarity with them.

A number of people here are aware of a 5-year study I directed to ascertain the effects of main stem reservoirs on water quality in the Central Missouri River. Progress reports had a limited distribution and the final report(*1*) was received from the printer only a few days before this symposium.

As indicated, the Love and Slack paper is difficult to review. I would assume that discussion of the various findings reported would require several times the space used for listing them. Since Love and Slack were largely concerned with the role of individual factors and actions, a brief discussion of some more general relationships that determine water quality in impoundments will complement their presentation. Water quality in streams below reservoirs is often greatly influenced by reservoir operation, which may at times negate or unduly emphasize certain events occurring in the impoundments.

I have studied various phenomena affecting quality of surface inland waters for more than 20 years. During this period I have become very impressed with the effects of living organisms operating

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within limitations imposed by physical and chemical conditions, which they themselves often modify. Only in its course through the atmosphere to the ground may water be assumed to be insignificantly affected by life. When it strikes the earth and moves across or into it, materials owing their existence to living processes in the soil are taken into solution or suspension and carried across or just beneath the earth's surface to water courses, or deeper into the ground to be discharged later. Carbon dioxide, which makes water much more corrosive of limestone, dolomite, apatite, etc., chiefly owes its existence to the biota of the soil, as do numerous other substances. Inorganic suspended materials and soluble minerals are also acquired from contact with the earth.

When runoff reaches a stream, pond, lake, or impoundment, materials it contains are subject to modifying influences of various factors operative therein, and it may also pick up additional solutes and suspended particles. Surface runoff usually or frequently transports loads of suspended sediment into streams from which it enters reservoirs. Most particles may be expected to settle out when currents are slowed or stilled in headquarters. Deltas of silt and sand are normally built up in these areas, but they may be eroded and displaced down reservoir if the water level declines sufficiently to permit their channeling and undercutting by the inflowing stream. Surface runoff discharges often differ in density from reservoir surface waters and, upon entering impoundments, flow above or under the latter, dependent upon their relative density, as density currents. Much of the silt contained in runoff segments of this sort may be carried some distance into reservoirs where it precipitates slowly. The character of suspended materials and processes encountered in reservoirs may markedly affect rate of sedimentation. Particles bearing the same charge (+ or —) repel each other and tend to remain in suspension if small and light, but they may be precipitated rapidly if neutralized by ions bearing opposite charges. Many finely divided clay particles carry negative charges that are often neutralized by hydrogen ions arising from respiration and/or decomposition of aquatic organisms. This reaction leads to aggregation and sedimentation of clay particles, which may often take organisms down with them.

Surface runoff differs in density from reservoir surface waters during several periods of the year, and it is common for such discharges to flow under or across upper waters as density currents. Such movements are designated as over-, inter-, and underflows, depending upon the level at which they move down reservoir. Currents that move down at some depth often displace upper layers and induce an upstream flow along the reservoir surface. The upstream surface movement is stilled at the point where the inflow sinks into the reservoir, and this "convergence" line is often marked by a narrow zone of floating debris that has been carried both into and up the reservoir. Water quality may fluctuate markedly at this point with a change in wind direction from upstream to downstream or vice versa. Development of a convergence line is not a necessary

prerequisite for changes in water quality to accompany shifts in wind direction in headwater areas.

Turbid density currents often carry suspended sediment considerable distances into reservoirs and may play a large role in accumulation of "bottomset" siltation. They may lose turbidity very slowly and if perched in upper levels may restrict penetration of light. Behavior of turbid inflows is by no means static, and few patterns may be relied upon unless there is considerable familiarity with the reservoirs in question.

It has long been assumed that seasonal inflows are generally homogenized by mixing in reservoirs at some time during the year, and that overall water quality reflects the proportional influences of various seasonal discharges. Water contributed during seasons of high runoff is usually less mineralized than that entering during low flow periods, and could be expected to dilute the more highly mineralized segments. In some quarters reservoir reduction of hardness and alkalinity concentration has been assumed due to such dilution. Records(*1*) on the Central Missouri River indicate that seasonal flows tend to maintain their individuality in the huge main stem reservoirs, mixing only along their forward and rear margins. Prior to impoundment, river discharges with lowest mineral content occurred in July and August. As impoundment was augmented, appearance of these waters was delayed, and, finally, they left the reservoir area in midwinter. The most highly mineralized flows, normal to the midwinter season of low river discharges, were released during the summer period that formerly contributed flows with lowest mineral content. A reversal in the native seasonal mineral variation pattern was effected. These changes in water quality were not as abrupt as before impoundment.

Studies of the Central Missouri River furnished data on pre- and post-impoundment phenomena in Ft. Randall, Garrison, and Gavins Point Reservoirs, and their effects upon quality of discharges. None of these impoundments developed stratification or density layers during the period of our investigation. Water level rise in each instance inundated previously open soils and leached various substances from them. Suspended sediment carried in the muddy river was dropped to the bottom in headwaters and phytoplankton growth soon began, and was evidently stimulated by materials leached from the soils. In Ft. Randall Reservoir, photosynthetic precipitation of hardness and alkalinity soon exceeded or overshadowed quantities picked up from the basin and the net effect on an annual basis was reduction of bicarbonate (Ca and Mg) in the water passing through the reservoir. Garrison Reservoir reduced the hardness and alkalinity of its inflows during its first year of impoundment but leaching of its floor increased hardness and alkalinity during the second year. Operation during the second year resulted in a net increase in surface elevation. Leaching became less noticeable in both impoundments with passage of time. Progressively smaller areas were inundated per foot of elevation increase, and sedimentation of organic and inorganic particles soon began to form a barrier between the water and original

soil substances. The sediment layer was disrupted and leaching promoted by fluctuations in surface elevation. It is expected that photosynthetic precipitation will eventually overshadow bed solution in all units of this reservoir system.

Reservoirs are lakes, a rather unique type to be sure, but a type that can be formed by natural actions when an earthquake or landslide blocks a stream. Construction of a reservoir therefore imposes lentic or lake conditions in a previously and exclusively lotic or stream environment. It is normal for a standing body of water to work toward its own extinction by filling its basin with various materials. This tendency is quite contrary to the normal lotic pattern of enlarging, deepening, or changing channels and flood plains. Settling or precipitation of materials in a reservoir is the major action behind its influences on water quality as aging proceeds, but these processes can be disrupted by fluctuation in water depth.

The subject of reservoir classification has not received any concentrated nationwide attention. Distinctions that may be noted in the Tennessee River system, for example, should not be expected to characterize other areas where water demands, operation, climate, etc. are different. The nature of a reservoir is essentially determined by its surface area, depth, capacity, rate of flow through, topography of its surroundings, soils in its contributory drainage system, climate, mode of operation, orientation to prevailing winds, age of impoundment, etc.; location on a tributary stream or main stem is at most secondary in the great majority of cases. In many instances, major storage is provided by main stem impoundments.

The authors (Love and Slack) devote considerable attention to climate, chemical reactions, stratification, etc. that have marked influences on water quality. The classical picture of stratification and the effects they ascribe to it, supported by the findings of various investigators, assume that the dividing line between the upper and middle water layers (epilimnion and thermocline) is below the level of effective light penetration. This is not always true, and since quality of water may be and often is dominated by photosynthesis, thermally separate layers of water may exhibit identical or very similar chemical characteristics if light penetrates both. Two distinct types of photosynthesis occur in surface waters, and it is normal for the less common type, that carried on by certain bacteria and liberating sulfur instead of oxygen, to occur beneath the "photosynthetic zone" of green plants. The bacterial type utilizes longer light rays and seemingly is restricted to levels where sulfides exist in excess of demands or are continually being formed for use. Hence, organisms carrying on this activity may exist in the upper oxygenless zone or at the boundary between aerobic and anaerobic conditions. Sulfur that they liberate sinks toward the bottom and builds up noticeable layers under certain conditions. Some may be oxidized to form gypsum if it enters aerobic water. Activities of photosynthetic bacteria may therefore afford hardness increases under certain conditions when $CaCO_3$ is being precipitated by algal or flowering plant photosynthesis.

Major effects of the commoner (O_2 liberating) sort of photosynthesis on water quality are removal from solution of various elements necessary to plant growth and metabolism, supply of oxygen, and precipitation of $CaCO_3$ ($MgCO_3$) from $Ca(HCO_3)_2$ ($Mg(HCO_3)_2$) as the latter compound is decomposed to provide CO_2. Algae can remove great quantities of phosphorus and nitrogen when these elements are present in abundance, and in most natural waters they are usually effective in restricting phosphorus to the organic or "unavailable" state. Great quantities of alkalinity and hardness were removed from water by photosynthetic precipitation in Ft. Randall Reservoir on the Missouri River during 1953 through 1957.

Photosynthetic organisms may restrict depths to which they may occur by proliferating sufficiently to limit penetration of light to upper layers. Photosynthetic bacteria may be forced to migrate nearer the surface or cease photosynthesis when light is restricted to upper levels. Phytoplankers produce hydrogen ions by respiration or decay, and these ions often neutralize negatively charged silt particles and contribute to clarification when the latter aggregate in sufficient quantity to precipitate and carry organisms down with them. A number of normally photosynthetic organisms are able to exist as saprophytes or with other modes of energy acquisition when they are deprived of light. Under these conditions they may have influences foreign to those associated with their normal modes of life.

REFERENCES

1. Neel, J. K., H. P. Nicholson, and A. Hirsch. Main stem reservoir effects on water quality in the central Missouri River. USDHEW, PHS, Kansas City, Mo. Mar. 1963, 112 pp.

DISCUSSION FROM THE FLOOR:

Mr. McLean, U. S. Public Health Service: The lack of questions indicates that we have not been as much concerned with chemical quality as we may be in the future. In work on the Kansas River, we have been concerned with chemical quality, and I think we will be increasingly concerned with this problem in the future. I expect that the next time a similar symposium is held there will be more questions, because these problems will have intruded themselves upon us.

Dr. Ingols, Georgia Institute of Technology: Dr. Neel, what were the orders of magnitude of the high and low hardness values? In other words, was the range 1 or 2 milligrams per liter out of a hundred, or two or threefold in magnitude?

Dr. Neel: Hardness values ranged from about 300 to about 150 milligrams per liter.

Dr. Ingols: This is a twofold variation in magnitude at a very high level. We have observed a fivefold change in ionic concentration in the hypolimnion in some of the Piedmont zone lakes, but of course

when this is discharged from a lake or reservoir, the dilution of the hypolimnion in the total flow is so great that it does not show as a very big change downstream. Your orders of magnitude are tremendous for a stream downstream from a reservoir where there is mixing.

Dr. Neel: We did not detect any type of stratification in these reservoirs during the periods of our study.

Dr. Ingols: To what do you attribute the transition? Are ground water discharges causing this order of magnitude of change in mineral quality?

Dr. Neel: The low flows are made up mainly of ground water, yes.

Dr. Ingols: Is it a matter of change in the time of occurrence of low flow versus high flow?

Dr. Neel: Yes. The high concentrations originally occurred in the winter; they occurred in the summer after the impoundments were completed, which was a reversal.

Mr. Whitehouse, Central Electricity Research Labs, England: Mr. McLean said that apparently you were not as yet concerned very much with the chemical control of water. In England we have had to concern ourselves with this. An interesting and useful paper both from the biological and chemical point of view was published in 1959 in the proceedings of the Society for Water Treatment and Examination by Dennis Hammerton, who was the biologist with the Bristol Water Works in England.

Session 3

EFFECTS OF FLOW REGULATION ON WATER QUALITY (Part 1)

Moderator: **L. W. Gebhard**
U. S. Public Health Service

CHANGES IN WASTE ASSIMILATION CAPACITY RESULTING FROM STREAMFLOW REGULATION

R. A. Vanderhoof
Director, Ohio River Basin Project
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INTRODUCTION

My first impression of this subject was that it should be limited to a discussion of the effects of increased minimum flows downstream from a dam on dissolved oxygen concentrations resulting from the assimilation of organic wastes by biochemical oxidation processes. It became apparent, however, that a much broader consideration of the changes in waste assimilation capacity resulting from streamflow regulation was necessary. Changes in temperature, changes in pH, and changes in coliform numbers observed in field studies will be described. Since flow regulation requires that water be stored, changes in quality of impounded waters will also be discussed.

It is assumed that the reader is familiar with the Streeter-Phelps oxygen-sag formula and that its basic assumptions are generally understood(*1*, *2*), i.e., that the oxidation of decomposable matter is proportional to the amount present, that it is independent of the dissolved oxygen level, that reaeration is proportional to the dissolved oxygen deficit, that it is dependent on surface turbulence and internal mixing as well as absorption, and that both deoxygenation and reaeration are temperature dependent.

It is further assumed that the reader is generally familiar with the provisions of the Federal Water Pollution Control Act (as amended in 1961 by Public Law 87-88) relative to streamflow regulation. Section 2b of the amended law provides that "in the survey or planning of any reservoir by the Corps of Engineers, Bureau of Reclamation, or other Federal agency, consideration shall be given to inclusion of storage for regulation of streamflow for the purpose of water quality control, except that any such storage and water releases shall not be provided as a substitute for adequate treatment or other methods of controlling waste at the source." Note that both storage and water release are mentioned in the Act. Therefore, both waste assimilation in impoundments and in the stream below are discussed here.

WATER QUALITY CHANGES IN A RESERVOIR

Let us first consider water quality changes that might be expected when a flowing stream is converted to a reservoir. When a large river is impounded, the tributary streams that are flooded become the "arms" of the reservoir. My first major discussion concerns such "arms."

Let us look at a hypothetical situation: a waste load discharged to a small stream that runs into a larger river. After impoundment of the larger stream, a part of the small stream and its valley would be an arm of the impoundment. What changes in water quality, and hence in assimilation capacity, should be anticipated? The cross-sectional area in the arm of the impoundment would be larger than it was in the flowing stream. Consequently, the time of passage between any two points along the trace of the stream would be longer. As a result, the shape of the oxygen-sag curve would be changed significantly; i.e., you would expect that the long curve of degradation and recovery extending many miles in the free flowing stream would be compressed to perhaps about 1 mile, though the time element may not be greatly changed. Because of the loss of the mechanical aeration and mixing effects found in the free flowing stream, the critical oxygen deficit in the reservoir arm might be expected to be greater than the deficit observed in the free flowing stream. The minimum dissolved oxygen concentration must be modified and revised upward, however, for three reasons:

1. The increased absorption of oxygen from the atmosphere resulting from greater water surface area.

2. The greater clarity of water, which encourages increased growth of algae if necessary nutrients are available, and the resulting addition of dissolved oxygen resulting from photosynthesis.

3. The availability of dilution water within the reservoir arm.

With the exception of the effects of increased activity of algae, the major considerations that are expected to change water quality resulting from impoundment are included in the oxygen-sag formula. With a knowledge of the cross-section of the flooded valley, the flow rates of the incoming stream, and the quality of incoming waters, the quality of water in the arm, after reservoir stabilization has taken place, can be approximated.

If the assimilation capacity is defined as the organic waste load that can be accepted without degrading the water below a minimum acceptable quality, then in the preceding case there would likely be a loss of assimilative capacity. But is this loss the most important consideration? While a small area may be degraded below the quality objective, the water quality in a much larger downstream area may be greatly improved. In this small degraded section, the flow through time is greatly increased. Instead of rapidly passing on down the stream, the water is retained in the reservoir arm. While the oxygen resources are heavily taxed and are replaced slowly, the increased detention time permits the satisfaction of BOD and the die-off of coliform organisms within a confined area.

A further consideration is the use of the land and water in the vicinity of the area of greatest quality degradation. If there is a loss of legitimate water use in the area of greatest degradation in the impoundment, the question arises as to who should be responsible

for the mitigation of the damage; the one(s) discharging the waste or the one who built the impounding reservoir? No attempt is made here to answer this question.

Now suppose we leave the hypothetical situation and consider actual observations that were made in a free flowing stream in 1956 before impoundment and in the arm of a reservoir in 1960 after the stream was impounded(*3*). Both sets of observations were made in the summer season. The stream was relatively small, not more than 5 yards wide over most of its length. The arm of the impoundment is not more than 5 yards wide at the upper end and about 300 yards wide at the end of the first mile.

The major source of waste is an industrial plant located about 2 miles above the head of the reservoir arm. The organic waste load was about 25 percent larger at the time of the post-impoundment survey than at the time of the pre-impoundment survey. The number of coliform organisms discharged at the time of the post-impoundment survey was only half what it was during the pre-impoundment survey, however. In neither case were the industrial wastes treated.

The 5-day, 20°C-BOD (BOD_5) observed in 1956 showed a steady reduction from about 80 milligrams per liter to an estimated 30 milligrams per liter, or a reduction of about 60 percent, over a distance of 5,000 feet. In 1960, after impoundment, the BOD_5 dropped from 51 to 1 milligram per liter, or 98 percent, in approximately the same distance (Figure 1). While oxygen depletion, or an oxygen block, might be expected in the arm of such a reservoir, considering the BOD_5 load, no area was observed where the oxygen resources were exhausted. Where the free flowing stream merged into the reservoir, the rate of oxygen use roughly approximated the rate of reaeration, as indicated by the flat section in Figure 2. This section was about 4,000 feet long. For comparative purposes, all oxygen measurements were taken at a depth of 1 foot. With the exception of the flat section at the head of the reservoir, the rate of recovery in the impoundment was observed to be approximately equal to that of the free flowing stream. Vertical temperature and dissolved oxygen profiles (Figure 3 and 4) indicate that the dissolved oxygen concentration decreased rapidly through the thermocline and then more slowly until values below 1 milligram per liter were observed below 75 feet.

The coliform die-off occurred as expected. Figure 5 shows a reduction of 50 percent in the free flowing stream and 99 percent in the equivalent portion of the impoundment.

Thus this heavily polluted stream whose only use was to convey wastes to a larger body of receiving water was converted into a body of water usable for every recreational purpose, without benefit of manmade treatment devices. Except for a distance of about 4,000 feet where oxygen consumption equalled reaeration in the surface layers, the oxygen concentration increased in the reservoir. At the head of the reservoir, the oxygen content was approximately 5

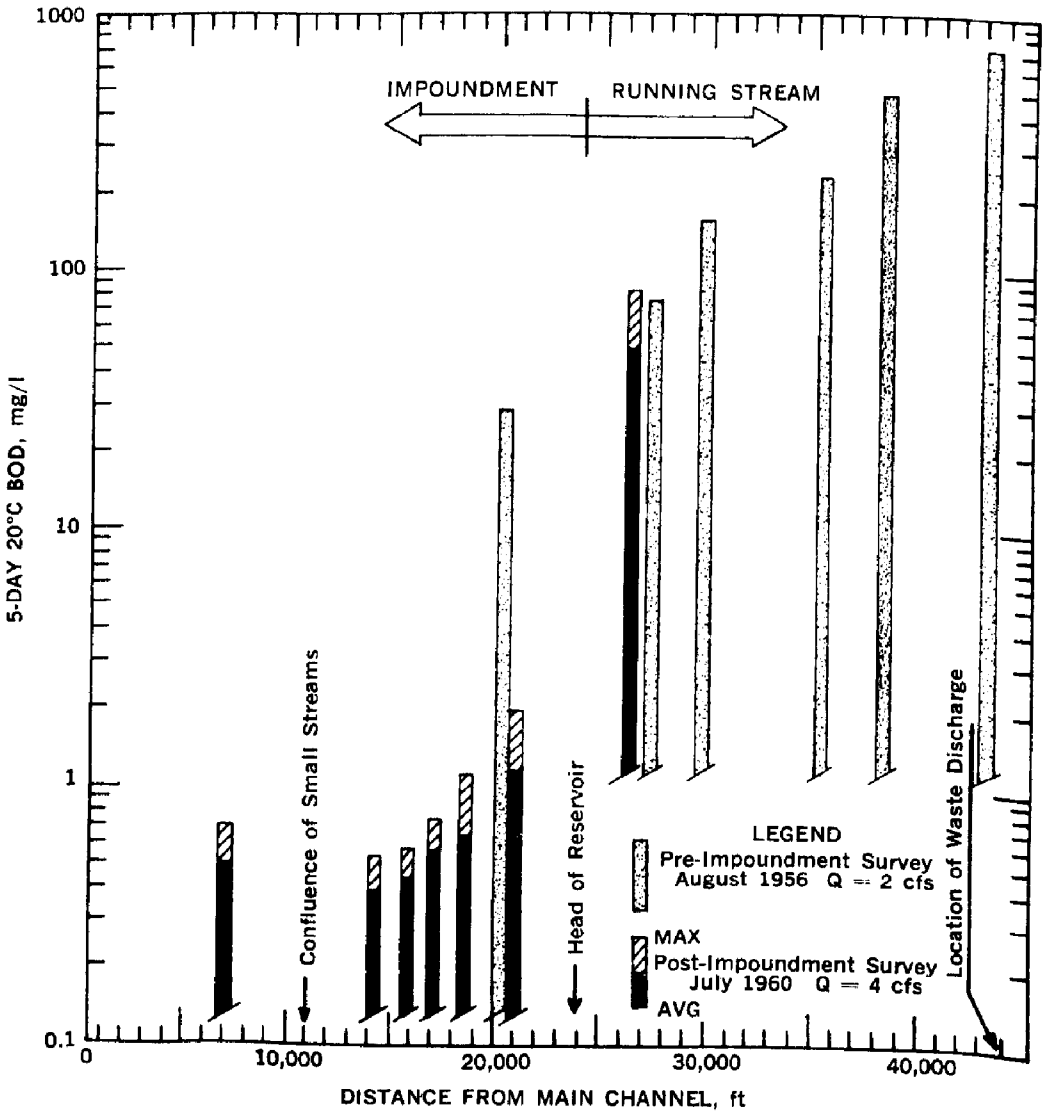

Figure 1 — Comparison of BOD_5 before and after impoundment.

milligrams per liter. If the industrial waste is treated, the quality picture should be even brighter.

In another arm of the reservoir, prior to impoundment, the free flowing stream received untreated municipal and industrial wastes; after impoundment, the wastes were adequately treated. The BOD_5, coliform content, and dissolved oxygen content were observed under both conditions over a distance of 11,000 feet(4).

The BOD_5 declined in the free flowing stream from 292 to 51 milligrams per liter, or 82 percent (Figure 6). In the impoundment, a reduction from 54 to less than 1 milligram per liter was observed over the same distance. This last reduction was observed for a waste

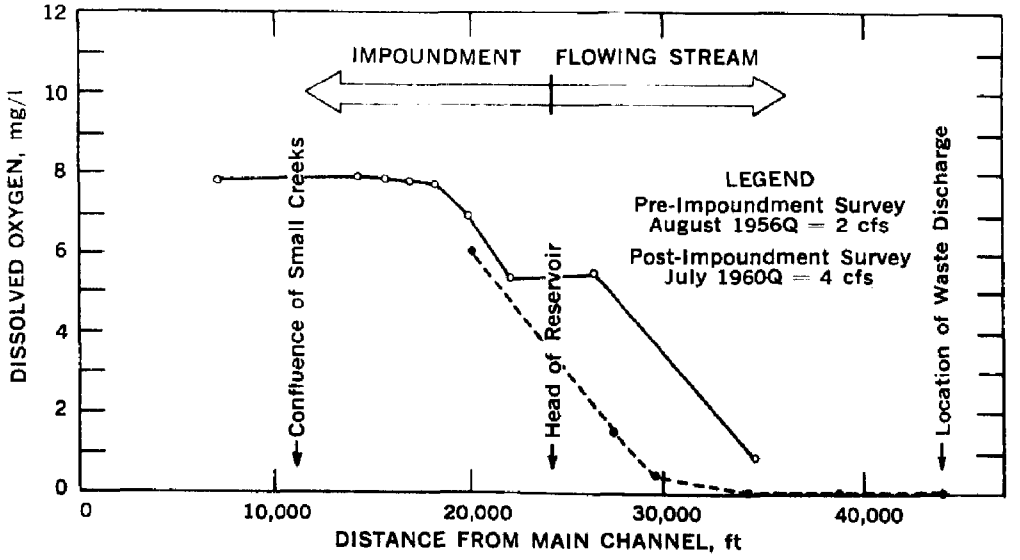

Figure 2 — Comparison of dissolved oxygen content before and after impoundment.

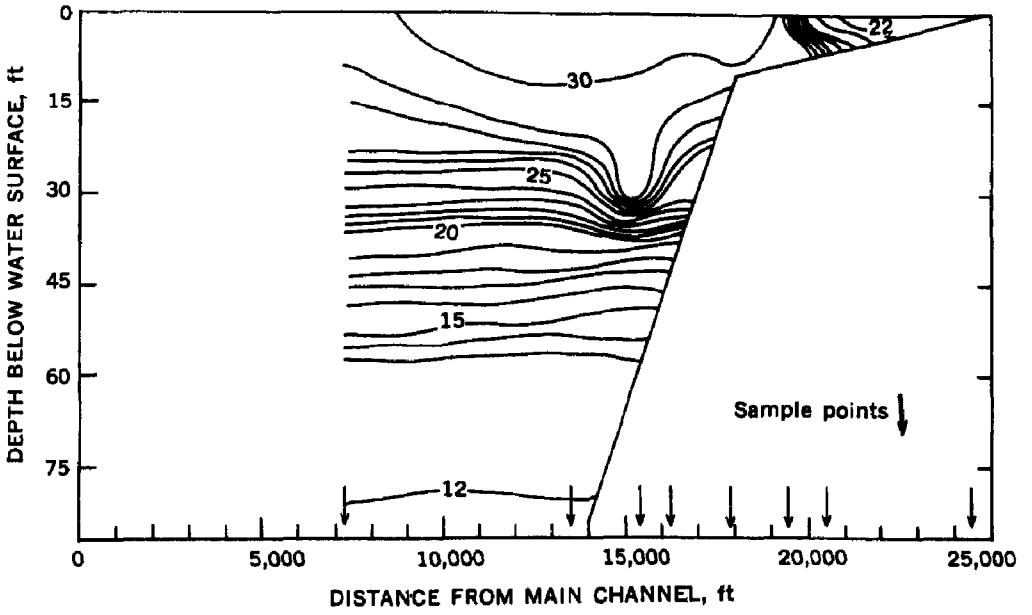

Figure 3 — Temperature profile, °C. July 14, 1960.

treatment plant effluent, not for a raw waste load. These comparisons were made in terms of concentration rather than load since the true load in the impoundment, if the organics that were undoubtedly leached from the bottom lands after they were inundated are considered, was not known. This certainly points to the need for more understanding of this complex problem.

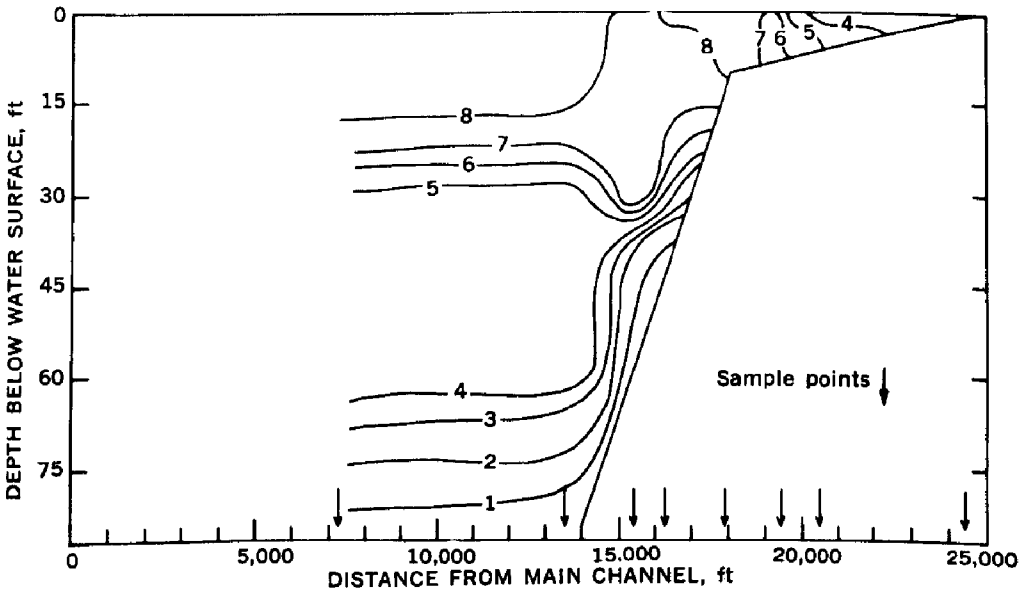

Figure 4 — Dissolved oxygen profile, mg/l. July 14, 1960.

Although the coliform content of the flowing stream was extremely erratic, as shown in Figure 7, the reduction amounted to about 99 percent. The coliform content of the waters discharged from the study area was still very large, however — over 3 million per 100 milliliter. On the other hand, the impoundment was extremely effective in reducing the coliform content. In a distance of 10,000 feet the coliform content was reduced from 790,000 per 100 milliliter, a condition of heavy contamination, to 40 per 100 milliliter, a condition acceptable for swimming.

The average dissolved oxygen content in the free flowing stream below the source of pollution was less than 1 milligram per liter over its entire length (except where tributary inflow provided a temporary improvement), as shown in Figure 8. After impoundment (and treatment of wastes), the waters entered with a dissolved oxygen content of 4.5 milligrams per liter, or 50 percent of saturation, and left the study area with an oxygen content of 7.8 milligrams per liter, or nearly 100 percent of saturation. No oxygen blocks were observed in the upper end of the reservoir. Temperature and dissolved oxygen profiles (Figures 9 and 10, respectively) show that the dissolved oxygen declined steadily from about 10 feet below the water surface, that the decline was more pronounced along the sloping bottom, and that a zone of degradation with one small pocket below 1 milligram per liter was observed. In this discussion, I am most interested in the effects on minimum water quality of changing a free flowing stream to an impoundment. It is recognized that in certain seasons of the year reservoir stratification may occur below depths of 15 to

30 feet, which can result in reduced dissolved oxygen concentrations at the lower depths.

While the dissolved oxygen sag question can be used to approximate the changes in water quality that occur in the upper end of an

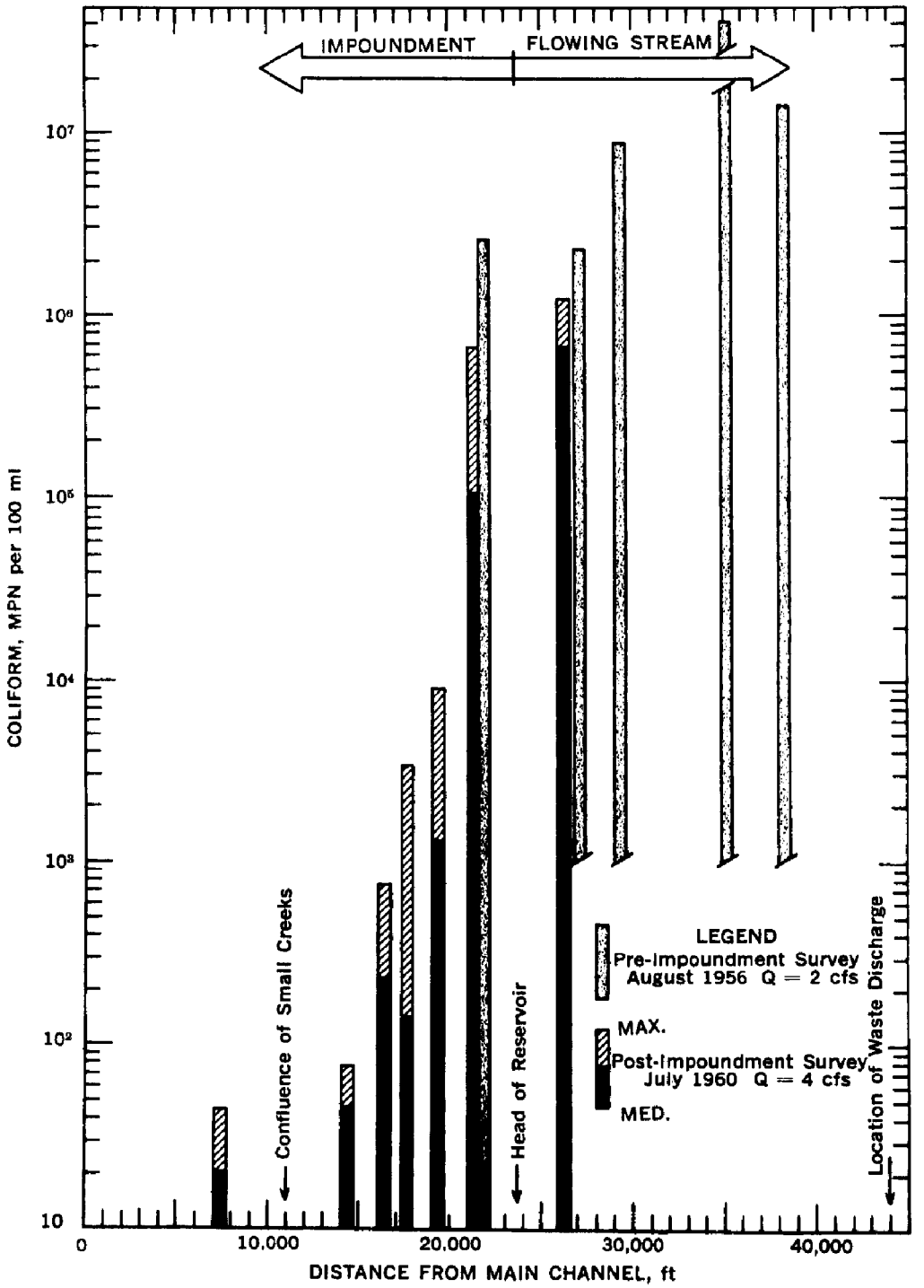

Figure 5 — Comparison of coliform numbers before and after impoundment.

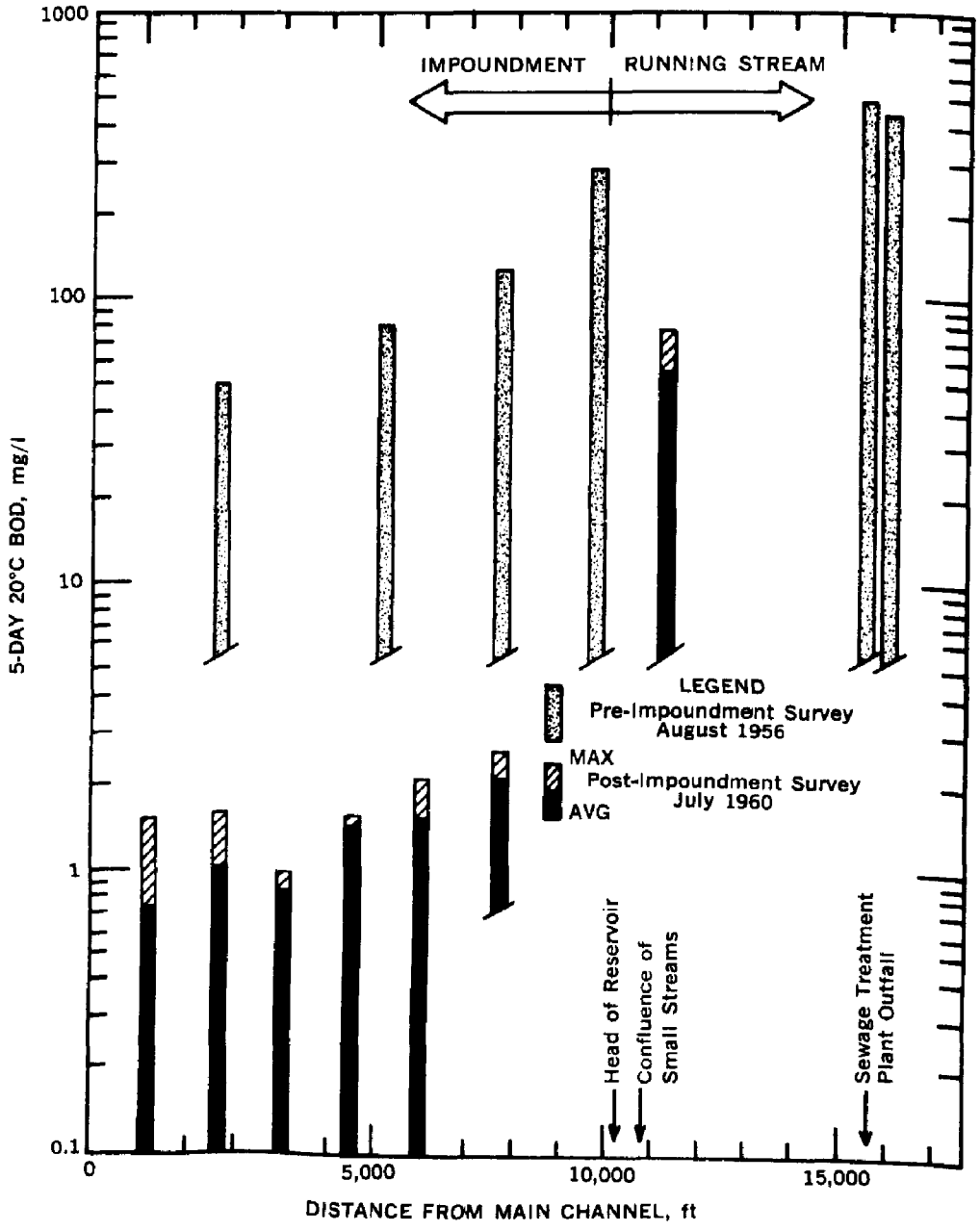

Figure 6 — Comparison of BOD_5 before and after impoundment.

impoundment, intensive studies on this general subject are needed to evaluate properly the changes in quality. For example, there is some indication that polluted water moved into the lower levels of these reservoirs as a density underflow.

These two examples are by no means conclusive evidence that the effects of impoundments are always beneficial. On the other hand,

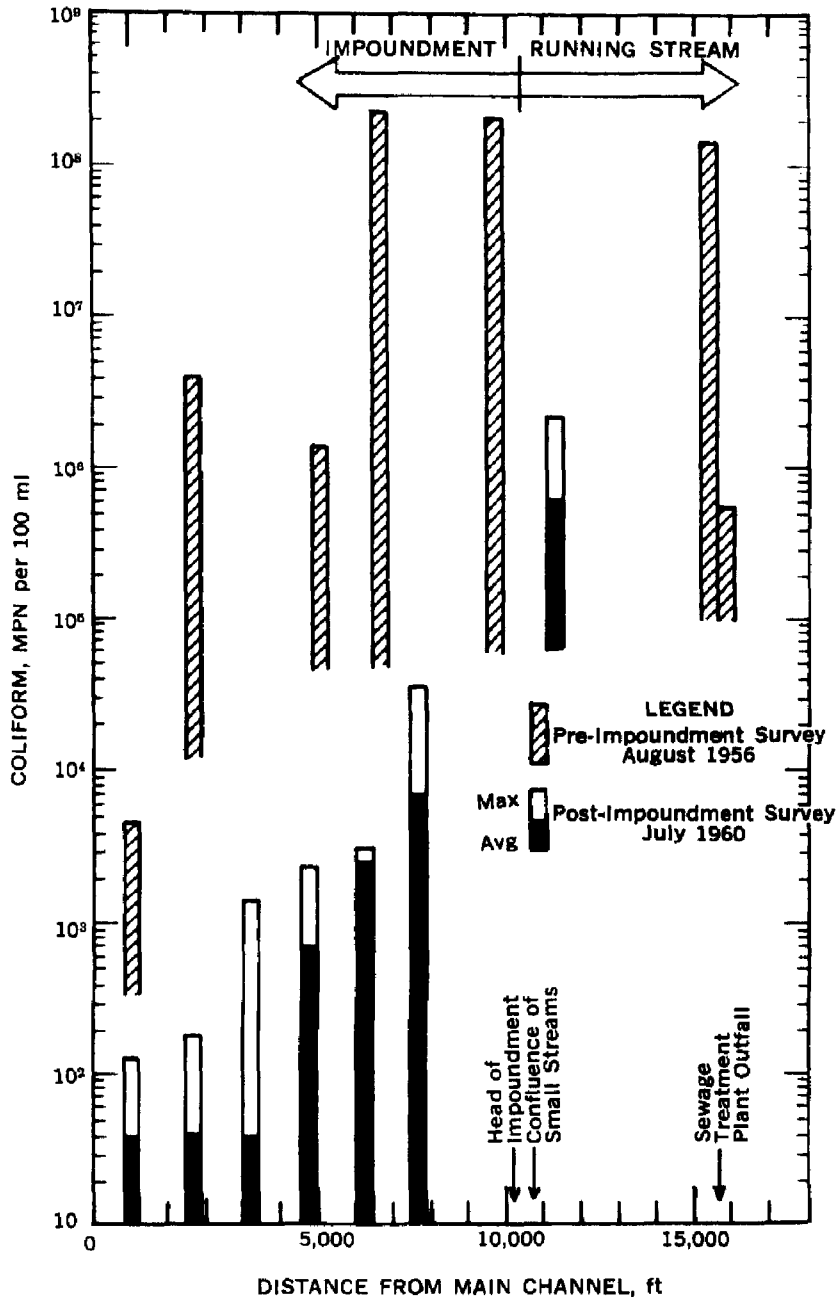

Figure 7 — Comparison of coliform concentrations before and after impoundment.

one should be most cautious in drawing the conclusion that impoundment of a small polluted stream will always result in nuisance conditions and the depletion of oxygen resources, even in a small area. Confinement of the polluted waters to a relatively small area can make the remaining portion of the water course available for higher water uses.

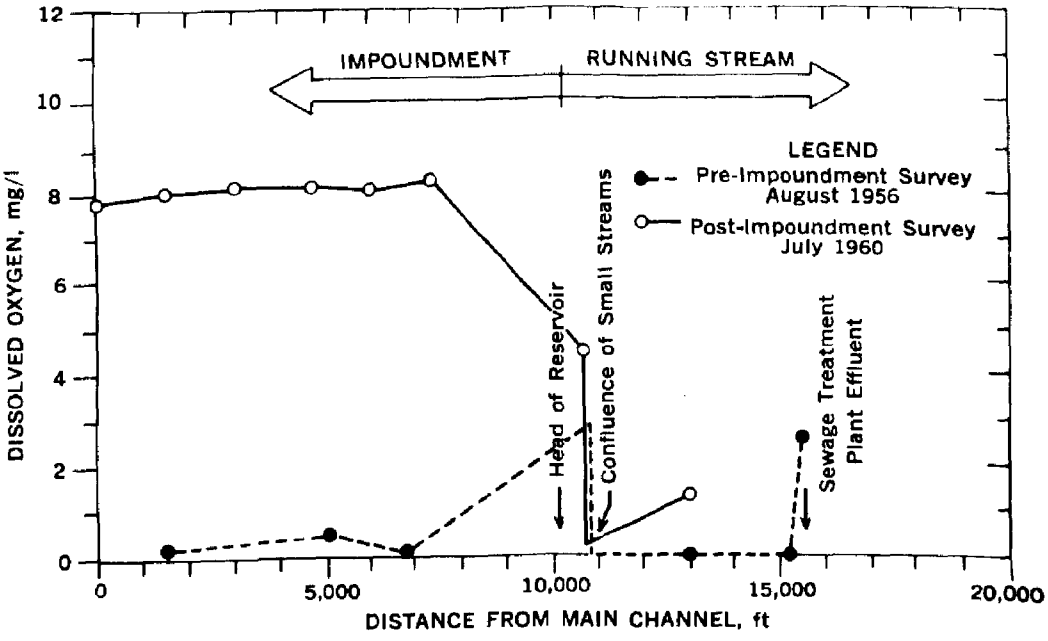

Figure 8 — Comparison of dissolved oxygen content before and after impoundment.

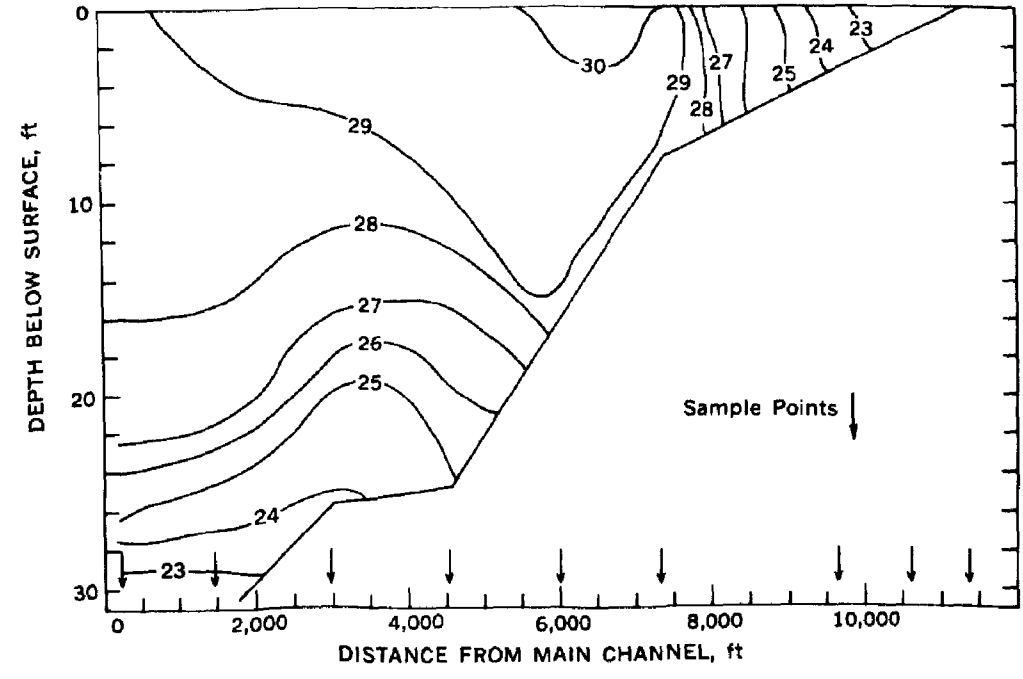

Figure 9 — Temperature profile, °C. July 11, 1960.

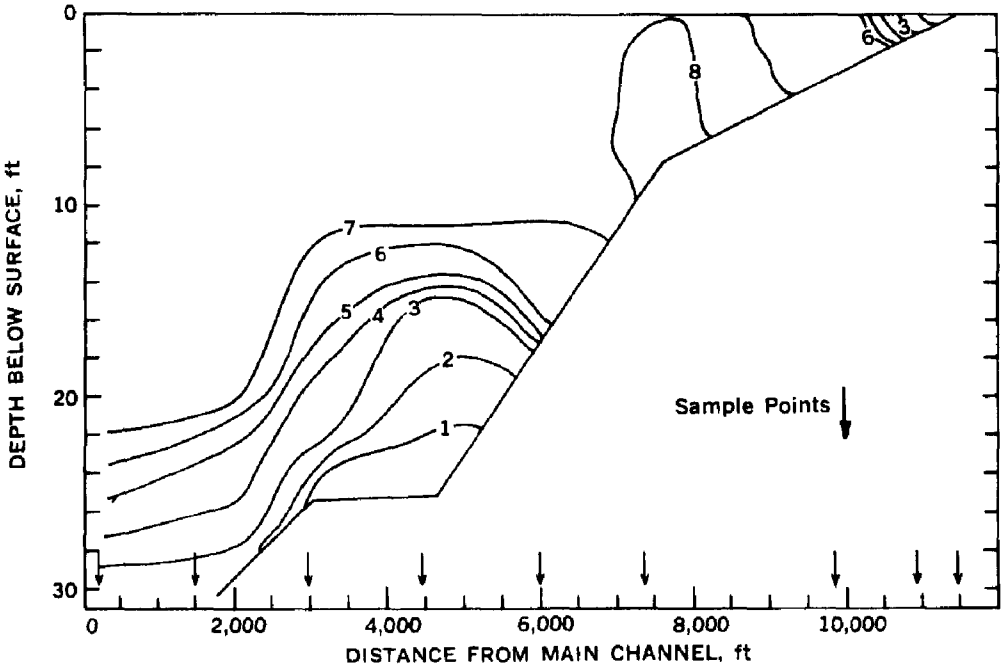

Figure 10. Dissolved oxygen profile, mg/l. July 11, 1960.

WATER QUALITY CONTROL DOWNSTREAM FROM A RESERVOIR

Now, let us consider the changes in organic waste assimilation capacity resulting from streamflow regulation downstream from a dam. Since temperature is discussed in another paper, only general remarks on its effects will be made. To compute the change in assimilative capacity, the characteristics of the stream and the quality of water prior to flow regulation by impoundment must be known.

The determination of dissolved oxygen content of waters released from a reservoir requires careful study; previous papers dealt with the development of thermal stratification and consequent oxygen changes that may be expected. This difficulty should now be considered prior to construction of any dam and, if depths are over 40 to 50 feet, if the period of storage is significant, or if organic wastes and/or nutrients are present in substantial amounts in the incoming water, appropriate measures should be taken to assure the discharge of waters of adequate quality. For a dam with no hydropower installation, it is usually recommended that facilities be provided to allow discharge of waters from the upper, middle, and lower levels. Then, according to downstream uses and needs and the quality of water available, water of appropriate quality can be released. Multiple level outlets provide a flexible system that can accommodate changing water quality and altered downstream uses. While today's uses may be known, it is not possible to be completely sure of tomorrow's uses. The general subject of improving the quality of reservoir discharges is discussed in the fifth session. Of most importance is the recognition that quality changes do occur in reservoirs, that there

are methods for improving the dissolved oxygen content of waters discharged from reservoirs, and that the quality of the water discharged must be considered. The BOD of waters released from a reservoir should, of course, also be determined. It is not unusual for waters to have a long detention time in the reservoir and it can be expected that the BOD will be low. BOD_5 values of less than 1 milligram per liter have been observed in many of our field studies.

The temperature of waters released from reservoirs is generally lower than in the flowing stream. Water temperatures can be expected to approach the mean air temperature, the change being proportional to the difference between the air and water temperature, the rate of flow, the distance downstream, and other factors(4).

The reaeration constant is a characteristic of the stream hydraulics and should be the same after as prior to impoundment. The reaeration constant varies greatly, however, with different flows(5, 6).

It is assumed for purposes of comparison that the waste loads are not changed and that the deoxygenation rates of the waste loads entering the stream below the reservoir are the same before and after impoundment.

Observations should also be made to compare the pH of waters from the reservoir with that of the free flowing stream. If there was an acid problem in the stream before impoundment, we can anticipate some improvement in the water released from the reservoir through dilution and neutralization, since the most severe acid problems are generally associated with short periods of runoff following periods of less than average flow. Although the stoichiometry of acid mine drainage waters is not well understood, the low flows and high flows are mixed in the reservoir, and dilution and neutralization of the slugs of low pH water should assure that the discharge from a reservoir would be more nearly neutral than the slug discharges occurring occasionally under natural flow conditions. It should be determined whether the changed pH has any effect on the deoxygenation rate. Acidity and alkalinity should be considered in the evaluation of pH changes that may result from impoundment.

Flow Augmentation

The major variables in the oxygen sag equation have been considered, except the effect of quantity of flow released from the reservoir. How much water should be released from a reservoir? What pattern of flow will the reservoir operation produce? The answers to these questions depend upon the purposes for which the project was authorized and the water uses downstream. Flow augmentation, or regulation of streamflow, can be provided to serve a number of purposes including public and industrial water supply, navigation, power production, propagation of fish and aquatic life and wildlife, recreation, and full or supplemental irrigation as well as water quality control. All such uses are considered in the multipurpose concept.

Two of these purposes — municipal and industrial water supply and water quality control — are the primary interest of the Public Health Service. The following discussion is confined generally to storage for regulation of streamflow for purposes of water quality control.

Flow augmentation implies the increase of an existing flow. The stream's total flow cannot be increased except by unusual means such as importation of water, but its ability to continuously assimilate wastes without excessive quality deterioration can be improved by storage of flood flows and subsequent controlled release so that flows can be increased when natural flows are low and water quality conditions are poor. Although flow augmentation is the topic, we are really interested in increased waste assimilation capacity provided by increased flow and this, of course, means maintenance of some selected quality objective.

Municipal and industrial waste treatment plants usually are designed to maintain a desired water quality objective in the receiving stream based upon the anticipated waste load and the conditions that most severely affect stream quality. For organic wastes for which the oxygen-sag equation was developed, these generally occur in the late summer and fall when flows are low and water temperatures are high. Generally speaking, it has not been considered practical to design waste treatment facilities to maintain the desired quality under the most severe or absolute minimum flow conditions. The design flow has been determined after consideration of the effect of lower flows on other water uses.

Treatment plants have thus generally been designed to allow maximum use of the stream for waste assimilation, consistent with other uses. The river below such a properly designed treatment plant should maintain the water quality objective essentially all of the time and be satisfactory for all legitimate uses.

The design flow often used is the annual 7-day mean low flow that has a frequency of occurrence of once in 10 years. The 10-year recurrence interval and the 7-day duration are used, for example, by the North Carolina State Stream Sanitation Commission. The design flow occurs within the critical period when, if dissolved oxygen is considered as the parameter of quality, the most adverse combination of low flow and high temperature can be expected. Thus, if minimum flow occurred in the winter when more oxygen is available because of the higher dissolved oxygen saturation level and the lower rate of waste decomposition, then minimum flows would be considered for the summer-fall period only, rather than for the entire year. If color is the controlling consideration, however, minimum flows at any time of the year would probably result in critical conditions. In the eastern states, the area with which I am most familiar, the design flow assures protection of aquatic life and the maintenance of a minimum acceptable quality of water over 99 percent of the time since the design flow is found to be equaled or exceeded in excess of 99 percent of the time in this area. If this be true, quality

lower than the objective occurs less than 1 percent of the time so long as waste treatment satisfactorily removes excess waste constituents. Beyond that point flow regulation is needed, and the duration and frequency of adverse conditions rapidly increase in its absence.

Peaking Power Discharges

If the main purpose of a reservoir is production of peaking hydropower, however, the downstream flow characteristics are seriously altered, even for those projects that plan to release the design flow at all times. In the eastern United States, flows at or below the design flow occur less than 1 percent of the time under natural conditions. It is estimated that flows at or below the design flow could occur as much as 75 percent of the time, however, based on 8 hours of discharge on weekdays under the altered conditions of peaking power production; flows would of course become more uniform as a result of channel storage as the distance from the dam increased. The changes in flow that result from peaking power production are illustrated by conditions downstream from Alatoona Dam, near Cartersville, Georgia(*7, 8*). Comparison of the duration curve of daily flow before and after power production was begun shows that the flow formerly occurring only 1 percent of the time now occurs 30 percent of the time. Thus the daily average flow exceeds the design flow only 70 percent rather than 99 percent of the time. Since daily average flows were used, the actual occurrence of low flow would actually be a much higher proportion of the time.

Hydropower plants that do not provide for at least the release of the design flow used for sewage treatment plant design create even more difficult downstream problems with respect to waste assimilation. Such hydropower plants can drastically alter the hourly, daily, and even weekly flow patterns when operated to generate peaking power. In some instances, stream flows may be completely shut off below the dam, especially during weekends. Such practices may not appreciably affect or may even improve the average monthly flow, but can completely alter the minimum continuous flow available to receive treated waste loads downstream while maintaining acceptable quality conditions. Peaking hydropower plant operations can thus become a more limiting factor affecting the waste assimilation capacity of the river than the natural flows.

What is the effect of retarding the minimum flow? When the flow is reduced as a result of storage during off-peak hours, pollution continuously entering the river from municipalities and industries accumulates in the channel downstream from the dam; when water is later released for power production, the accumulated pollution is swept downstream. The initial hydraulic wave is dampened as the water flows downstream, but the wastes are carried downstream as a slug of polluted water and are diluted only gradually. Under such conditions, wide fluctuations in water quality may persist for a considerable distance downstream, generally further than the fluctuations in discharge, and may seriously affect downstream uses.

There are other and equally important effects of limited dilution in addition to reduced dissolved oxygen. For example, toxic concentrations of wastes may adversely affect the aquatic life of the stream for considerable distances. Concentrations of taste- and odor-producing materials may cause periodic conditions of unpalatable water in downstream municipal water supplies. Coliforms and pathogens may be carried to downstream water plants relatively undiluted and with little die-off, resulting in increased hazard to the health of the community. Studies indicate that a modern, well operated water plant can handle the above described situation(*9*). Equipment can break down, however, and operation is not always at top efficiency!

The wastes discharged concurrently with the higher flows may be more than adequately diluted, but the excess of available oxygen is generally of little or no help in diluting the succeeding slugs of polluted water. The larger volume of water discharged during the production of peaking power will eventually mix with the slug of waste, but often not until after the maximum effect of the wastes has been felt. Average monthly, weekly or even daily discharges do not adequately disclose the ability of a stream to assimilate wastes.

There is an additional difficulty observed with peaking power hydroplants. The release of water accompanying peaking power production makes the water course downstream hazardous for recreational uses and in a sense, limits the use of the river to power production. The dedication of a river to a single water use is no longer considered reasonable. All streams should be available for a variety of uses, and should be physically safe for instream uses, as well as of an acceptable quality.

Are we saying that peaking hydropower and waste assimilation are mutually exclusive uses? That we can't have both? The answer is definitely, "No!" These uses can exist together to mutual advantage.

There are means of improving the dissolved oxygen content of reservoir discharges. A re-regulating structure can be built a short distance downstream to release waters at a more uniform rate, thus increasing the minimum flows and reducing the peaking flows. As holidays frequently involve 3-day weekends, sufficient storage should be provided in the re-regulating dam, or releases should be planned, to maintain a continuous minimum flow over the 3-day period. Re-regulation would probably eliminate the need to discharge water at the power dam during off-peak power periods. The downstream flow could be provided from storage by the re-regulating dam.

An advantage to recreation would be that the rapid rise of water resulting from peaking flows would no longer be a threat to safety of swimmers, boaters, or wading fishermen.

Since power production often involves increased summerflows, an overall increase in waste assimilation capacity could result from power production and re-regulation in that the design flow would always be exceeded, compensating somewhat for the previously dis-

cussed extension of the duration of occurrence of the design flow. Some loss of reaeration could be expected, however, in the re-regulation reservoir.

COMPATIBILITY WITH OTHER PROJECT PURPOSES

The single-purpose flood control reservoir generally has little influence on the waste assimilation capacity of a stream since it has a relatively small conservation pool. An exception is the provision of quality control storage during the part of the year when floods are less likely to occur. In the Ohio Valley a part of the flood control pool may safely be used to store water for purposes other than flood control from about April 1 to December 1. This part-time storage, or "seasonal storage," may be used for flow regulation for quality control. Such storage is extremely useful in the Ohio Valley as critical periods (defined as the period when high temperature and low natural flow result in the least assimilation capacity) occur within that period. This storage can be added to a project with relatively little additional expenditure and can be very useful at the time of need. Some modification of the normal outlet works may be necessary to provide needed flexibility for water quality management.

Dams built to provide storage of water for navigation purposes are certainly also useful in increasing the waste assimilation capacity by increasing minimum flows during normal low flow periods. Addition of multiple outlets in such structures would make the project equally applicable for regulation of stream flow to control water quality. Whether there is a downstream need for water quality control is another subject.

The navigation lock and dam structures *may* reduce the reaeration coefficient of the canalized stream. Whether the reduction in the overall reaeration coefficient is significant depends on the individual situation. Differences in surface area, depth, and velocity of water are all factors to be considered. A factor that should not be overlooked is the increased flow that will be available in the stream if flow is maintained for navigation purposes.

Reservoirs built for municipal and industrial water supply undoubtedly interfere with the waste assimilation capacity of the stream during periods of low flow. Water stored for these uses is returned to the stream as the effluent from a waste treatment plant and is not available to assimilate wastes. In at least one situation in Ohio, a city pays damages to downstream riparian owners where nuisance conditions result.

In some of the 17 western states, use of water for quality control purposes is not recognized as a legitimate use. If storage for regulation of stream flow for the purpose of quality control is included in such a project, it is not now apparent how such water can be reserved for water quality control purposes when prior legitimate water rights are not satisfied.

CONCLUSION

Multipurpose reservoirs that include provision for storage for regulation of streamflow for the purpose of water quality control should of course be designed to increase the waste assimilation capacity by increasing the flows above the design flow as well as releasing such flows with proper quality. The need for such flows is estimated according to results of an economic base study. The nation's water resources developments must be timely to ensure that lack of water will not constitute a limit on our economic growth. On the other hand, construction should not get too far ahead of forecasted needs for water, for this would result in a part of the investment being unproductive and therefore not efficient. It must be apparent that water quality control storage must efficiently meet the anticipated need in a timely fashion.

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DISCUSSION

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In his paper, "Changes in Waste Assimilation Capacity Resulting from Streamflow Regulation," Mr. R. A. Vanderhoof presents a hypothetical case in which he discusses the effect of an impoundment upon the stabilization of a waste originally discharged into a one-directional-flow stream. The author follows with an actual example by presenting a segment of his extensive studies with regard to the change in water quality before and after an impoundment construction. The opportunity to evaluate an area of size, before and after impoundment, is certainly the envy of most investigators. The author is to be complimented on his approach and more specifically upon his apparent capability of presenting a potentially complex problem in a manner that has practical significance.

When Mr. Vanderhoof discusses changes upstream resulting from streamflow regulation as induced by the construction of a reservoir, he stresses the effect of time and its indirect influence upon resultant water quality. This time aspect, when altered by changes in the runoff pattern and specifically with regard to recovery capacity, is probably the most important and least stressed factor in this type of quality investigation. It was hoped that the author would have pursued this time influence consideration at greater length.

In discussing potential change downstream, at various controlled flows, the author stresses the resultant effect of sudden large releases and/or "diversion" represented by releases of less than critical design flow. Here again, however, it would have been desirable for the author to pursue the time aspect and its indirect influence upon resultant water quality.

The author's comments lead one to conclude generally that if controlled releases are made from stored water in a manner proper to prevent sudden fluctuation in dissolved oxygen, temperature, and flow, only beneficial effects with regard to waste assimilative capacity would result downstream with increasing flow. At one time this concept was accepted completely; however, in recent years extensive estuarine studies have forced us to conclude that "dilution is not the solution to pollution." This finding also has led us to look more acutely into data from one-directional-flow systems.

We have endeavored to look hard at the influence of time and temperature in association with increasing regulated flow. With inorganic constituents, increasing flow results in lower concentrations by dilution alone. With decomposable organic material subjected to variations in time, temperature, and flow, however, we have found

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that reduced quality in estuarine systems can result with increased flow under specific conditions. We have also observed that when a drainage basin is considered in its entirety, it is possible to have the overall beneficial effects exceed the undesirable aspects. Much depends, however, upon which portion of a drainage basin is affected by the highest concentration of pollution. The distance, timewise, from the center of population and industry to a specific best water-use area becomes critical and controlling.

In recent years we have been forced to conclude that assimilative capacity may not have the same meaning to all investigators. The author defines assimilative capacity as that "load which can be accepted without degrading the water below a minimum acceptable quality." His effort to establish assimilative capacity before and after impoundment for his findings, however, raises some doubt as to whether our understanding of assimilative capacity is the same. Changing the environment by means of an impoundment and thereby inducing a change of water quality followed by a comparison of conditions before and after does not automatically ensure that this comparison constitutes a measure of the change in assimilative capacity. An understanding of the cause and effect relationship is required. A measurement of change in concentration alone, before and after, does, however, record the change between two points by changing the flow pattern and time aspect, but it does not measure the full recovery capacity of the system under varying time, temperature, and loading conditions. The former approach may reflect the work done by the system or net change in concentration, whereas the latter provides a progressive measure of capacity of the system to assimilate wastes without ill effects for future consideration. The tendency is to create or induce a degree of dilution and conclude that the comparative findings represent the extent of assimilative capacity. For example, unless we provide a measure of ultimate oxygen demand (only one of many potential parameters) on a pound basis and fully consider the multiple discharges of variable age, we are over-simplifying and erroneously judging a complex problem. We must have a full understanding of the total input and output covering the period under consideration. Perhaps, if we tentatively divorced from our thinking the standard of quality desired for a specific use at a given point, which incidentally can be achieved in some areas by dilution alone with unlimited resources, and confined our evaluations to a true measure of capacity to assimilate, we would more readily achieve our objective. Assimilative capacity can be more concisely stated as a measure of the net change in water quality within a given area under a specific set of conditions when subjected to a series of increasing and/or decreasing loadings added as continuous discharges.

In any applied-research study of assimilative capacity, one is unable to separate the evaluation of this capacity from the location simply because in any implementation of the findings the best water usages of a specific area will eventually determine the adopted criteria, or desired water quality. Quality at any location is affected notably by the proximity to the source of pollution and/or by the time of flow.

As pointed out by the author, when we impound water we change the flow pattern or the transit time in the "arms," i.e., the affected upstream tributaries. Similarly, in a free-flowing system below an impoundment, an increase or decrease in released water changes the time of transit between two given points. The question arises, "What will be the net progressive change in quality at various temperatures and rates of flow between two given points?" Does the loss of time for stabilization result in a condition sufficiently degrading to offset the benefits attributed to dilution with increasing flow? For example, if we had a waste discharge at point A, and a water intake downstream at point B, a loss of degradation time between A and B might result in an undesirable water quality condition at B in spite of the increased flow or dilution. This could be particularly significant with bacterial discharges, where a loss of time corresponds to a lessening in total number of organisms destroyed between the two points under consideration. In an estuarine system, where the time of transit is markedly affected by the river configuration as we move downstream, the net water quality in the lower reach could become considerably depressed with an increased rate of flow or regulated release, in spite of the beneficial aspects of dilution evident in the uppermost reaches.

The generally accepted concept that increased flow improves water quality is open to serious question when considering pollutional aspects, particularly in estuarine waters. Studies of the Delaware River prototype during the past 8 years have shown that the effect of increased flow is not the same in all portions of the tidal area. Initially, it was assumed that the shift producing decreased quality in the lower reach of the estuary during periods of increased flow was of a temporary nature. This reduced quality became more marked with increased flows, and at much higher than normal flows there was a tendency of reversal in which the quality began to improve in the lower reach of the estuary. The question remained whether this conclusion was sound and whether a series of hydraulic model experiments could be performed to resolve this apparently unpopular observation.

In an attempt to simplify or generalize what takes place within an estuarine segment when a waste discharge enters the upper end, the following analogy is made. If the flow or transit time to pass through a segment is constant, a specific amount of stabilization of organic matter is assumed to take place, depending on the deoxygenation coefficient "k_1" at a given temperature. If "k_1" or the temperature should increase, the amount of stabilization would increase or vice versa. If the flow increases, the time to traverse the segment under consideration decreases, with a corresponding decrease in time for stabilization. The latter would result in not only less stabilization of organic matter within the segment under consideration, but would project an increased loading of less stabilized organic matter into the next downstream segment. On the credit side, however, increased flow would result in decreased buildup concentrations. The question is whether the loss of stabilization time within a given segment is sufficiently compensated by the lower concentration buildup level induced by this increase in flow.

A series of tests with the Delaware River Model at Vicksburg, Mississippi, was carried out with equal dye loadings applied to the same location at progressively increasing flow stages. It was considered reasonable that the effect of flow on organic stabilization could be shown if the rate of deoxygenation and the decreasing buildup with increased flow could be compared under similar conditions. Initially, four consecutive segments of equal length were compared. The model data were able to provide, for each of these segments, the percent change in buildup concentration with increasing flow. In addition, the time of transit within each segment was related to flow. Finally, the stabilization, expressed in percent of the original concentration, was plotted against time under various deoxygenation coefficients. The effect of flow on stabilization could then be illustrated. The average concentration within a segment during a specific flow period was used. This procedure allows for the normal concentration gradient corresponding to increasing volume. In combining the two effects (changes in stabilization and concentration), we derived what we termed relative amounts of unstabilized organic matter. The amount of stabilization is initially substracted from 100. This results in the percent of unstabilized organic material. These values are multiplied by the corresponding concentrations. The net increase or decrease of organic matter resulting from increased flow conditions at various deoxygenation coefficients was plotted for a series of consecutive segments. The Delaware River Model data presented in Figure 1 showed that at a constant "k_1" value of 0.04, increased flow is always beneficial in the uppermost upstream segment under consideration and similarly, although not as marked, in the adjacent downstream segment. In the more remote downstream segments,

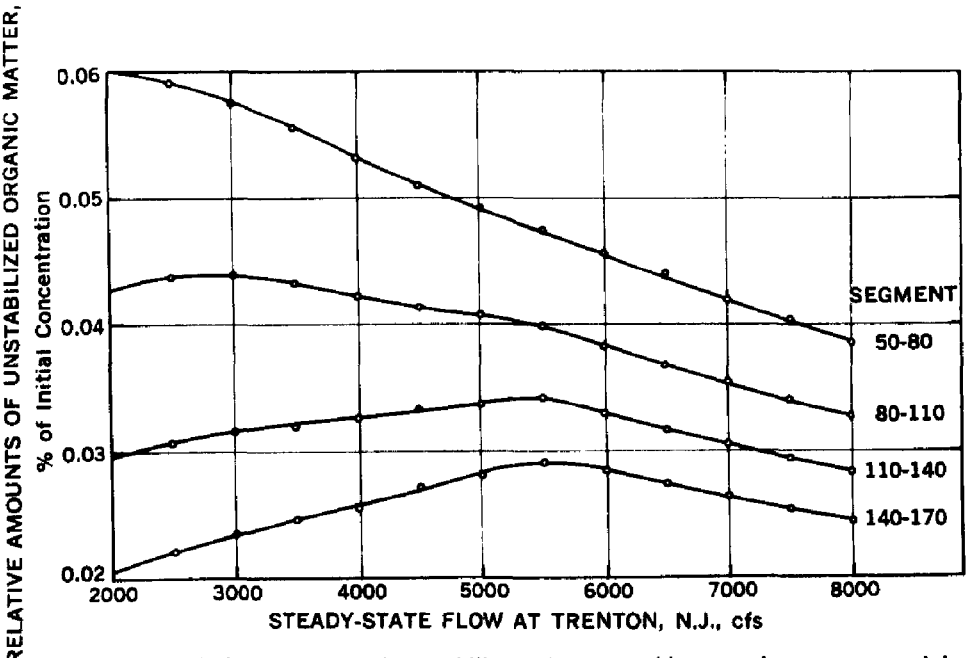

Figure 1 — Relative amounts of unstabilized decomposable organic matter remaining between progressive river segments under different flow conditions and at a deoxygenation coefficient of .04.

however, a decrease in stabilization was progressively evident up to a streamflow of 5,500 cfs and thereafter additional flow increases were beneficial; in the downstream stations flows as much as 8,000 cfs, 66 percent of the annual average, did not result in net stabilization greater than at 2,000 cfs. This general pattern varies, however, with the deoxygenation rate and/or temperature.

A typical example of the change resulting from different rates of deoxygenation and/or changes in temperature is shown in Figure 2 for a specific 30,000-foot station interval. In general, at deoxygenation rates of .072 and greater, increased flow results in progressively

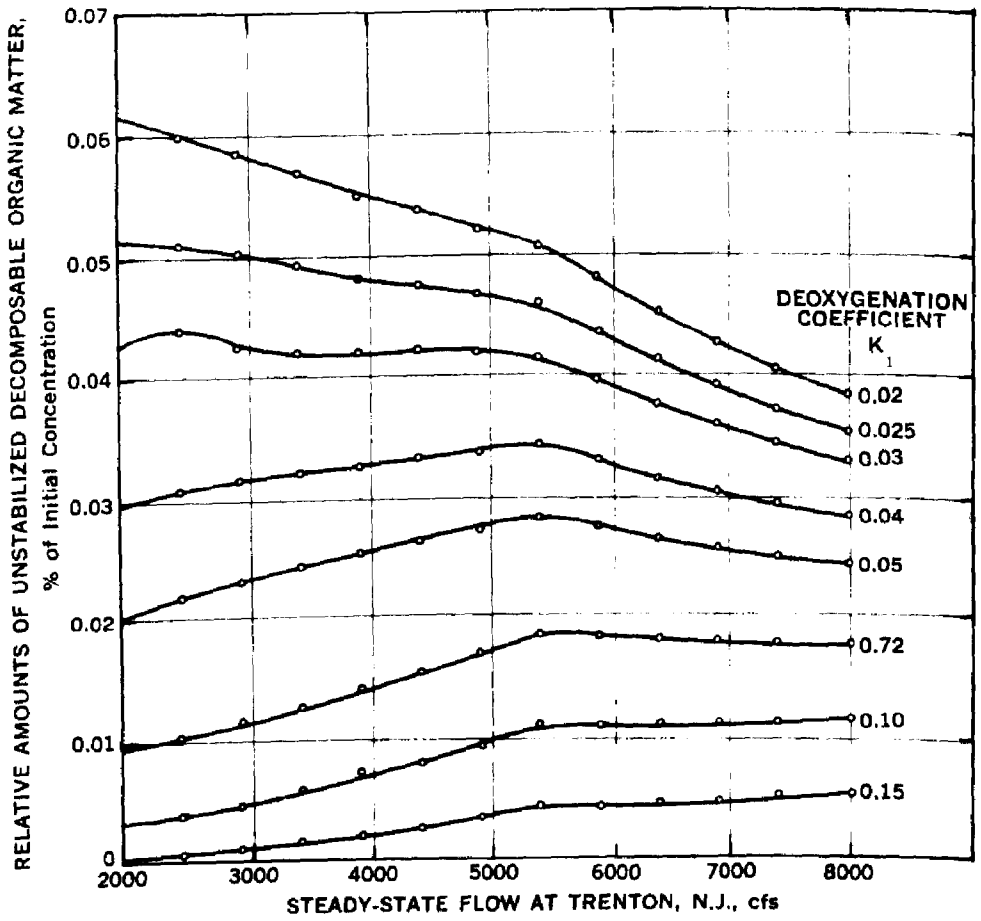

Figure 2 — Relative amounts of unstabilized decomposable organic matter remaining under different flow conditions and at various deoxygenation rates between channel segments 110-140.

poorer conditions. At a lower deoxygenation rate of .05 (20°C) and with decreasing temperatures comparable to the late fall, winter, or early spring, conditions could result in essentially less change or even improved conditions with increasing flow, all at the same location. This phenomenon is even more evident as we move downstream.

The analogous effect of the transit time in an estuary leads to a summary observation. Temperature and transit time are critical and

controlling. Accordingly, one can understand why a river system subjected to a continuously uniform organic loading may show, at a single location, a wide variation of quality with season. Further, if the design of treatment facilities is to be guided by dry-weather flow conditions, the resultant water quality and the controlling factors occurring during this period directly influence the final design. Water quality levels during other seasons normally become more of academic interest. Understandably, the location of the pollution source and the proximity of the recipient water user may create a situation whereby the adopted dry-weather period might not be the most critical time. Obviously, each system and each problem area must receive an independent evaluation.

The following discussion of water quality changes in Brandywine Creek by Mr. Vasuki* presents data compiled from a one-directional flow stream and depicts the effect of season and flow upon certain water quality parameters.

DISCUSSION: N. C. VASUKI

The Brandywine Creek has been an important source of water supply in the lower Delaware Valley since the early colonial settlements. The City of Wilmington (population approximately 98,000 — 1960 Census), Delaware, is situated at the lower reach of the Creek and draws approximately 35 mgd for public water supply. In recent months it has become increasingly important to establish existing water quality and potential change with flow. The proposed construction of an upper-reach reservoir and, therefore, controlled release of water precipitated an immediate need for the evaluation of projected water quality with varying controlled flow regimen.

The Wilmington Water Department has on record the various chemical and bacteriological analyses dating back several decades. For this evaluation, the period January 1, 1943, through December 31, 1961, was chosen. This represents a period of 228 consecutive months. Analyses were made on samples collected at 8:00 a.m. each day. The same two people analyzed the samples during the entire period of the study. The results of the analyses for 6,947 days were punched on IBM cards. Each card contained the following information: date, corrected average river flow, turbidity, alkalinity, chlorides and most probable number (MPN) of coliform bacteria. An IBM 101 Statistical Machine was used for statistical analyses. These analyses indicated the frequencies of occurrence of various concentrations of the variables and the mean values of each variable for each month, season, and year. The annual mean concentrations of turbidity, alkalinity, and chlorides are given in Table 1. The annual loads are shown in Table 2 and in Figure 3.

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TABLE 1. ANNUAL MEAN CONCENTRATIONS OF TURBIDITY, ALKALINITY, AND CHLORIDE. BRANDYWINE CREEK AT WILMINGTON, DELAWARE

Year	River flow, cfs	Turbidity, mg/l	Alkalinity, mg/l	Chloride, mg/l
1961	540	15.8	39.7	13.1
1960	585	21.9	38.0	15.5
1959	333	20.1	42.4	14.3
1958	722	26.8	35.4	9.5
1957	306	14.2	42.5	12.0
1956	430	20.0	38.7	10.7
1955	389	17.0	41.7	8.6
1954	247	19.0	40.4	10.1
1953	585	29.8	33.8	8.5
1952	677	27.0	32.5	9.4
1951	469	28.6	34.8	11.0
1950	402	23.9	35.8	11.0
1949	484	20.1	36.1	11.0
1948	544	31.7	31.9	11.1
1947	357	24.9	37.8	13.0
1946	453	33.9	36.4	10.4
1945	440	41.9	35.4	9.7
1944	325	37.3	35.6	14.7
1943	437	31.9	40.3	13.3

Routine coliform measurements, by season, are presented in Figures 4 (a, b, and c). Grouping by season was intentional to minimize the effect of variable temperature and thereby improve the evaluation of the effect of the variable of flow. Most interesting is the apparent increase in coliform content with increasing flow. Sources of coliform reaching the Brandywine Creek are well upstream, and the reduced bacterial decay between source and downstream intake associated with increasing flow is evidenced by the progressively higher coliform levels.

On the basis of these preliminary examinations, further analysis of the data is planned utilizing an IBM 1620 Computer. Additional information on change in population, industrial output, land use by agriculture, etc., is being collected. It is hoped that a sound determination of the change in water quality as a result of other man-made changes will be possible.

Several interesting observations may be made from the data as analyzed:

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1. Chloride values declined commencing with 1953, followed by a uniform increase since 1956. The latter trend has continued and now chloride loads exceed values of former years.

2. Turbidity levels show two distinct patterns, namely, a continuous decline over the entire period of record and a marked reduction commencing with 1954. The latter coincides with new waste treatment facilities at a paper mill 4 miles upstream. Implementation of contour farming during this period may have contributed to the steady decline.

3. Alkalinity showed no marked deviation over the period of evaluation.

4. A segregation of coliform data by season showed an increase in coliform content with increasing flow. This persistent pattern is attributed to a loss of time, associated with increasing flow, for bacterial decay between upstream sources and the downstream water intake.

TABLE 2. ANNUAL LOAD OF TURBIDITY, ALKALINITY, AND CHLORIDE (in Lbs. x 10^6). BRANDYWINE CREEK AT WILMINGTON, DELAWARE

Year	Turbidity	Alkalinity	Chloride
1961	16.770	42.139	13.917
1960	25.321	43.935	13.335
1959	13.156	27.753	9.377
1958	38.138	50.376	13.480
1957	8.541	25.563	7.192
1956	16.997	32.889	9.079
1955	13.034	31.972	6.562
1954	9.250	19.668	4.935
1953	34.360	38.973	9.798
1952	36.028	43.367	12.555
1951	26.293	31.993	10.156
1950	18.729	28.055	8.658
1949	19.175	34.438	10.481
1948	34.083	34.298	11.934
1947	17.521	26.598	9.147
1946	30.268	32.500	9.286
1945	36.337	30.874	8.412
1944	23.959	25.886	9.442
1943	27.476	33.247	11.456

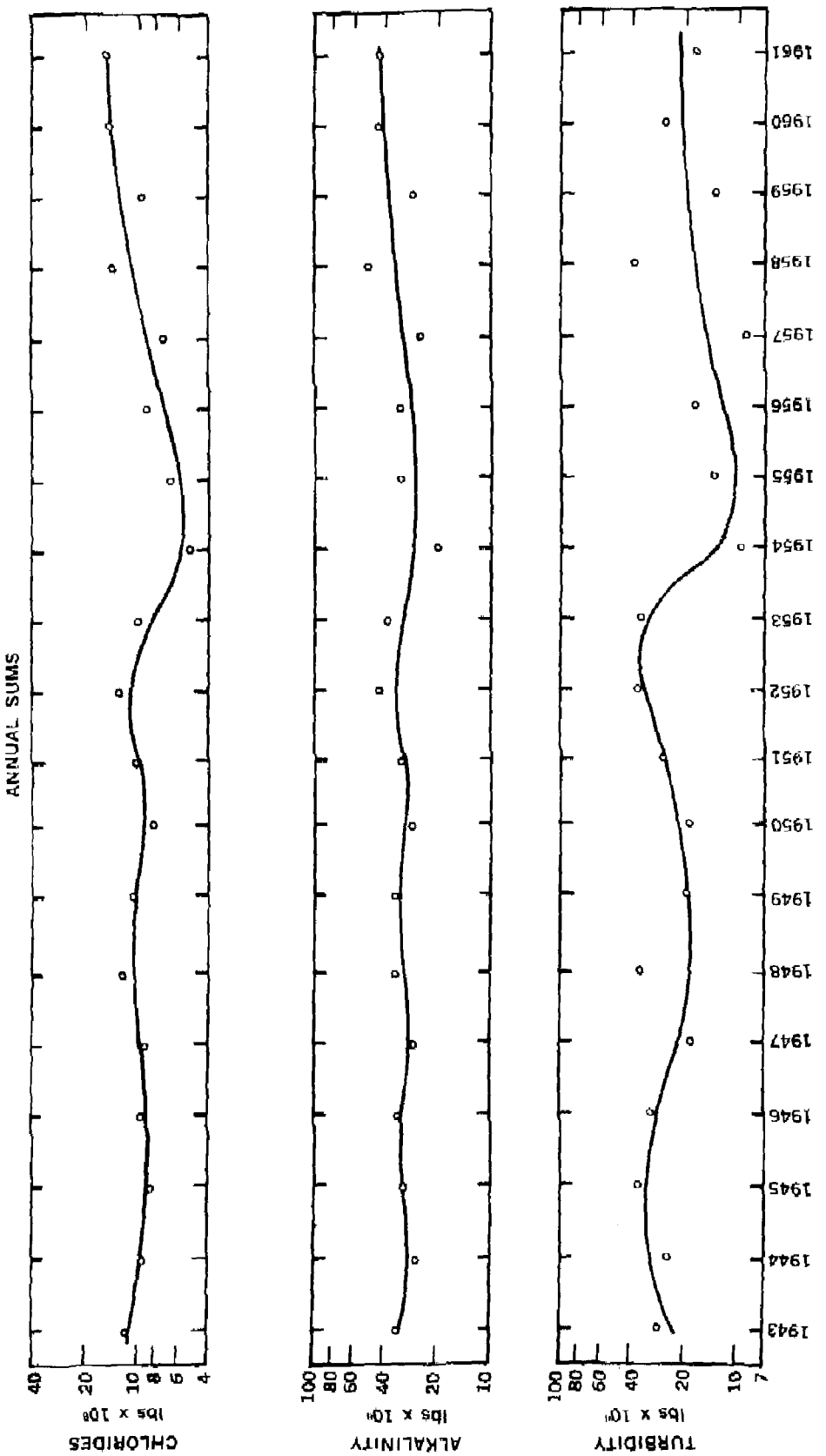

Figure 3 — Brandywine Creek water quality.

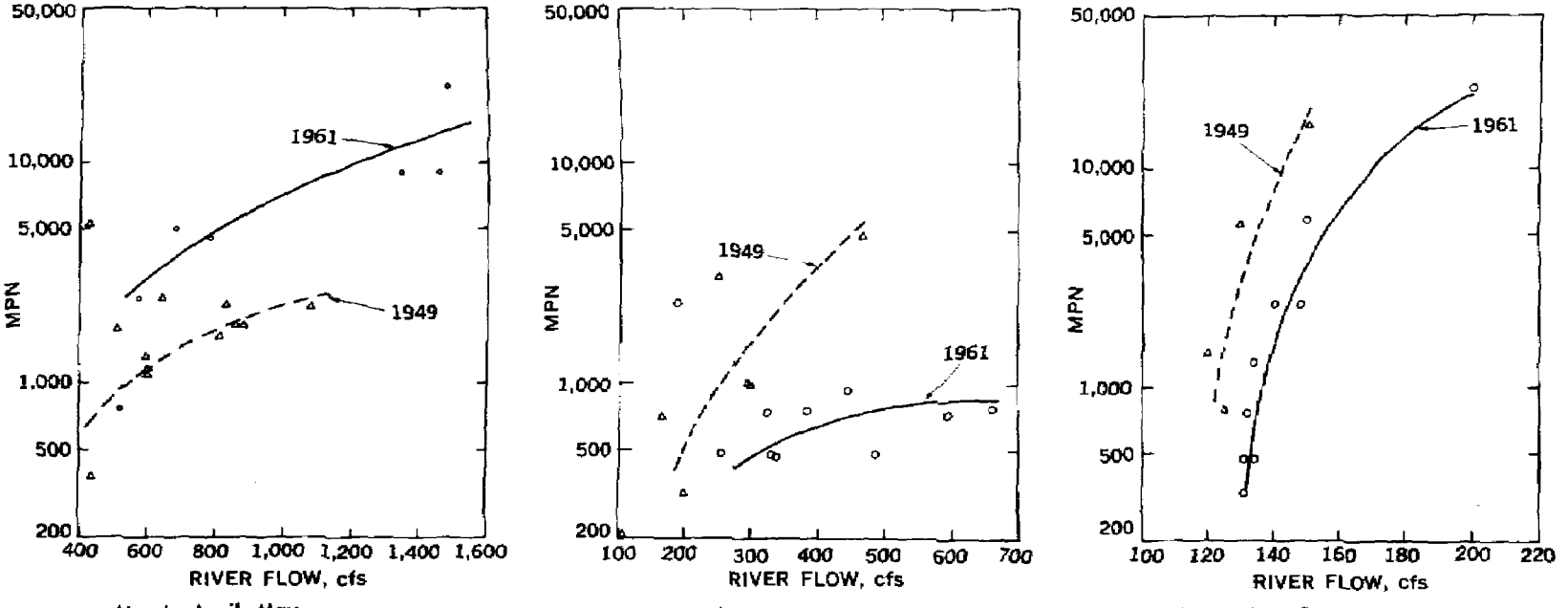

Figure 4 — Coliform bacteria (MPN per ml) versus flow, Brandywine Creek at Wilmington, Delaware.

DISCUSSION FROM THE FLOOR

Mr. Grounds, U. S. Army Engineers: Over the years, the Corps of Engineers has improved the navigation channel on the Mississippi River. They have done this by the construction of locks and dams and by the dredging of the channels. This results, of course, in a series of impoundments up and down the Mississippi River.

Do you think that the incidental benefits resulting from the assimilation of waste in these impoundments could be applied in the economic justification of future channel improvement projects?

Mr. Vanderhoof, Ohio River Basin Project: There is a great big plus for quality control in the navigation system, insofar as upstream storage dams are built to maintain a quantity of flow. Generally this is released at the time of the year when it is also needed for quality control. This is a plus.

At this time we are not sure just how much the lock and dam activity affects quality and how much benefit or loss may be attributable to the navigation locks and dams. In fact, the Ohio River Division has us working on the effects of changing the Cincinnati pool from a series of smaller locks and dams to the larger Markland Lock and Dam project. We are only halfway through that, since Markland Dam was just put into operation this winter. Post-impoundment observations are scheduled for this summer (1963).

Mr. Grounds: In other words, we are not at a point yet where we can actually say there is any definite benefit from main stem navigation dams for assimilation of waste?

Mr. Vanderhoof: At this point, no, not from the locks and dams themselves. But the upstream reservoirs that control quantities, if they happen to release water at the time we need it, do benefit water quality.

Dr. Kaplovsky: You were probably acutely aware in my discussion, that I represent a downstream state below a heavily populated, industrialized area in a tidal estuary, and also that we have to take a slightly harder, more practical view of development upstream because we are not only the sole recipients of everybody's beneficial development, but we are also the sole recipients of everyone's errors. I am not completely familiar with the area that you are referring to, but if you are interested in the tidal portion — and I assume this is why you have directed the question to me as well as Mr. Vanderhoof — you would find that as you deepen and widen the navigation channel, the pollution problems tend to change; e.g., saline water moves further upstream.

If you build a reservoir and release water at low-flow periods, the time of transit in the area downstream is reduced and the transfer of pollution from one point to the next point downstream is decreased time-wise. In other words, your buildup of pollution will be higher in most cases in your downstream area unless you provide sufficient

additional augmentation of flow to keep that build-up level at a reasonable point.

A lot also depends upon what use you will make of the water behind your impoundment. If it is to be used for water supply that you are going to divert out of the area, then your use of this storage will not provide additional increased flow.

Mr. Grounds: If you are contemplating an increase in the channel depth, you are going to provide a greater surface area for oxygenation in the impoundment. Is there any way to estimate this beforehand?

Dr. Kaplovsky: I think we are talking about two different things. While damming a river to increase depth results in a greater surface area, the Corps of Engineers in our estuary area deepens the channel by dredging, so that there is no increase in surface area.

It would probably be possible to estimate the change in aeration, but I believe it would require extensive study. I should say that observations at short intervals both vertically and horizontally would be required. I, personally, would be hesitant to make an estimate of how much improvement you would get in DO until you get an indication of the depths involved.

Mr. McLean, U. S. Public Health Service: Mr. Vanderhoof and I have worked on this problem in the Ohio River. The items involved have already been outlined — the changing of time of flow and the changing of the cross section. The changing of the cross section gives more surface area for aeration, but reducing the velocity and increasing the depth tend to reduce the amount of oxygen that goes into the system per unit of surface area.

There will likely be increases in photosynthesis.

Our conclusion in the Ohio pool was that we need to observe the changes in at least a few situations before we reach an answer to this question. Our hesitancy in arriving at a definite answer to this question is one of the reasons this symposium was called.

Dr. Krenkel, Vanderbilt University: The idea of reaeration is increased because the presence of an impoundment increases surface area is not always true. The entry of oxygen into water depends upon the area over velocity (A/V) factor which is proportional to the depth. If you have a long, deep channel the increase in depth may actually cause a tremendous reduction of oxygen absorption or waste assimilative capacity.

Furthermore, if we consider that the reaeration coefficient is proportional to some form of turbulence intensity — I am sure everyone will agree that it is — and if we take the mean stream velocity as a measure of turbulence intensity, then the turbulence intensity is reduced behind these impoundments, and the corresponding reaeration must also be reduced. Also, if we take the depth as a measure of mixing length, then the mixing length is increased. I think it has

been fairly well shown that the reaeration coefficient varies inversely as the square of the depth. In other words, for a small increase in depth, a tremendous reduction in reaeration capacity may result.

One other thing that has been encountered in several reservoirs in the Southeast is thermal stratification — not the classical type we talked about yesterday, but that which results from thermal discharges from power plants. The cooling water may essentially inhibit mixing in the downstream or impounding reservoir. This can cause a tremendous reduction in waste assimilative capacity.

A lot of factors in impoundments have not been considered that I think should be.

Mr. Whitehouse, Central Electricity Research Labs, England: Mr. Vanderhoof, considering the graphs in your paper, wouldn't you regard the change in oxygen sag more apparent than real on the following grounds: You said that when you put an impoundment on a stream you leach out or oxidize organic materials in the soils that are inundated and are, in effect, trapped in the impoundment.

I would suggest that this might be true in the upper reaches — or the water in the upper layers — of the impoundment, but if you take into account the carbon:nitrogen ratio of the bottom deposits a different conclusion might be reached. If the carbon:nitrogen ratio is greater than about 10, organic material accumulates on the bottom; therefore, only in the surface water will you have this change in the oxygen sag curve. This is a feature of normal stratification and will increase the depletion of oxygen in the lower waters of a reservoir.

Do you think a real change occurs in the oxygen conditions throughout the whole depth of the water, or are you deluding yourself by just looking at surface waters for these results?

Mr. Vanderhoof: I think what you have said is quite true. In many cases the improvement in DO is more apparent than real, but it is observed. In the case of untreated waste you would of course expect the deposition of settleable solids. I cannot disagree with any of your comments. I think you again emphasize why we are here today; we are facing a most complex problem.

Dr. Ingols, Georgia Institute of Technology: Having made some observations downstream from a power impoundment receiving a very heavy waste load, I would like simply to underline Dr. Kaplovsky's comments concerning the lower assimilative capacity of somewhat higher flows. The nighttime minimum flow below this reservoir frequently receives a greater pollution load than the peaking flows because of a very much higher reaeration capacity. If only one turbine is put on line the flow is about double the minimum, but the increased dilution below the dam is not adequate to compensate for the loss in reaeration so a very much more severe dissolved oxygen problem occurs. Sometimes the scour of the organisms from the bottom of the river at maximum flow creates a much more severe oxygen deficiency than occurs at lower flows.

*Mr. Coutant, **Lehigh University:*** Mr. Vanderhoof, you made a couple of rather dangerous generalizations in your presentation. One is that reservoir releases generally tend to be low in BOD as a result of storage. I wonder if you have any comment on the fact that hypolimnetic waters quite often have a high BOD aside from any additional wastes that are added to them?

Mr. Vanderhoof: Yes. I agree that I have made many assumptions here, but I have based these assumptions on the fact that high-BOD hypolimnetic waters can be avoided by use of multiple-level outlets. With proper selection of waters from the various levels of the impoundment, you can avoid the very high BOD of which you speak.

Mr. Coutant: Also, with regard to pH, what are your comments regarding an impounded bog valley in which seepage tends to be of very low pH as a result of organic acids? This would be quite different from a stream having high mineral acidity.

Mr. Vanderhoof: I hope I did not say that pH's were increased. I meant to say that if there was a pH problem, it would tend to be corrected as a result of mixing as the high flows tend to neutralize the low flows in the reservoir.

With respect to the pH of water from bogs, I have never had occasion to observe such a situation. Perhaps you could enlighten me.

Mr. Coutant: My very limited knowledge comes from the Pocono Mountain area in eastern Pennsylvania where rather small reservoirs have been built, mainly for recreational purposes, which have very often been put across extinct lake areas. A good peat bog deposit forms the bottom. When flows coming into the reservoir are low, the seepage water coming up through the peat deposits on the bottom and sides of the reservoir constitute a large percentage of the total flow. This is rich in humic acids, and despite the fact that the normal tributary waters are more on the alkaline side, it is a fairly common occurrence to find low pH values, especially if the water is drawn primarily from the hypolimnion.

Mr. Vanderhoof: Could not such a condition be corrected by multiple-level outlets?

Mr. Coutant: Yes, definitely.

Mr. Whitehouse: Not in all situations, I would suggest, because humic acids in impounded waters completely control the chemistry of the waters irrespective of the oxygenation rates. Though photosynthesis may provide considerable oxygen, this does not prevent deoxygenation below a depth of 3 or 4 feet of water. As the organic acids are being brought in all the time by seepage water, in the case of humic acid impoundments, multiple-level outlets do not solve the problem of drawing out water extremely low in pH.

MINERAL QUALITY CONTROL THROUGH STREAMFLOW REGULATION

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Water is found everywhere on the surface of the earth, but in no two places does it occur in the same quantity, quality, frequency, and duration. Man's effort, historically, has been to improve this resource to meet his needs or desires. Among those factors for which control has long been sought in areas of limited water resources is mineralization, either in the form of dissolved solids or suspended materials. The amounts of materials carried into the ocean are tremendous. In the United States alone, it is estimated that 270,000,000 tons of dissolved solids and 513,000,000 tons of suspended matter are delivered by our rivers to the tidal waters each year. The size of these figures makes one wonder:

1. What areas contribute these materials?
2. Are they associated with the high rainfall areas?
3. Can these stream loads be controlled to an acceptable degree?
4. Can control be accomplished by managing stream runoff?

Consideration is given to these questions (not necessarily in the order stated) in this paper.

WATER QUANTITY DISTRIBUTION

This country, logically, can be divided into three principal runoff areas according to topography and moisture conditions:

1. The area east of the 95th Meridian, which has an annual average runoff of 10 inches or more, may be classified as moist. Within this area, all the larger streams have continuous-flow and well-developed stream networks.
2. The Great Plains area running north and south through the central portion of the United States characteristically has a minimum number of streams with continuous flows because of low precipitation, low relief, and high evaporation-transpiration. There are periods of the year when runoff may be very high, such as during spring thaws in the northern portion or during severe rainstorms in the southern half of the region.
3. The western part of the country is comprised alternately of mountains and dry lowlands or plateaus. (The North Pacific Coast Region is an exception to this pattern.) The runoff in this area comes substantially from the mountains, which provide the water used on the flat lands.

For all the runoff regions, the flow is seasonal. In the arid and semi-arid parts of the country, 75 percent of the year's runoff usually occurs within a very few weeks. These widely varying runoff characteristics produce uneven streamflow patterns. In humid regions, between 50 and 70 percent of the total annual runoff occurs during a short interval following rainstorms or the melting of snow or ice. Short periods of fluctuation occur in all streams, but in many of the smaller ones peak flows are several hundred times the average flow over the year. Salvaging quantities above the average flow would, in many cases, increase the stream's ability to supply a potential demand. Generally, the larger and climatically more diverse the watershed of the stream, the less severe the fluctuation in flow is likely to be. The influence of extensive tree cover, as well as cultivation or other land uses in farming areas, is clearly perceptible in runoff.

Infiltration rates are notably greater for grass-covered lands than for crop lands. Close-growing crops, such as grasses, are associated with higher infiltration rates than row crops. Fluctuations in runoff are reduced where infiltration rates are increased. Thus, not only is runoff distributed unevenly geographically, but also seasonally and daily.

MINERALIZATION

Attempts to reduce variations in quantities of water traveling the stream, unfortunately, produce other undesirable effects. Water, because of its superior capacity as a solvent, tends to increase in mineralization with longer contact times. Other factors also influence the suspended and dissolved solids loads carried by the streams.

In general, the mineral sediment content of surface water in the United States is greatest in the arid or semi-arid sections. The sediment content also tends to be relatively large where water flows over loosely consolidated sedimentary rocks, as in the Missouri Basin, or over unconsolidated marine sediments, as on the Atlantic and Gulf Coastal Plains. It is significant to note that mineral sediment in stream flow or natural and artificial storage may come from as far as 100 or more miles away.

Plate 3 in the U. S. Geological Survey Atlas HA-61 shows mean annual weighted sediment discharge concentrations of river systems in the United States. This value represents the amount of suspended solids passing a given point in a definite time divided by the volume of water discharged during the period. Differentiation should be made here between suspended sediment and total sediment discharge. Suspended sediment is made up of those particles that can be lifted by the water from a place of residence and transported as a suspension to a new site. Total sediment includes suspended particles plus the material sliding along the stream bed.

Sediment concentrations shown on the plate represent the major flowing portion of the stream. Streams of the vast majority of the land east of the 95th Meridian and of the Northwest United States have the lowest annual sediment concentration. The largest suspended

sediment concentrations occur in the band between the 95th and 107th Meridians and in the southwestern portion of the United States. The concentration of suspended solids in streams draining 50 percent of this land area averages less than 600 milligrams per liter. Water flowing from 10 percent of this land area has over 8000 milligrams per liter.

Plate 1 in the U. S. Geological Survey Atlas HA-61 shows the general modal concentration of dissolved solids in streams of the United States. Values shown represent larger streams, usually at the lower-flow conditions. Smaller tributaries vary widely in water quality and quantity, making it difficult to present a value that can be considered representative of the waters. A comparison of this plate and the one showing sediment load discloses many similarities. This is to be expected, since water assumes characteristics of the materials it contacts.

With some exceptions, water in the United States east of the 100th Meridian, particularly from the Mississippi River eastward, has a low dissolved solids content. The exceptions are the saline underground waters, such as those underlying Kentucky and Michigan, and certain industrially caused saline conditions such as on the Holston River downstream from Saltville, Virginia. On the other hand, high dissolved mineral content tends to characterize streams west of the 100th Meridian, particularly after they leave their mountain sources. Exceptions to this pattern occur in the mountain sections themselves, on the Pacific Coast north of the San Francisco Bay area, and west of the Cascades and Sierra Nevada Mountains. As distance from the oceans increases, mineralization becomes heavier. The water, in general has its highest concentration of dissolved matter in the areas of lesser rainfall. Fifty percent of the country's waters contain less than 250 milligrams per liter total dissolved solids; 90 percent contains less than 900 milligrams per liter.

CHEMICAL QUALITY

The mineral content of the waters of this country varies greatly. The principal differences center on the amounts of sodium, chlorine, calcium, carbon, magnesium, and sulphur contained. Other constituents that show minor but important differences are iron, manganese, potassium, boron, silica, arsenic, zinc, selenium, lithium, and fluorine. Surface and shallow ground waters in the arid and semi-arid sections of the United States, in general, contain more sodium, chlorine, magnesium, and sulphur than waters in the more humid sections of the country. Waters of high bicarbonate and carbonate content are found in both the humid and arid sections of the country. High calcium concentrations are found in ground and surface waters over a large section of the midwest and over the interior southeast, as well as in the arid and semi-arid west. The occurrence of iron in water at harmful concentrations is geographically sporadic, but has occurred in all sections of the country. The same may be said for each of the remaining secondary elements, such as boron, zinc, or fluorine. Plate

2 in the U. S. Geological Survey Atlas HA-61 identifies surface waters according to the more commonly identified gross water contaminants. The various divisions indicate regions where the waters are of the calcium-magnesium, carbonate-bicarbonate type; calcium-magnesium, sulfate-chloride type; sodium-potassium, carbonate-bicarbonate type; or sodium-potassium, sulfate-chloride type. Eighty-seven percent of the waters of the country are of the calcium-magnesium type.

WATER QUALITY CRITERIA FOR MINERAL CONSTITUENTS

Even when mineralization alone is considered, the criteria for judging a raw water supply for its many uses, regardless of the means of attaining it, are varied and complex. Sources of supply found satisfactory for one purpose are not necessarily (in fact, usually are not) adequate for other uses.

Domestic water supplies certainly are most important to us individually and collectively. The criteria generally used for judging drinking water in the United States are the U. S. Public Health Service Drinking Water Standards, last revised in 1962. Technically, these standards apply only to water supply systems providing drinking water used by interstate carriers and others subject to the Federal Quarantine Regulations. The characteristics identified in Table 1 do not directly measure the safety of the water, but they are related to its acceptability to the consumer. At 5 units of turbidity, the water becomes unacceptable to a number of people. Chlorides, sulfates, and dissolved solids are important because of their taste and laxative properties. Iron is objectionable to the consumer because of the taste it imparts to drinking water and the brownish color it imparts to laundered goods. Excessive amounts of these constituents can result in rejection of the supply by the consumer or in his providing individual treatment. Desirable mineral quality ranges for several industrial uses are also shown.

SATISFYING QUALITY REQUIREMENTS

Because of the sensitivity of a number of uses and the infrequent natural occurrence of a completely satisfactory supply of water, techniques for adjusting the quality-quantity demand requirements are extremely important. In the past, three common ways have been used to reduce the quality problem: (1) treatment of the supply; (2) development of uses tolerant to high dissolved solids content; and (3) restriction of activities causing quality deterioration. All of these methods are important because, in one way or another, they affect availability and regulation of aqueous flows. In this paper, however, control of quality by managing available water will be given primary consideration.

The use of impoundments to dilute and secure a water of uniform quality has been suggested as a means of making available the optimum surface water resources of a drainage area. Although this method may be useful insofar as quantity is concerned, there is seri-

TABLE 1. DESIRABLE CONCENTRATION RANGES FOR COMMON CONSTITUENTS FOR VARIOUS WATER USES

Use	Turbidity, units[a]	Hardness, mg/l	Alkalinity, mg/l	Total dissolved solids, mg/l	Chlorides, mg/l	Sulfates, mg/l	Iron, mg/l
Domestic water supply	5 or less	250 or less	Hardness plus 35 mg/l or less	500 or less	250 or less	250 or less	0.3 or less
General food processing	1 - 10	10 - 250	30 - 250	850 or less			0.2 or less
Pulp and paper production	0 - 50	0 - 400	0 - 200	0 - 400	0 - 100	0 - 300	0 - 1.5
Textile manufacture	0.3 - 25	0 - 50			100 or less	100 or less	0.1 - 1.0
Irrigation water (for most plants under most conditions)				700 or less	175 or less	950 or less	
Cooling water	50 or less	50 or less					0.5 or less

[a] Silica scale.

ous doubt that dilution is economically justified if mineralized waters containing high concentration of chlorides and sulfates contribute significant loads and volumes over most of the year. An example of the mixing technique can be shown from information available on one of the larger manmade lakes in the southwest.

Lake Texoma was authorized by Congress in 1938 and constructed by the Corps of Engineers for flood control, hydroelectric power, municipal and industrial water supply, and other allied purposes. The surface area is 91,200 acres at the top of the power pool and 144,100 acres at full flood control pool. Water depth at the dam can reach a maximum of 135 feet. The major objectionable contaminant in the lake waters is chloride. Two large rivers, the Washita River entering from the north and the Red River entering from the west, are the principal streams contributing to the reservoir.

The Washita River is over 600 miles long and drains nearly 8,000 square miles (primarily agricultural and ranch lands) of Central

and Northwest Oklahoma. Some relatively small petroleum operations are located in the lower reaches of the stream. Flow and quality information has been taken near the mouth of this stream for a number of years. Seven years of data on chlorides is summarized in Table 2. It is clearly evident that the concentration of chlorides may be regarded as low — at least for the southwestern section of the country.

TABLE 2. CHLORIDE AND FLOW DATA — LAKE TEXOMA

Water year	Washita River above Lake Texoma[a]			Red River above Lake Texoma[b]			Red River below Lake Texoma[c]		
	Flow,[d] cfs	Chloride,[e] mg/l	Chloride,[e] ton/day	Flow,[d] cfs	Chloride,[e] mg/l	Chloride,[e] ton/day	Flow,[d] cfs	Chloride,[e] mg/l	Chloride,[e] ton/day
1953	522	41	58	651	698	1230	1850	304	1520
1954	1260	36	122	3090	394	3290	4370	299	3540
1955	878	33	79	2630	462	3280	2760	309	2310
1956	445	62	75	2180	532	3140	3550	343	3290
1957	3490	26	245	7790	280	5890	11,100	258	7700
1961[f]	1135	46	142	3044	644	5296	4299	399	4630
1962[f]	1835	49	180	2605	464	3258	4340	403	4726

[a]At Durwood, Oklahoma; the Washita River is 626 miles long and drains 7945 square miles.

[b]At Gainesville, Texas; the Red River above Denison Dam is 495 miles long and drains 30,782 square miles (probably 5936 square miles is noncontributing).

[c]At Denison Dam.

[d]Yearly average.

[e]Weighted average.

[f]Values from U. S. Public Health Service Network.

The Red River enters Lake Texoma from the west. It is a sluggish stream draining almost 31,000 square miles of northern Texas and southern Oklahoma. The river and its several tributaries collect runoff from a number of large oil-producing areas and 10 large natural salt sources. Many of the tributaries in the upper Basin, including the Red River itself, flow intermittently, allowing considerable storage in the alluvial plains. As a result, the water entering the lake from this stream is high in chlorides. None of the 7 years of record, 1953 through 1957, 1961, and 1962, lists a monthly average chloride concentration below the Public Health Service's recommended Drinking Water Standard of 250 milligrams per liter.

Within the lake, mixing occurs between the two major streams, other small tributaries, and runoff from the immediate area. Yearly

weighted average concentrations tended to increase within the lake for the period cited. In fact, with the exception of 1 year (1957), the yearly averages substantially exceeded the levels recommended by the Public Health Service for drinking water supplies. A review of the monthly average concentrations reveals variation from 1 to 50 percent. If inflow remained fairly constant, concentration in the outflow tended to remain near the same level. Floods occurring in either the Washita or the Red River Watershed diluted the chloride concentrations in the lake.

Some investigators, having noted the changes in mineral constituents flowing into and out of large bodies of water, have expressed the opinion that reservoirs in some manner act as storage sites for the unaccountable amounts of minerals. Stratification of waters in the relatively shallow lakes of this region has been found, but not deposition of the more soluble minerals on the lake bed. Studies conducted by the Public Health Service during the Arkansas-Red River Basins Water Quality Conservation Project revealed that dissolved chlorides will eventually leave the lake. Attempts to find water of usable quality at constant lake depths have not been successful. Apparently, water entering the lake represents a highly unstable system, which varies with time, stream volume, temperature, concentration, and other chemical and physical factors. The combining of the water from the two streams in Lake Texoma results in degradation of a good quality water.

The period 1953 through 1957, selected for illustration of the quality data for Lake Texoma, represents a period of severe drought in this portion of the United States. The need for maintaining desirable water quality in the lakes and rivers was most urgent. Unfortunately, waters being released were already so highly mineralized that their use for improving the quality of other waters was limited. It is interesting to note that the city of Dallas, which was suffering from an extreme shortage of water at the time, obtained water from the Red River above Lake Texoma during 1957. In a period of 3 months, 45,000 tons of salt flowed into Dallas homes from the Red River, causing extensive damage to property and plants. The city of Dallas since that time has made provisions for an adequate supply of water.

An interesting quality control operation has been conducted for a number of years on a tributary to the Red River above Lake Texoma. It consists of a two-lake system constructed on the Wichita River to supply water to irrigable lands in the vicinity of Wichita Falls, Texas. The uppermost lake, identified as Lake Kemp, impounds 560,000 acre-feet of water when full. This lake catches the drainage of three branches of the main stream and, more importantly, the chloride contamination of three large natural salt-emission areas. An average of 650 tons of chloride per day was found to be entering the lake during 2 years of continuous study by the Public Health Service. This structure at the present time is used for flood control, storage of brine-contaminated water, and as a make-up source for approxi-

mately 10,000 acre-feet per year needed to satisfy irrigation water demand.

Lake Diversion, the lower lake, is a smaller impoundment, holding approximately 40,000 acre-feet of water. It is from this lake that irrigation waters for the area are obtained. Insofar as possible, water stored and used from this supply comes from the watershed below Lake Kemp and is good water. Unfortunately, water demands, which average about 30,000 acre-feet per year, exceed by about 10,000 acre-feet the quantity that Lake Diversion can supply. Drawing the water from Lake Kemp to make up this deficiency results in a decrease in the quality of the irrigation water.

Quality characteristics from such a supply vary greatly, as would be expected. During years of heavy rainfall, total dissolved solids decrease. As rainfall lessens, chlorides and solids increase until the water becomes unfit for use. Generally, water is considered unfit for use when the total dissolved solids climb to about 2500 milligrams per liter or when the chloride concentration becomes approximately one-half of this value. Even now, after 2 years of above-average rainfall, the water for irrigation supply contains 1800 to 2000 milligrams per liter of dissolved solids and 900 or more milligrams per liter of chlorides. Only when Lake Kemp has a better quality water than Lake Diversion is the latter lowered and filled with Lake Kemp water prior to the irrigation season. Most of the time, however, Lake Kemp holds the spring runoff without overflowing and thereby allows Lake Diversion to fill with better quality water from the drainage area below Lake Kemp. Nevertheless, this practice is not entirely satisfactory and some land is often out of production because of low tolerance to minerals.

The Public Health Service, Region IX, recently prepared a report on the proposed Kellogg Reservoir in California. One purpose of the reservoir would be improvement of water quality in the Contra Costa Canal. At present, the canal receives its water from Rock Slough, an off-channel slough of Old River, which over the years has deteriorated in quality. During certain times of the year, however, the water in Old River contains less than 100 milligrams per liter chlorides and 400 milligrams per liter total solids. As planned, water would be pumped from the Delta-Mendota Canal, which receives water from the river, to the Herdlyn Reservoir and from there to the Kellogg Reservoir. Water will be taken from the Delta-Mendota Canal only during periods when water quality is good. The proposed Kellogg Reservoir, with a maximum capacity of 135,000 acre-feet, would provide good water to the Contra Costa Canal during other periods of need. It is recognized that this comes more under the category of selective withdrawal than under flow regulation, but it does provide for the availability of better quality water.

A somewhat similar method of quality control was practiced by a city in the north-central part of the country. This, too, was selective withdrawal, as the city diverted river water during the spring runoff to a large abandoned gravel pit. By this method, the underground

gravel basin from which the city obtained its water was annually recharged with excellent water. Since the construction of a large reservoir above the city, both the quality and quantity of the flow have been stabilized.

The water is still of good quality, but the city no longer has the spring snow melt available as its source of supply. A major reservoir on the main stem of a river did not, in this case, improve the quality of the water available to a municipality; it merely averaged it out. For the past few years the Public Health Service, with assistance from Corps of Engineers, State Health Department, U. S. Geological Survey, and others, has been conducting a study (Arkansas-Red River Basins Water Quality Conservation Project) of the mineral concentrations and loads in the Arkansas-Red River Basins. Specific attention has been focused on chlorides, sulfates, and total dissolved solids. In these basins, most chlorides appear to originate from 15 large natural-occurring salt (NaCl) sources and from brines from numerous past and present oil-producing operations (See Figure 1).

The distribution of chloride load in the Arkansas River is presented in Figure 2 in average tons per day for the 2-year period of the study. Contributions from the natural salt sources varied from 205 to 2850 tons of chlorides per day. Brine loads from oil-producing operations were highly variable, depending on size of field, years of operation, past and present water disposal practices, and other factors.

It is obvious from the many measurements that desirable water quality can be obtained only if a considerable number of sources are regulated or controlled to prevent the release of chlorides into the receiving stream.

To obtain an idea of the control measures necessary to maintain quality in the Arkansas River at the Keystone dam site near Tulsa, Oklahoma, data obtained during the last 2 years of intensive study were used to estimate the effect of controlling natural and manmade chloride sources with flow conditions as they existed during the drought period of 1951 through 1957. It was assumed that uniform chloride concentrations existed at the site and that the majority of the loads not originating from the natural salt sources were manmade. Table 3 indicates that if a high degree of control of both natural and manmade loads can be maintained this undesirable contaminant can be reduced to a concentration well below that recommended in the Public Health Service Drinking Water Standards and, at times, to acceptable levels for other critical uses.

The feasibility of control is presently being studied by the Corps of Engineers, Tulsa District Office. Basically, the measures considered consist of one, or some combination of the following:

1. Diversion of fresh water around salt source areas.
2. Construction of lined channels through salt source areas.
3. Isolation of salt sources by levees, dikes, and dams.

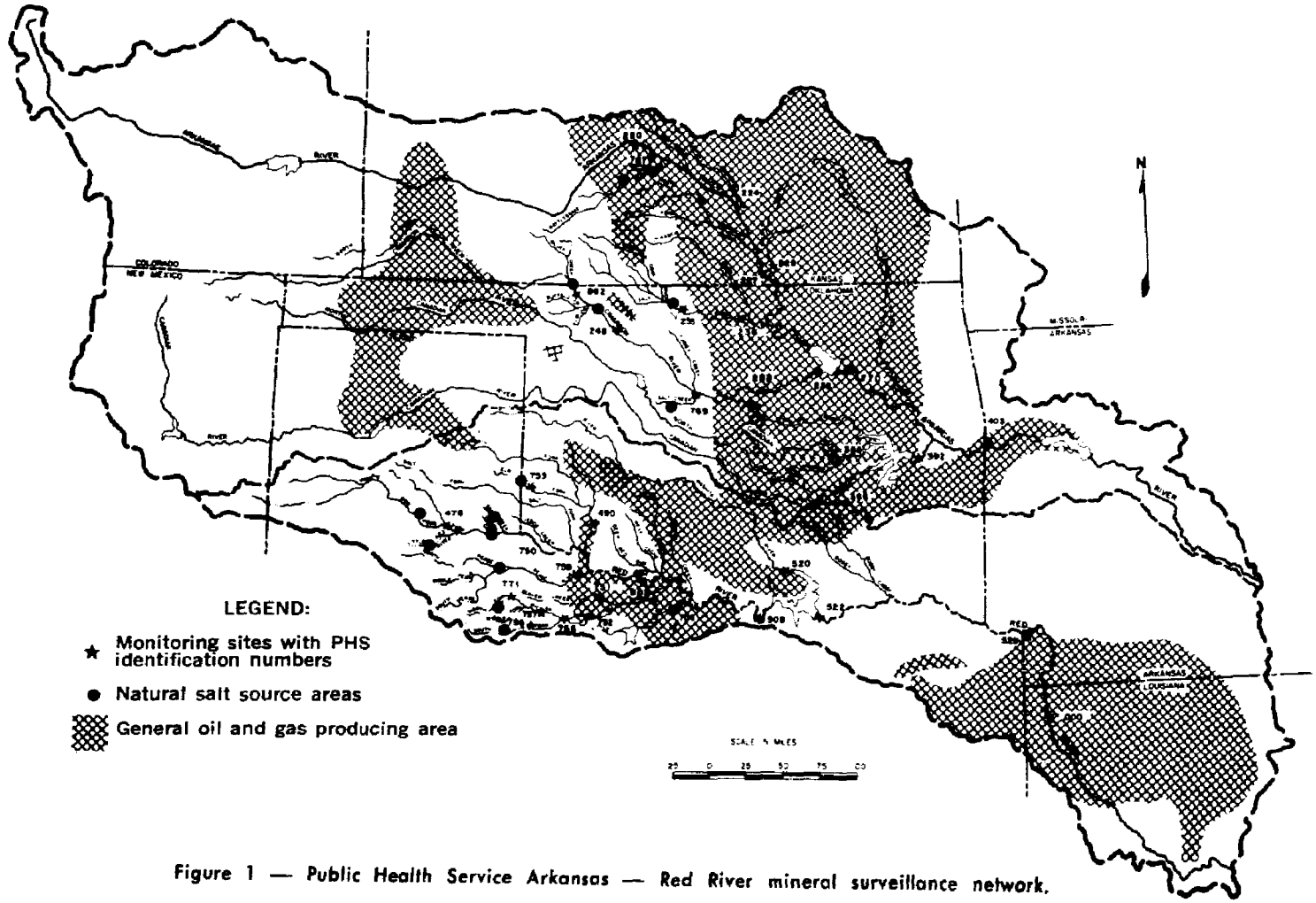

Figure 1 — Public Health Service Arkansas — Red River mineral surveillance network.

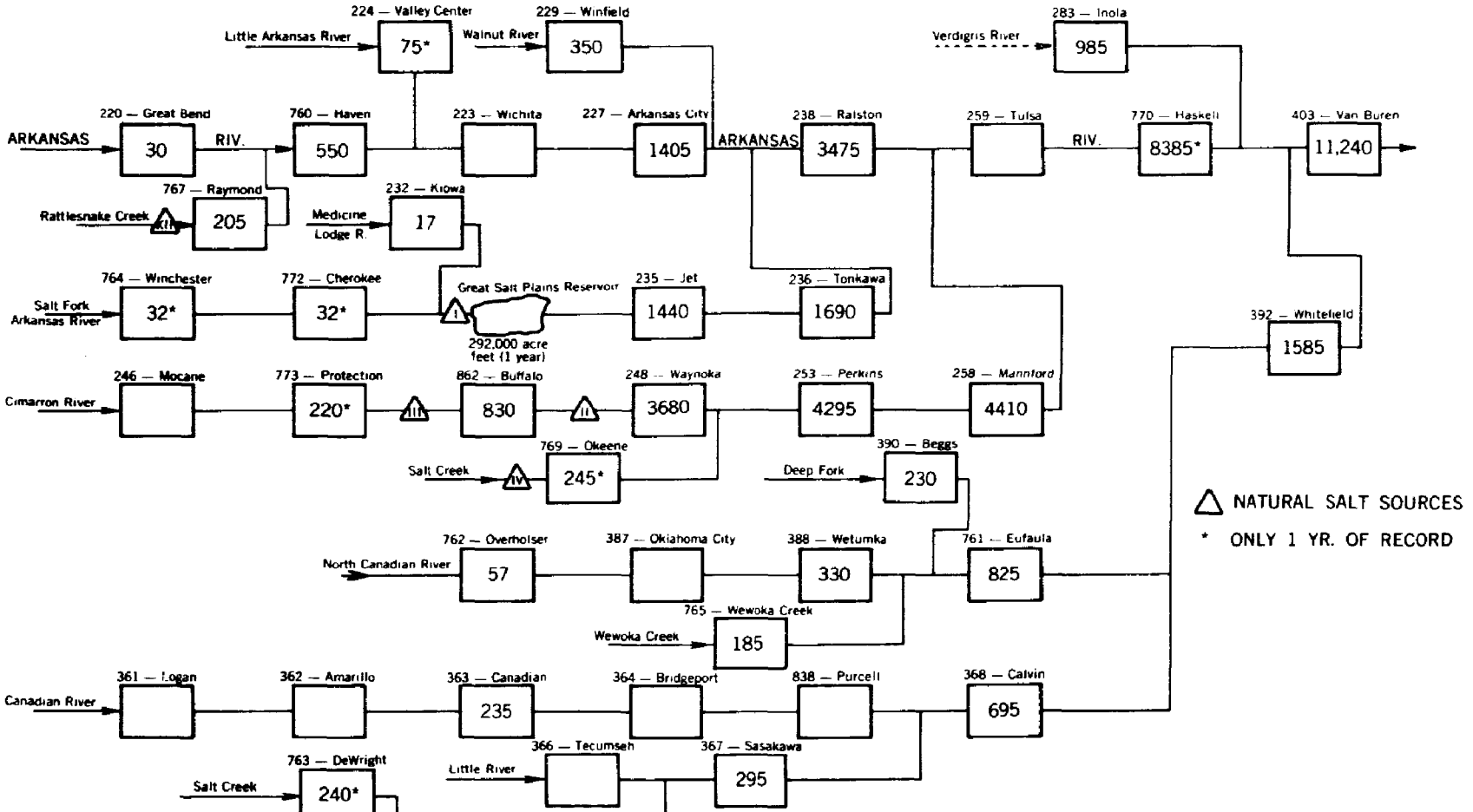

Figure 2 — Typical material balance worksheet for the Arkansas River showing distribution of chloride load (in tons per day) — July 1960 to September 1962.

4. Construction of lined channels through recharge areas.
5. Construction of dams and levees to impose a hydrostatic head on salt sources.
6. Interception of brines and pumpage to subsurface strata.
7. Interception of brines and pumpage to off-channel storage.
8. Interception of brines and pumpage through a pipeline to the Gulf of Mexico.
9. Provision of brine storage reservoirs on the channel and diversion of fresh water around these reservoirs.

TABLE 3. EXPECTED CONCENTRATION OF CHLORIDES IN ARKANSAS RIVER AT KEYSTONE DAM SITE NEAR TULSA, OKLAHOMA, UNDER VARIOUS CONTROL CONDITIONS,[a] mg/l

Excedence frequency,[b] %	Condition 1	2	3	4	5	6
1.0	1900	276	220	220	100	50
10		215	165	140	65	35
20		189	135	120	50	25
30		166	115	100	45	
40		147	100	90	40	20
50	450	119	90	80	35	
60		112	80	70	30	15
70		98	75	60	25	
80		72	65	55	20	10
90	250	56	50	45	15	

[a] Condition 1: No control of natural or manmade sources.

Condition 2: 100% control of natural sources; no control of manmade sources.

Condition 3: 90% control of Areas, I, II, and III; 85% control of manmade sources.

Condition 4: 90% control of Areas I, II, and III; 75% control of Area IV; 85% control of manmade sources.

Condition 5: 100% control of Areas I, II, III, IV, and XII; 85% control of manmade sources.

Condition 6: 100% control of natural and manmade sources.

[b] Excedence frequency is expressed as percent of time the monthly average chloride concentration will equal or exceed quoted value under the specified control system.

The usefulness of a stream is affected by the volume and quality of its minimum flow. Any changes that increase flow at low stream stages without increasing total dissolved solids excessively improve the potential value of that streamflow and may reduce the need for impoundment. The optimum combination of land use and water yield practices should be the deciding element. Water-conserving farming practices are directed not only toward the infiltration of water that otherwise immediately would runoff, but also toward the reduction of on site evaporation and unproductive transpiration. Such practices include mulching, weed control, and shelter-belt planting. To the extent that the additional soil moisture thus is directed toward productive use, a net water gain and flow regulation are both achieved.

There are times, of course, when situations demand a supply of water without regard to its mineralization. Such requirements have been receiving increased attention during the last few years and are of interest here because they center around having a constant water supply available for use. Once available, a number of methods have been used to make the quality of the water acceptable to the customers. The basic methods or processes that are in use can be classed as distillation, osmosis, solvent extraction, freezing, adsorption, electrodialysis, thermal diffusion, and ion exchange. With each of these methods there are two major difficulties: (1) producing an acceptable quality and quantity of water at a cost comparable to that for water from alternative sources, and (2) disposing of mineral residues.

In this limited consideration of controlling mineralization of streams, some attention needs to be paid to abilities of streams over various portions of this country to maintain regulated flows as compared to the estimated uses of these streams now and in the future. Since it is impractical to consider streams individually here, the 22 regions defined in the Senate Select Committee on National Water Resources Print No. 32, will be used as a basis for indicating a real variability of the supply and demand for water from a physical point of view.

Table 4 summarizes the estimated water needs for consumptive plus waste dilution uses for the years 1954, 1980, and 2000. Three broad categories of use were considered in arriving at the values under each of the yearly headings. They were (1) demands necessitating withdrawal such as agriculture, mining, manufacturing, and municipal use, (2) in-stream flows required by hydroelectric power, sport fish habitats, and waste dilution, and (3) consumptive losses. Of all the demands considered, that for waste dilution was greatest in most cases. These demands were based on organics, however, not minerals.

Supplies of water, as listed in the last column, appear adequate to meet the needs, except in those areas pertinent to this discussion. A review of the regions with the previously defined highly mineralized waters shows the coincidence of high total dissolved solids with shortage of supply.

TABLE 4. WATER DEMAND VERSUS MAXIMUM SUSTAINED LOW FLOW FOR YEARS 1954, 1980, AND 2000

	Region	Water demand,[a] bgd			Maximum sustained low flow, bgd
		1954	1980	2000	
1	New England	48.9	14.2	19.4	64.7
2	Delaware and Hudson	25.1	13.8	19.8	31.1
3	Chesapeake Bay	32.1	24.0	26.9	50.8
4	Southeast	27.4	75.4	99.4	207.4
5	Eastern Great Lakes	49.8	15.8	28.9	38.6
6	Western Great Lakes	129.1	36.2	59.1	40.0
7	Ohio	10.2	19.4	34.3	108.5
8	Cumberland	3.1	7.7	12.7	15.5
9	Tennessee	12.6	24.4	29.7	42.6
10	Upper Mississippi	58.9	30.4	32.8	58.9
11	Lower Mississippi	6.5	22.2	36.1	47.5
12	Upper Missouri	33.0	33.6	51.1	26.9
13	Lower Missouri	1.9	3.6	7.1	14.5
14	Upper Arkansas-Red-White	17.7	7.9	11.7	10.5
15	Lower Arkansas-Red-White	16.1	16.9	27.3	70.3
16	Western Gulf	33.5	40.9	43.5	40.4
17	Upper Rio Grande Pecos	10.9	7.3	10.3	1.0
18	Colorado	21.7	19.3	21.6	10.4
19	Great Basin	15.4	12.1	13.5	9.3
20	Pacific Northwest	17.5	42.8	44.3	136.3
21	Central Pacific	33.9	44.5	54.5	55.3
22	South Pacific	23.8	10.3	15.7	0.3

[a] Consumptive losses plus waste dilution flows.

The importance of quality improvement or quality adjustment techniques in American water development is accentuated by the size of most American drainage basins. Although water quality problems have always been met locally, any upstream deterioration of water quality is of concern everywhere within a basin. In the extreme situations found throughout much of the West, cumulative quality deterioration may eventually cause even the better waters to become unusable if their quality is not protected. Quality improvement by methods associated with streamflow regulation cannot be ascertained without regard for the ultimate use, but it certainly does not appear to be more than a stop-gap measure at best in securing

mineral reduction. Because of the nature of our available water supply and its use and re-use, control of mineralization of the streams as close to the source as possible would seem to offer the best single solution.

Large quantities of controllable high-quality water in the upper reaches of our rivers can improve conditions throughout the entire length of a stream. Reservoirs below sources of mineral pollution can level off the quality but mineral concentration may still be too high to permit normal use of the waters.

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DISCUSSION

John D. Hem

U. S. Geological Survey, Menlo Park, California

The geochemical role of rivers involves transporting the soluble products of rock weathering to the ocean. The quality of the water of a stream is dependent in general on two characteristics of its drainage

basin — the available supply of soluble material and the amount of water available for dilution. Generally, the second is more subject to variation than the first. Hence, at low flow the concentration of solutes in the water may become objectionable.

The factors governing sediment loads are different, in that the concentration that may be carried is a function of the kinetic energy of the stream and is at a maximum at high stages of flow. By decreasing the stream movement nearly to zero, a reservoir impoundment is very effective in sediment deposition, although at a cost in storage capacity that may be uneconomic.

Because the dilution effect of released impounded water is the average of the flow entering the reservoir, it cannot be as effective as runoff from rainfall. As Mr. Svore has pointed out, in unfavorable circumstances the impounded water may be too poor in quality to be of any benefit to downstream water users.

Nevertheless, improvement in water quality by storage is readily observable in many areas. The disappearance of suspended sediment load has made most of the muddy Missouri River I remember from younger days into a relatively clear stream. An important instance of quality benefits is to be found in the Colorado River, as a result of the construction and operation of Hoover Dam. The Geological Survey has obtained water quality data on this stream for many years, and effects can be evaluated closely from these data.

Lake Mead, with a storage capacity of some 28 million acre-feet, can store about 2 years of normal river flow. The reservoir has normally been more than half full. The composition of the water entering the reservoir varies continuously. Analyses by the Geological Survey of samples taken daily at Grand Canyon, Ariz., during a period of 30 years show that the median dissolved solids concentration, the level exceeded 50 percent of the time, was 960 milligrams per liter, and that the dissolved solids concentration exceeded 1,000 milligrams per liter more than 40 percent of the time. The median hardness of the water during this period was 460 milligrams per liter. These are the values characteristic of normal flow. During flood periods, especially during the spring snow-melt season, dissolved solids values are lower, but very seldom has a concentration less than 250 milligrams per liter been observed. Values between 250 and 500 milligrams per liter occurred about 20 percent of the time. At these times, the water contained mostly calcium and bicarbonate ions.

The large amount of stored water in Lake Mead tends to iron out the fluctuations in composition of the inflow, even though mixing is incomplete. Considered on a time basis, the improvement in quality that results is striking. Water released from the reservoir since 1937, when the amount of stored water reached a moderate level, has never exceeded 1,000 milligrams per liter in dissolved solids, and has been between 750 milligrams per liter and 500 milligrams per liter about 80 percent of the time. The range of fluctuation of hardness also has decreased, and the water has a hardness between 300 and 400 milli-

grams per liter 87 percent of the time. The improvement in water quality available to the southern California area and to others who use this water for a public supply is highly significant.

It should be noted that reservoir storage has some quality effects besides averaging out fluctuations. In Lake Mead some solutes are added by solution of exposed gypsum and rock salt, and concentrations of some ions are increased as a result of evaporation of water. These effects are partly offset by precipitation of calcium carbonate and silica in the reservoir. The net effect of these influences in Lake Mead has been to give a small increase in dissolved solids in the water as a result of storage. Effects to be expected in other reservoirs will depend on local conditions.

DISCUSSION FROM THE FLOOR

Mr. Swiggart, U. S. Army Engineers: I would first like to make a statement, as a citizen of Dallas, on the Dallas water supply. Yesterday, Murray Stein mentioned the bad Dallas situation. Jerry just briefly mentioned what happened there during the droughts of the fifties. At the time of the droughts, Dallas had only about 100,000 acre-feet of water supply storage. We were in the process, through cooperation with the Corps of Engineers, of increasing that storage to 500,000 acre-feet. The war, of course, delayed some of these plans. Unfortunately, the drought came along before the storage was completed and we therefore had a bad problem. But the city of Dallas now has over a million acre-feet of water supply storage and we are in the process of adding about 400,000 acre-feet more. So, we now have a good water supply in Dallas.

Mr. Svore, in your example regarding the mixing of water in Lake Texoma, where we do not have good water primarily because about 70 percent of the inflow is of poor quality and only 30 percent can be considered good, isn't it true that the flow past the dam site now is of considerably better quality than it was prior to the impoundment?

Mr. Svore: Yes, Forrest, that is certainly true. As far as Lake Texoma is concerned, the resultant quality of water at the dam unquestionably is much better than it was in the past.

I might add, too, that because of the quality problem Dallas experienced 6 or 7 years ago, they are doing their planning a long way into the future. If the Corps of Engineers plan is authorized, the next hundred years are pretty well taken care of.

Dr. Gloyna, University of Texas: Mr. Hem, you showed that the reservoir reduces the large fluctuations in the dissolved solids content of the stream, but don't you agree that evaporation results in solids build-up, so that the average base level of the dissolved solids will very likely continue to rise in the reservoir over a long period of time?

Mr. Hem: Yes, there is no doubt that the effect of evaporation, along with the effect of solution of soluble rock from within Lake Mead, has had this effect. The Geological Survey report on the operation of Lake Mead, Professional Paper 295, pointed out that the net effect of the reservoir has been to give a somewhat higher dissolved solids load below the dam than above it.

Dr. Gloyna: This is important for the smaller reservoirs, particularly where water is recycled or reused within a reservoir system. I think this is a very important point concerning the dissolved solids, which should be stressed at this time.

Mr. Hem: Yes, I agree.

Mr. Churchill, Tennessee Valley Authority: I want to comment on that point because I think we need to understand something that apparently has not been brought out. This is the matter of the time-weighted average concentration of total dissolved solids compared to the flow-weighted average concentration. Although the mean concentration in terms of volume will be higher, the time-averaged concentrations will be lower. There is a big difference, and it is important to understand it.

CONTROL OF TEMPERATURE THROUGH STREAMFLOW REGULATION

Milo A. Churchill
Chief, Stream Sanitation Staff, Division of Health and Safety
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SYNOPSIS

If water is released through low-level outlets in the dam, significant effects on downstream water temperature result during the warmer months. If water is released through high-level outlets, the reservoir may have little effect on water temperatures. This paper presents data observed in, and downstream from, certain impoundments operated by the Tennessee Valley Authority. The data have been collected over a period of approximately 26 years. The paper not only includes information to illustrate the magnitude of thermal effects produced, but also data designed to explain why and how these effects are produced.

RESERVOIR OPERATION

In the TVA system, reservoirs are operated primarily for purposes of flood control, navigation, and the production of electricity. Two basic types of reservoirs are in use. Large, deep storage reservoirs are located on the principal tributaries of the Tennessee River. In these pools, water levels usually vary over a wide vertical range during the course of a year, with a vertical range of 100 feet or more being not uncommon. On the main Tennessee River, navigable depths must be maintained at all times throughout the full length of each of the nine contiguous pools. This means drawdown must be limited, and as a result the vertical range of pool-level fluctuations is relatively narrow. Other reservoirs also operated within a narrow range of pool levels are those relatively small pools located on principal tributaries below storage impoundments. These pools are operated primarily for power production.

Storage reservoirs are operated on an annual cycle. They are drawn down during late summer, fall, and early winter to reach a predetermined minimum flood-control level by January 1. The pools are allowed to fill slowly after that date. As the probability of heavy, widespread, flood-producing rains diminishes with advancing spring, these reservoirs are permitted to fill gradually to their maximum levels by early summer.

Since storage reservoirs are operated primarily to control floods, these projects reduce the magnitude of high streamflows and raise the general level of low flows. Although the general level of low flows is raised, the usual practice is to reduce or eliminate releases over weekends, and during other periods of off-peak power loads.

To fulfill its basic function, a flood-control reservoir must be drawn down to and held at a relatively low level during the season

when floods can be expected. So that power can be generated with water released during low-pool periods, low-level power intakes are provided in the dams. As explained later, these low-level intakes are the key to the effects exerted by a storage impoundment on water temperature.

A map of the eastern half of the Tennessee Valley is shown as Figure 1. Reservoir volumes, areas, depths, etc., for the projects discussed in this paper are listed in Table 1.

TABLE 1. PERTINENT DATA ON SELECTED IMPOUNDMENTS

			Full pool			
Reservoir	River	Date of closure	Volume, acre-ft	Area, acres	Length, miles	Depth at dam, ft. (approx.)
So. Holston	So. Fk. Holston	11-20-50	744,000	8,750	24	250
Watauga	Watauga	12-1-48	678,800	7,200	17	330
Boone	So. Fk. Holston	12-16-52	196,700	4,520	17	120
Ft. Patrick Henry	So. Fk. Holston	10-27-53	27,100	893	10	80
Cherokee	Holston	12-5-41	1,565,400	31,100	59	150
Douglas	French Broad	2-19-43	1,514,100	31,600	43	150
Norris	Clinch	3-4-36	2,567,000	40,200	77	210
Parksville	Ocoee	12-15-11	91,300	1,900	7	120
Ft. Loudoun	Tennessee	8-2-43	386,500	15,500	55	95
Watts Bar	Tennessee	1-1-42	1,132,000	43,100	72.4	80

EFFECTS OF STORAGE RESERVOIRS ON WATER TEMPERATURES DOWNSTREAM

Effects in open river channels downstream

A striking illustration of the effect impoundments can exert on water temperatures downstream is shown in Figure 2. Water temperatures in the Clinch River at Clinton, Tennessee, are shown for 1935 and 1941. Norris Dam was built on the Clinch River approximately 20 river miles above Clinton, and was closed in 1936. Uncontrolled, or natural, water temperatures and streamflows are shown for 1935. The lower section of Figure 2 shows that significant releases from Norris reservoir during 1941 were not made until late in May and were continued through June and into early July. During most of July and August, Norris releases were relatively insignificant again. The water temperature at Clinton dropped approximately 30°F when Norris releases began in May, and rose approximately an equal amount when releases were cut off in early July. In late August, temperatures again dropped approximately 30°F when releases began anew. By the time the releases starting in late August were finally cut back in late November, the temperature of local inflows had been lowered seasonally to approximately 10°F below that of the released

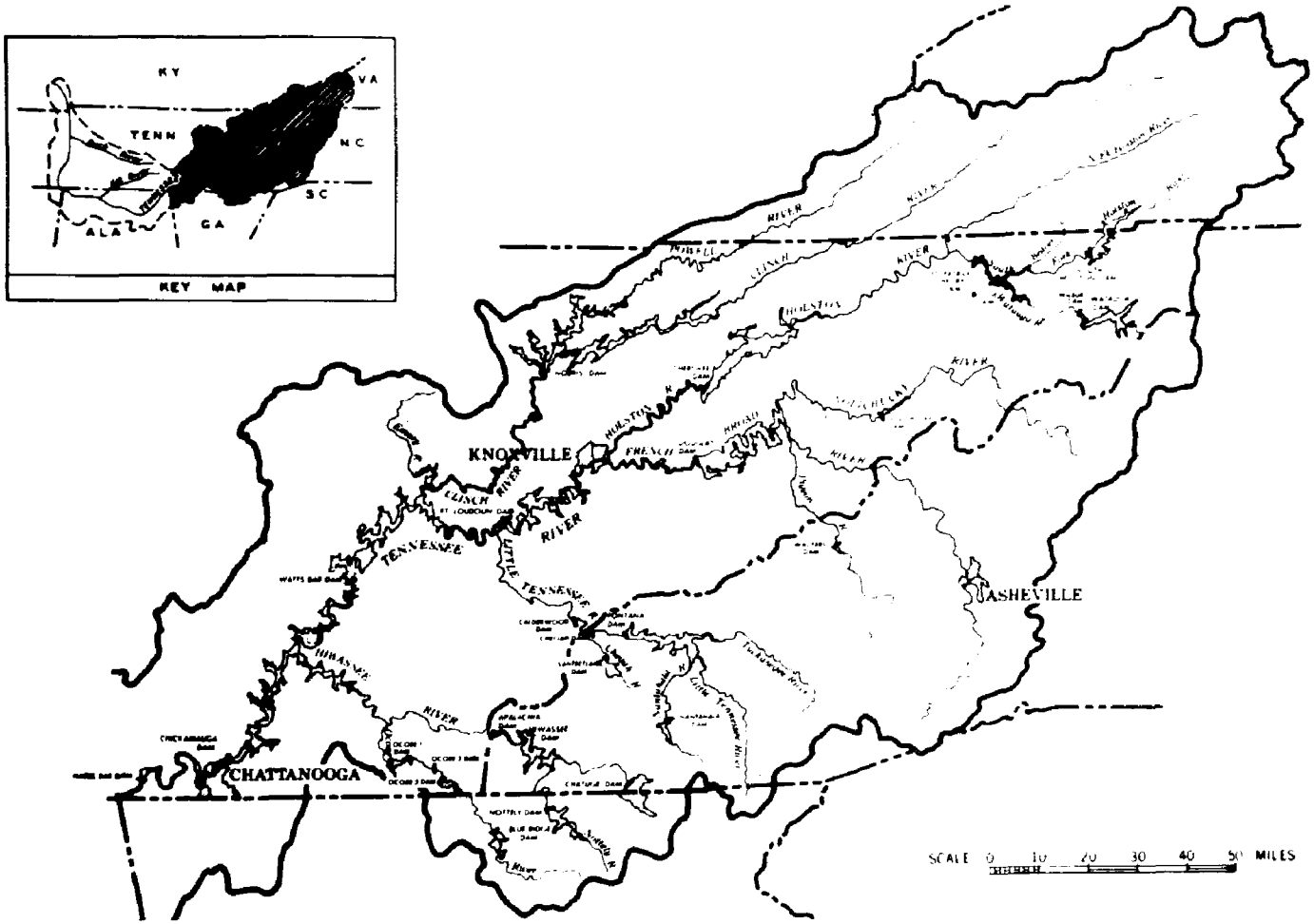

Figure 1 — Area map, eastern half of the Tennessee valley.

water. (The small crosses on the temperature plot for 1941 will be discussed later.)

This illustration of the marked influence on downstream water temperatures exerted by an upstream storage project may not be completely understood by those unfamiliar with thermal stratification in reservoirs. Temperature observations made throughout Cherokee reservoir in 1945 (Figure 3) may help gain an understanding of this important physical phenomenon — important because thermal

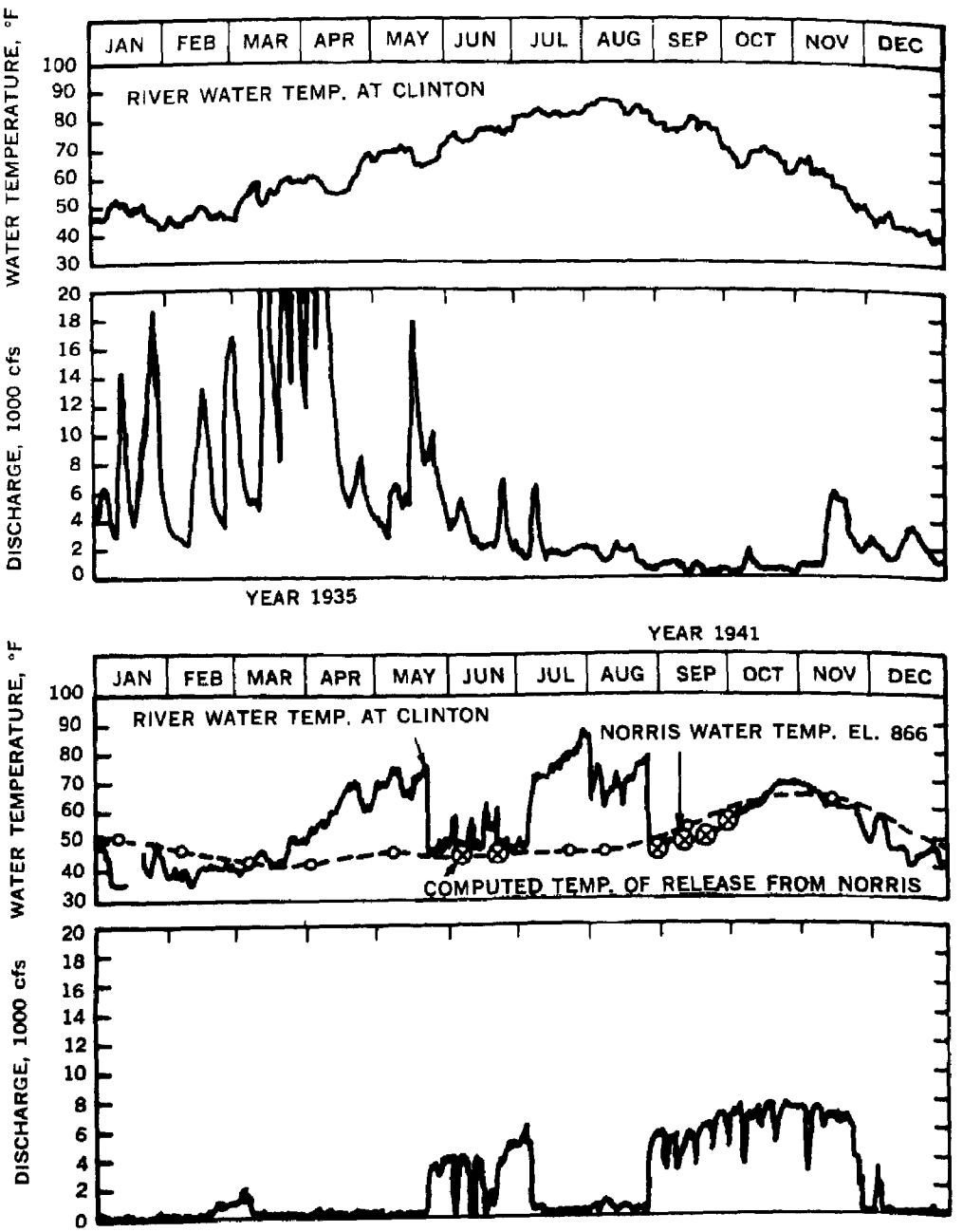

Figure 2 — Temperatures and discharges in the Clinch River below Norris Reservoir.

stratification controls the hydraulic path followed by water flowing into and through a reservoir. An understanding of reservoir hydraulics is essential to an understanding of the effects a reservoir may exert on water temperatures.

On March 1, 1945, there was little thermal stratification in Cherokee reservoir, as the isotherms show. Flow through the power intakes during such isothermal periods is drawn from the entire cross section of the pool, as the flow-net theory would indicate.

As spring advances, the warmer inflows from the tributaries and the increased direct heating of the lake waters by the sun produce thermal stratification in the pool. By June 6, the warm upper stratum (the epilimnion) was separated by the thermocline (which shows rapid changes in temperature with depth) from the colder waters of the hypolimnion below. Wind and diurnal atmospheric temperature changes mix and aerate the waters of the warm epilimnion. The thermocline marks the lower limit of the mixing effect.

During thermally stratified periods, flow through the power intakes is drawn from the hypolimnion exclusively, since the warmer waters of the epilimnion simply float on the cooler, more dense waters below, just as would oil on water. Since draft from the pool is through the deep intakes, the warmer waters from above settle downward to occupy the space vacated by the colder discharged water. Water velocities in the hypolimnion, induced by the draft, are, of course, very low except near the intake. Water is discharged according to its temperature (density), the coldest (most dense) water at or above the intake level going out first. In this way, water many miles upstream from the dam may be discharged ahead of water at the dam stored only 50 feet or so above the intake elevation but having a temperature several degrees warmer than that at intake elevation. As shown for June 6, the cold water trapped below the intake level cannot be discharged (unless the sluices are opened) since its density keeps it at the lowest elevation possible. Naturally, some mixing of this water with the overlying moving water takes place at the interface, but even so the water in this low pocket is changed very slowly.

By September 8, the waters of the hypolimnion, as the hypolimnion existed on June 6, had been discharged from the pool. On September 8, the thermocline was at the intake level. Very little cold or cool water from the previous winter remained in the pool.

Figure 3 also shows the effect in Cherokee reservoir on October 18, 1945, of then-cooler inflows from upstream. In the fall of the year, the tributary inflows are, of course, cooled more quickly by cooler fall air than the great mass of reservoir water. Consequently, these cooler inflows move into and through the pool along the bottom as density underflows(*1*). Such underflows move, by gravity, rather slowly along the old river channel, most of them having velocities of a few tenths of a foot per second. With a velocity of 0.25 foot per second, approximately 12 days would be required to pass through a pool 50 miles long. For a given volume of inflow, the velocity of the underflow is increased as the density difference of the two waters is increased and as the slope of the riverbed is increased.

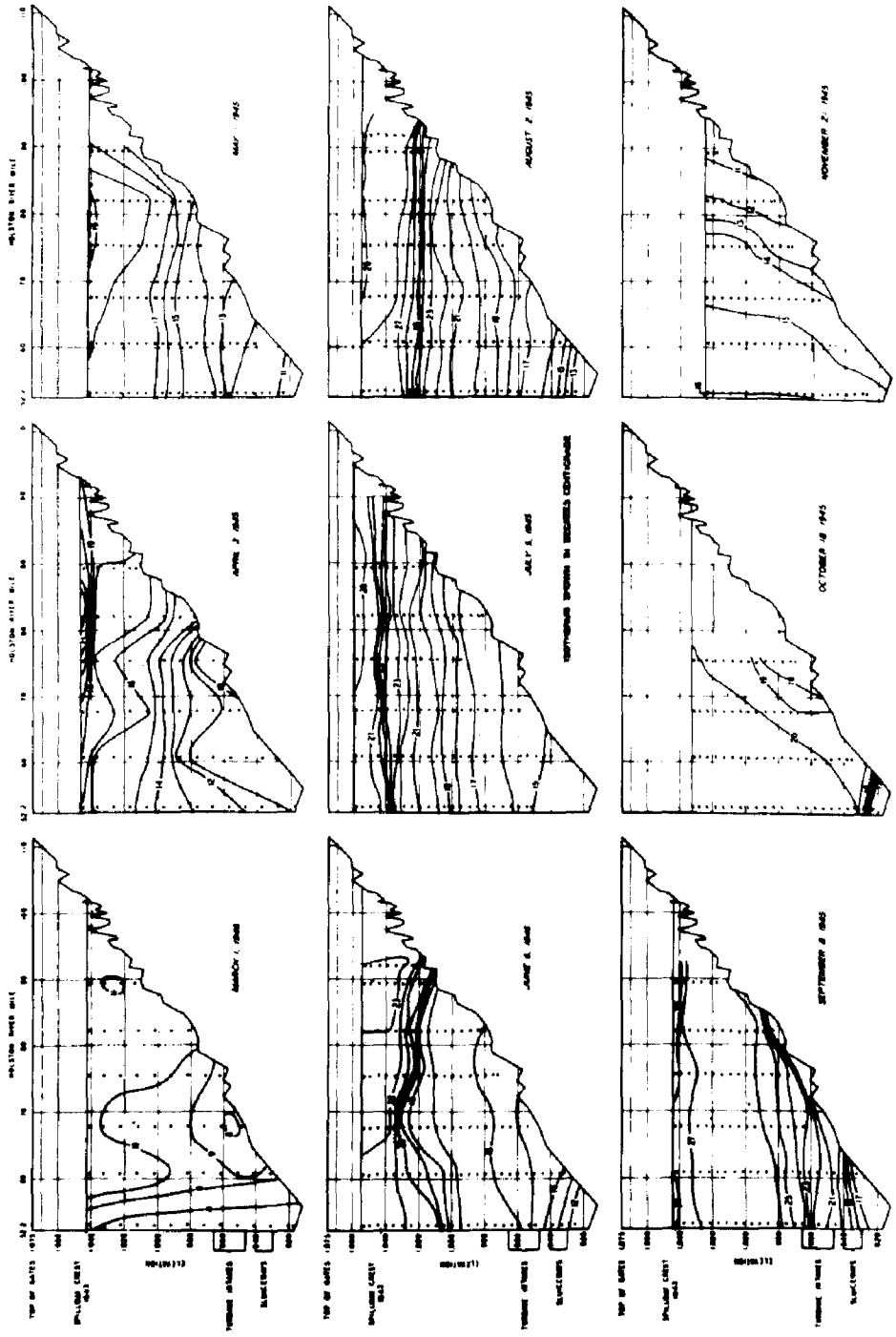

Figure 3 — Thermal stratification in Cherokee Reservoir, March to November 1945 (isotherms shown in degrees centigrade).

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Density underflows continue in the fall until the overlying pooled waters are cooled by vertical circulation to such an extent that there is little if any difference between the temperature of the inflowing waters and the pooled waters. For the latitudes of the Tennessee Valley, the pools are essentially isothermal from the middle of Dechamber until about the end of March or the middle of April. Dunring this period, the isothermal water offers little resistance to wind-induced mixing, and consequently, mixing continues all winter. There is no period of winter stagnation in reservoirs at these latitudes.

Figure 4 illustrates several interesting facets of reservoir effects on downstream water temperatures. A continuous record of water temperatures below Cherokee Dam on the Holston River for 1945 is shown, together with a plot of water temperatures on the Holston River 47 miles downstream. Note that very little difference existed between these two records in the summer months except when Cherokee releases were cut off. In other words, very little warming of the released water took place in the 47 miles of open river flow. (Little data are available on the time of water travel through this reach, but it is known that a flow of 7,900 cfs (cubic feet per second) requires 24.5 hours to flow from Cherokee to a point 50 miles downstream (2).)

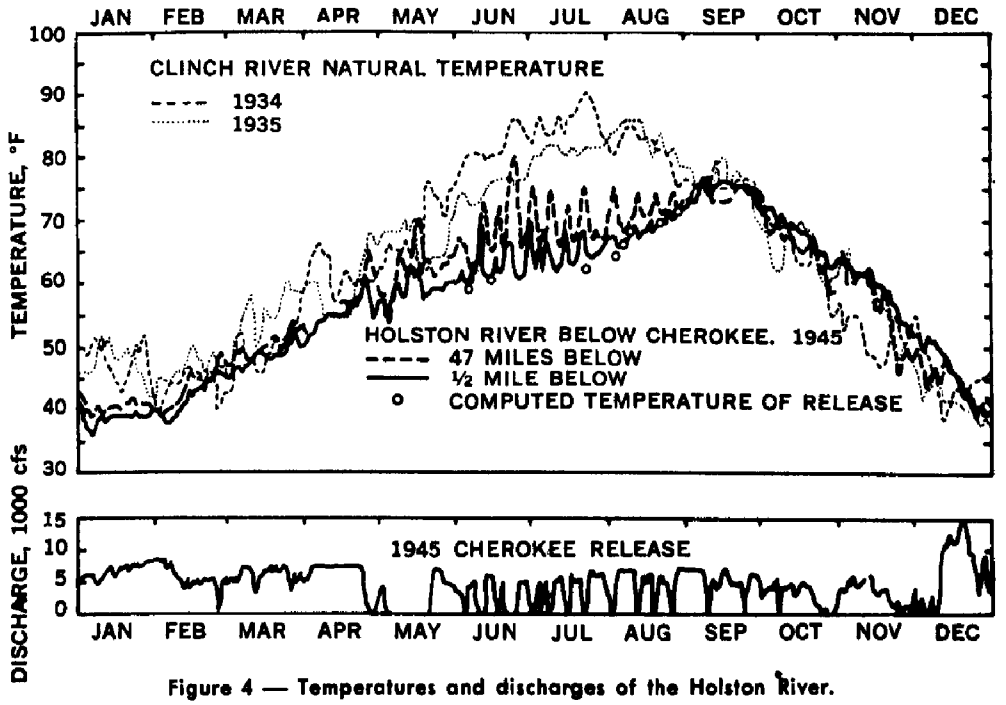

Figure 4 — Temperatures and discharges of the Holston River.

Note that the temperature of the released water, just below the dam, gradually increased as the summer progressed. If Cherokee reservoir were larger and deeper or releases during the spring and summer had been at significantly lower rates the temperature of the released water would have increased more slowly as summer progressed.

Water temperatures for 1934 and 1935, as observed for Clinch River at Clinton, Tennessee, are included in Figure 4 to indicate at least approximately what the temperature of the Holston River would have been during the summer of 1945 had Cherokee reservoir not existed. There was no reservoir on the Clinch River during 1934 and 1935.

During periods of thermal stratification, water is drawn from storage impoundments according to its density if the impoundment is provided with low-level power intakes. To demonstrate this, the temperatures of releases from Cherokee were computed for the summer months from a combination of (1) the temperature "profile" of the reservoir for June 6, 1945, (2) a record of water volumes released day by day after June 6, and (3) an elevation-volume curve for the reservoir.

In this computation, the starting date was June 6. The temperature of water in the reservoir at the centerline of the intakes on this date was taken at 15°C (59°F) from the reservoir survey data (see Figure 3). Horizontal lines were drawn by eye through the plotted isotherms shown for June 6 in Figure 3 to determine a specific elevation to be used in computing the volumes of water in the pool with temperature between 15°C and 16°C, between 16°C and 17°C, etc., on up in temperature and elevation to the upper edge of the thermocline which in this case showed 22°C. (Such computations probably should stop at the center of the thermocline.) The date on which water at 16°C should have been discharged was determined by adding up daily discharges after June 6 until a volume was obtained equal to that volume in the pool on June 6 between the 15°C and 16°C lines previously drawn. This date was found to be June 15. Correspondingly, a cross was plotted for June 15 at 16°C (60.8°F) in Figure 4. By continuing such computations, the date on which water at each degree of temperature between 16°C and 22°C should theoretically have been discharged was determined and plotted. The results, as indicated by the crosses in Figure 4, confirm the hypothesis that water is withdrawn from such pools during the summer months from the thin, horizontal stratum at or very near the intake level, and only after this water is discharged can warmer (less dense) water from the stratum next above settle downward and be discharged in turn.

A similar computation was made for estimating the temperature of Norris releases during 1941, starting with the thermal distribution of water in the reservoir as of June 6, 1941. Computed temperatures for the released water are shown as small crosses on the plotted data in Figure 2. Here also, the above hypothesis of draft from a stratified pool is confirmed.

It follows that the temperature of releases from a deep reservoir can be predicted for several months in advance during the spring and summer if estimates are available on reservoir releases.

Effects in reservoirs located downstream from storage impoundments

Just as density underflows are created during the fall months in the most upstream storage impoundment by cool unregulated river

inflows, underflows are created during the spring and summer months in downstream reservoirs receiving cool releases from upstream storage impoundments. One example of this phenomenon is shown in Figure 5.

Fort Patrick Henry reservoir, a small pool on the South Fork Holston River is located downstream from two large storage projects (South Holston and Watauga) and immediately below Boone reservoir. On Thursday, April 29, 1954, the rate of release of cool water from Boone reservoir to the upper end of Fort Patrick Henry reservoir was 3,400 cfs. This inflow passed through Fort Patrick Henry reservoir as a density underflow. The inflow rate was cut to zero at 11 p.m. on April 30, and held until 8 a.m. of May 3. Note the isotherms for Sunday, May 2, show the last of the water in the cool inflow that was cut off at 11 p.m. on April 30, had by that date (May 2) slid down into the lower levels of Fort Patrick Henry reservoir, and warmer water from the epilimnion *had moved upstream* to fill the space recently vacated by this sinking, sliding mass of cool inflow. Underflows also existed throughout this small pool on July 16 and on September 27, 1954 (Figure 5). In other words, density underflows normally exist in this reservoir during all of the warmer months. The data on dissolved oxygen also shown in Figure 5 confirm the flow patterns indicated by the isotherms.

Another example of a density underflow produced by thermal effects is shown in Figure 6. Here the underflow is passing through Fort Loudoun reservoir along the bottom as a result of the combined cool releases from the lower levels of both Cherokee and Douglas reservoirs during the summer months.

Note how parallel to the river bottom (disregarding the irregularities of the riverbed) are the sloping isotherms of the thermocline. The underflow mixes but little with the warmer water above and maintains essentially the same velocity (about 0.25 feet per second in this particular case) from the duck-under point at about river mile 630 on down to the dam at mile 602.3. A method for determining whether a density underflow will be created and, if so, for estimating the velocity of the density current has been presented earlier(*3*).

The cool water discharged at Fort Loudoun Dam flows through Watts Bar reservoir as a density *interflow* (Figure 7). In other words, this water does not pass through Watts Bar along the bottom, nor through the surface stratum, but in between. The reason for this is that still-cooler (and thus denser) inflow from the Clinch River arm of Watts Bar forces the water from Fort Loudoun up off the bottom. The cooler Clinch inflow passes through Watts Bar as a true density underflow.

Figure 7 shows a profile of the lower end of the Clinch River embayment of Watts Bar pool. The position of the left end of the Clinch profile in the figure denotes the river mile (567.7) on the Tennessee at which the Clinch River enters the Tennessee. Also shown is a profile of the Emory embayment, which is tributary to the Clinch and joins the Clinch at Clinch River mile 4.4.

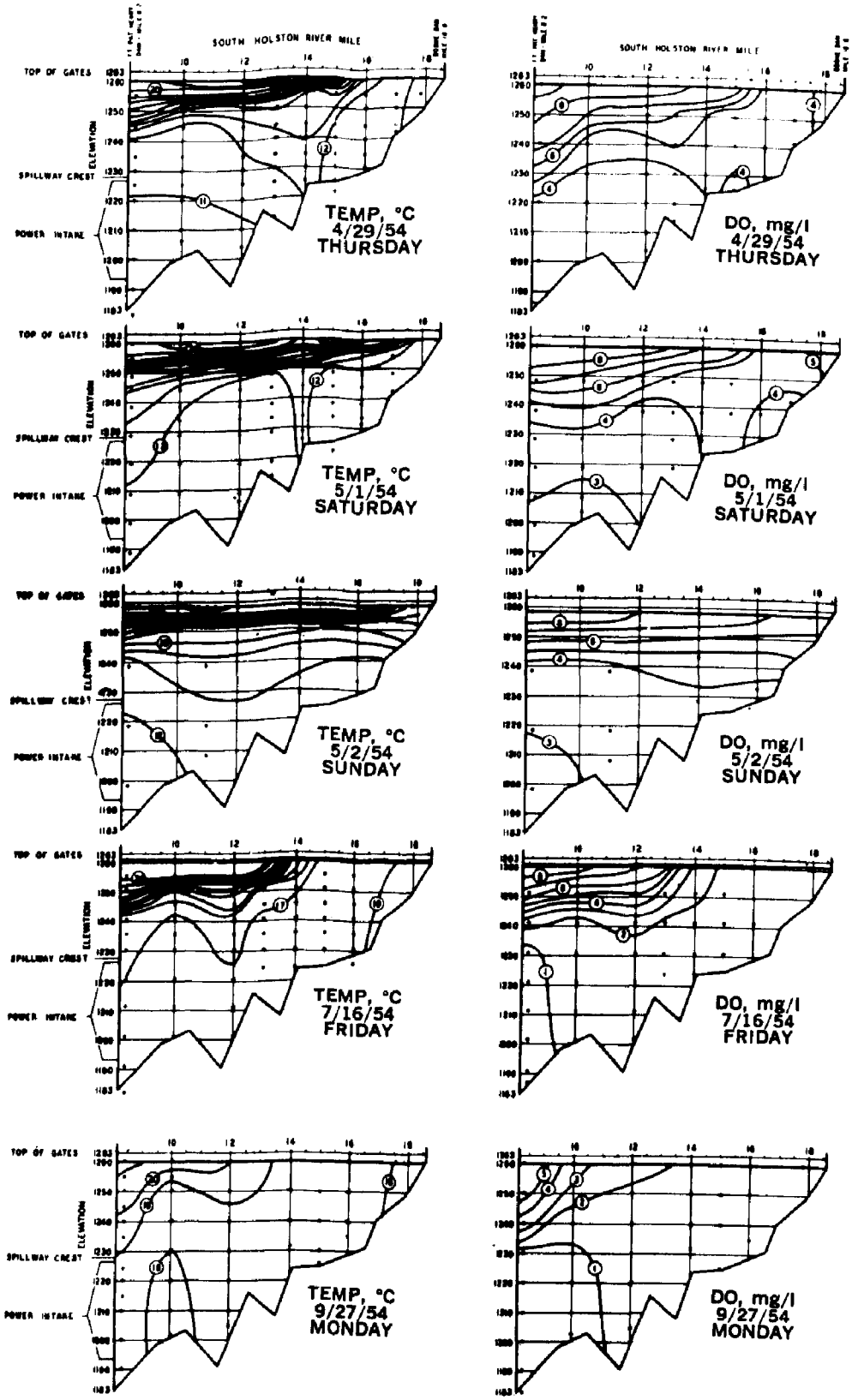

Figure 5 — Thermal stratifications and dissolved oxygen concentrations, Fort Patrick Henry Reservoir — 1954.

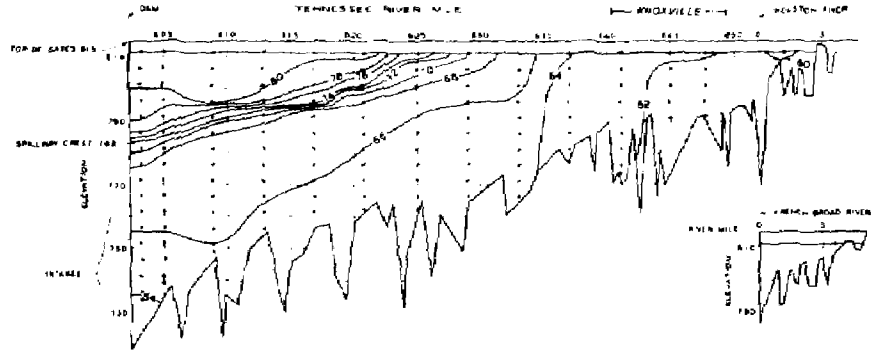

Figure 6 — Water temperatures in Fort Loudoun Reservoir, July 20-21, 1944 (isotherm shown in °F).

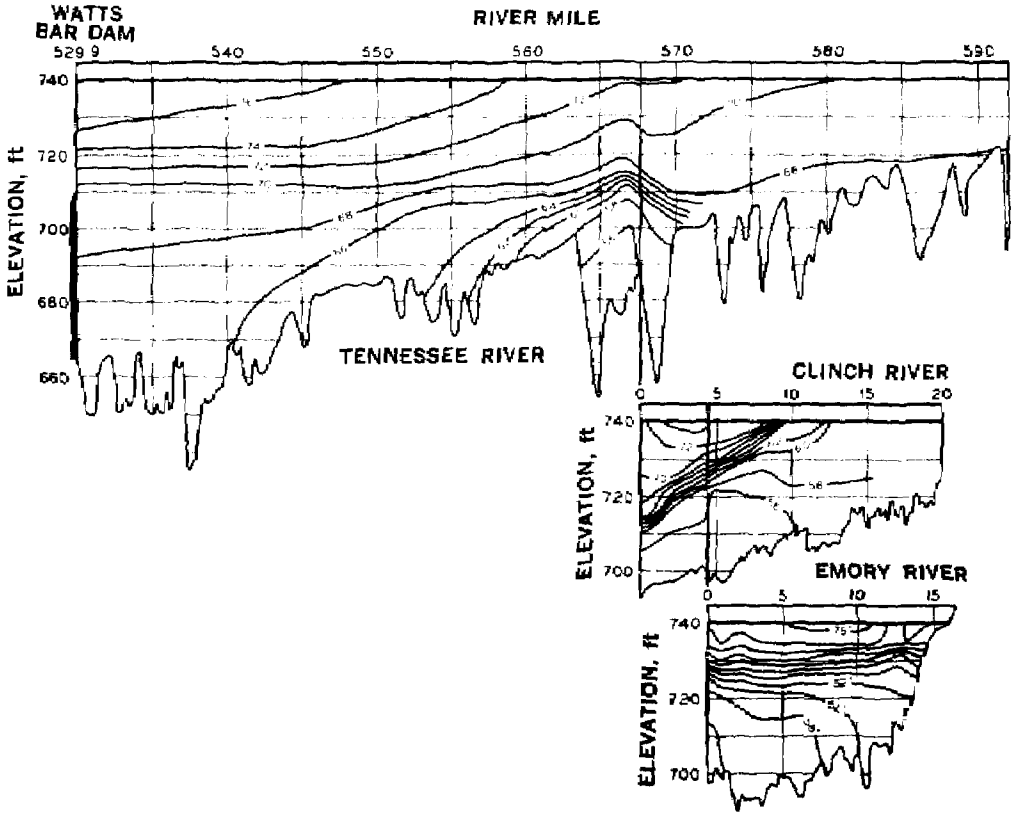

Figure 7 — Water temperatures in Watts Bar Reservoir (isotherms shown in °F). June 24-25, 1947

Cool underflows in the Clinch embayment flow upstream in the Emory embayment along the bottom. When releases from Norris reservoir on the Clinch are cut off during the summer months, the cool water in the Emory embayment reverses its direction of flow and

drains back out into the Clinch River and on downstream along the bottom.

Density underflows are more than just interesting hydraulic phenomena. They can produce both beneficial and detrimental effects on man's many uses of reservoirs and reservoir waters. In the case of Fort Loudoun reservoir (Figure 6), the effluent from the Knoxville sewage treatment plant is absorbed into the cool water and carried through the major portion of the reservoir along the bottom, thus reducing the detrimental effects of the sewage plant effluent on recreational uses of the downstream portion of the pool.

Probably the most beneficial use of density underflows in the TVA region, from an economic standpoint at least, is the use of these cool waters for steam condensing purposes in large steam-electric power plants. One such plant, the Kingston Steam Plant on the lower Clinch River, is so located that it can draw cool water from the Clinch via the lower Emory embayment. Details of this interesting situation and of how a "skimmer" wall was designed and built to exclude the warmer surface strata have been published in two earlier papers (4, 5). On the Cumberland River near Nashville, Tennessee, the TVA Gallatin Steam Plant takes advantage of cool underflows passing through Old Hickory reservoir.

The underflow in the Tennessee River below the mouth of the Clinch River absorbs the treated municipal and industrial wastes from the city of Harriman, Tennessee. These colored wastes are distributed across the streambed by means of a multiport pipe diffuser. They are absorbed into the underflow and do not rise to the surface. If a density underflow did not exist here, some surface discoloration could be expected that might be objectionable to recreational and other interests.

EFFECTS OF RESERVOIRS WITH HIGH-LEVEL OUTLETS ON TEMPERATURE OF RELEASED WATER

As stated earlier in this paper, reservoirs provided with high-level outlets in the dam have much less effect on water temperature than do those with low-level outlets. Perhaps the best available illustration of this situation is Parksville reservoir on the Ocoee River in east Tennessee. Water temperatures observed a short distance above the dam in this reservoir for each of the years 1943 to 1947 are shown in Figure 8. Temperatures of the penstock discharge are also shown for 1955.

Since the power intakes are located high on the face of the dam, the outflow is drawn from near the surface of the pool. This means that the warmest water available in the pool is drawn out. The result is that temperatures very similar to those that would have been observed under natural river conditions are found here. The warm inflow simply passes through the surface layers of the pool, over the cooler water below, and is discharged at the dam with essentially the same temperature it had on entering.

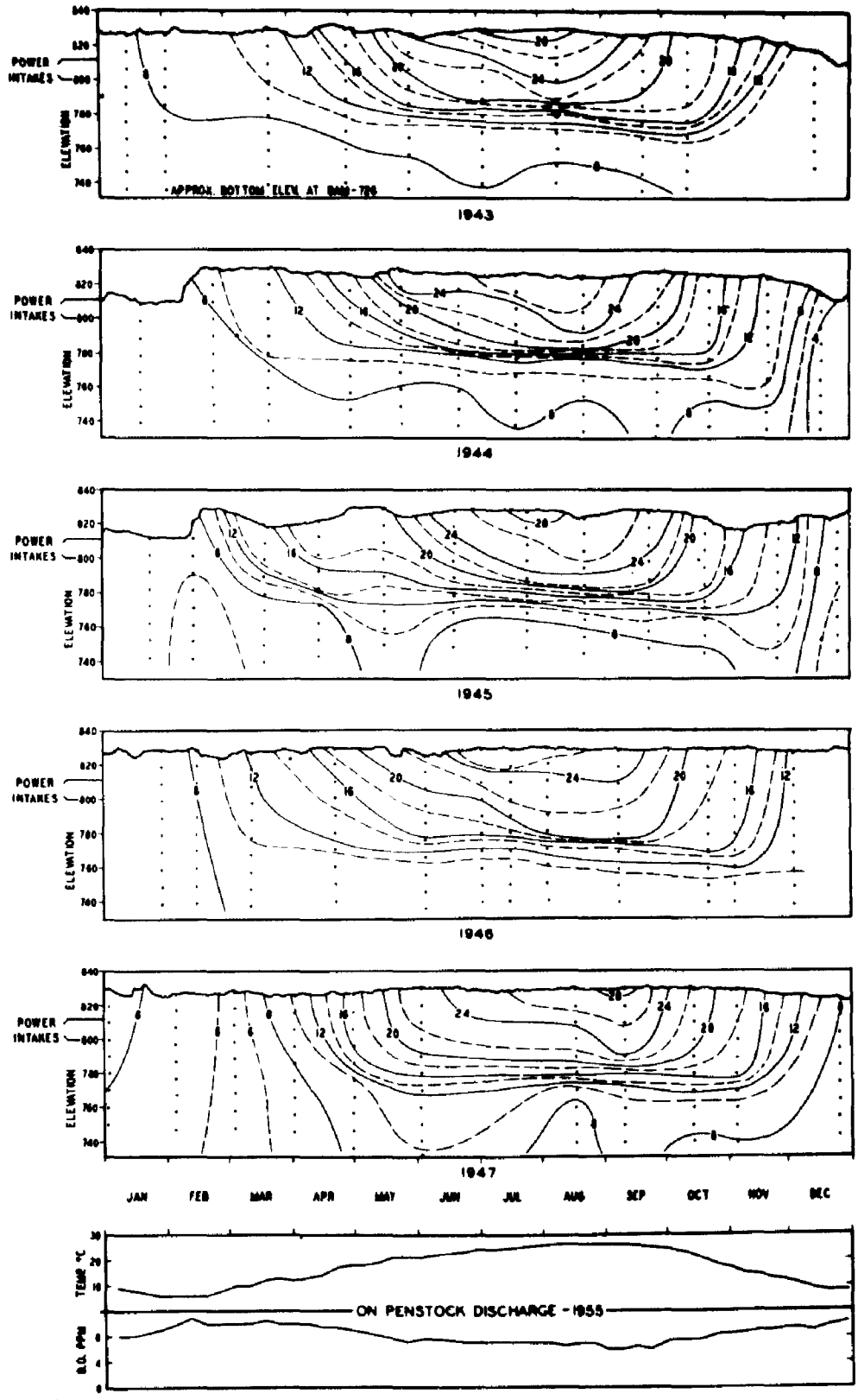

Figure 8 — Thermal stratification in Parksville Reservoir at dam showing effect of high-level power intakes (isotherms in degrees C.).

If cool inflows from upstream, released from the lower levels of a storage impoundment, enter a pool with high-level outlets, the pattern of flow through this pool will be essentially the same as in Parksville, but the outflows will be somewhat cooler than local inflows during the summer months. Inflows during the early spring from the storage pool upstream will have essentially the same temperature as the pooled water, and under such conditions will mix with the pooled water. As the supply of cool water from upstream gradually diminishes and slowly warms up, the flow path gradually will change, however, from one that occupies the entire cross section to one that occupies only the upper strata of the pool. The extent of warming these overflowing waters receive during the summer months will depend upon the length and width of the pool and the rate of draft from the pool. Naturally, in short, small pools with relatively high rates of draft, little warming will be produced. Conversely, long, large pools with relatively low rates of draft will retain the inflow much longer and it will be warmed more not only by the sun and atmosphere, but by warm local inflows that enter the surface stratum.

CONCLUSION

Water control structures may exert a profound influence during the warmer months of the year on water temperatures of both impounded and released waters. By understanding the forces that control these influences, the desirable effects can be used advantageously and the less desirable effects can be controlled or perhaps avoided.

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DISCUSSION

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The effects of varying temperatures of reservoir outflows are generally considered to be important with respect to biological, chemical, and physical quality. Most aspects of these effects have been or will be discussed by several well-qualified speakers. Certain features of temperature control of outflow, as mentioned by Mr. Churchill, and some results thereof appear worthy of additional comment.

Of particular interest in Mr. Churchill's paper are the results of his computations of temperature of releases from Cherokee and Norris Reservoirs. Using reservoir temperature data and information on depths and volumes of withdrawals, he was able to verify his hypothesis that summer withdrawals come from the thin, horizontal stratum at or very near the intake level. If the volume of outflow were to be increased greatly, however, the validity of the hypothesis would have to be demonstrated.

Some work has already been done on the physical theory of withdrawals from stratified reservoirs, particularly by D. R. F. Harleman and R. A. Elder, but as far as the writer is aware, little has yet appeared in the literature. The U. S. Geological Survey has begun preliminary work on the problem using analog techniques. Most engineers will concede that if water is withdrawn from a million-acre-foot reservoir by means of a ½-inch diameter pipe through the dam, the outflow temperature will be that of the water in the reservoir at the depth of the withdrawal. If the volume of outflow is increased, however, to say 100,000 cfs, the validity of the assumption is questionable. What is needed is a technique for withdrawal temperatures that will take into account withdrawal depth, variations in reservoir density, volume of outflow, and physical characteristics of the dam and reservoir.

It appears that dam designers in the future will give careful consideration to the desirability of providing for reservoir withdrawals at any selected depth. It appears also that the operator of the dam will continue to be subject to criticism for his choice of withdrawal level, for it will be difficult if not impossible to satisfy all downstream interests at the same time. For example, a sudden increase in outflow temperature, which might result from changing from a deep to a shallow withdrawal, may evoke anguished wails from avid trout fishermen; the reverse may bring on outraged howls from downstream rice growers who insist that the colder water will delay the harvest.

The temperature of reservoir releases can have a pronounced effect on the hydraulic characteristics of the stream, particularly in winter. Although the effect on the stage-discharge relation resulting from temperature-induced changes in viscosity(*1*) may be statistically significant, it is small. The possible effect of discharging warm water,

however, (as from a steam powerplant using river water for cooling) should not be ignored. If the site is in the North where streams are normally ice-bound throughout the winter, men engaged in the widespread stream gaging activities of the U. S. Geological Survey will applaud because locations where open-water conditions prevail in winter are few. The discharge of warm water may not be a blessing to all downstream riparian residents, for although the stream may be completely ice free for some distance below the point where warm water enters, shore ice will begin to form, and slush ice may cause ice jams downstream where complete ice cover again prevails. Without the warm water inflow, the stream might remain under complete ice cover all winter throughout its length, with no riparian damage save that traditionally associated with the spring breakup. On the other hand, the addition of warm water in winter does not guarantee any such unwelcome consequences; an orderly transition from open water to complete ice cover may occur.

A seldom-considered effect of cold and warm water withdrawals on the physical characteristics of reservoirs is that of evaporation losses. Generally, this is of little consequence in the humid East, but it can be shown, theoretically at least, that some saving in reservoir evaporation would result if it were possible to make withdrawals by skimming only the warmer surface water. For Lake Mead it was shown that the annual saving in evaporation might be 8 percent(*2*). This was a maximum figure, however, and it was considered that skimming the lake was not practicable from an engineering standpoint. Moreover, it was realized that the evaporation loss from the next reservoir downstream would be increased. Incidentally, the computed annual saving of 8 percent at Lake Mead was equivalent to about 70,000 acre-feet, which is more than the capacity of most other reservoirs in the United States; so the idea is attractive if perhaps impracticable.

An example of extreme temperature conditions is the shallow, meromictic lake, described by Anderson(*3*). Located in north central Washington, the lake has no outlet, and is saline of course. It has an average salt gradient of approximately 100 grams per liter at the top to 400 grams per liter at the bottom. The maximum temperature was more than 50°C in July 1955 at a depth of about 2 meters. Perhaps more startling was the fact that in December 1954, the lake was completely frozen over, yet the maximum temperature at the bottom was 33°C. Admittedly these are conditions that are not to be expected in reservoirs, but they serve to illustrate the effects that storage can have on water quality.

The control of temperature through streamflow regulation may well have its broadest application in reservoirs used for steam powerplant cooling. The effects of adding heat from a powerplant on the energy budget for a reservoir can be computed with adequate accuracy(*4*) when air-water temperature differences are small. When large temperature gradients exist, however, the commonly used Bowen ratio concept appears inadequate for computing the amount of

energy conducted from the water surface to the atmosphere. The basic equation for this type of heat flux is

$$H = -c_\rho \rho K_h (\partial T/\partial z + \Gamma)$$

in which H = heat flux

c_ρ = specific heat of air at constant pressure

ρ = density of air

K_h = heat less coefficient

$\partial T/\partial z$ = temperature gradient

Γ = adiabatic lapse rate

Considerable work has been done to develop instrumentation for the direct measurement of heat flux, and in the writer's opinion, further research in techniques for measurement of eddy flux of heat, momentum, and water vapor is most desirable. The theory is basically simple, but additional information concerning the eddy diffusivities of those three items is needed.

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DISCUSSION

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Where cool water is discharged from impoundments during the warm-weather months, the temperature change will be most noticeable in the open river channel immediately downstream from the impoundment. Mr. Churchill presented several illustrations of TVA reservoir systems that regularly discharge cool water to downstream river stretches because of low-level power intakes at dams that draw water from lower reservoir levels. This temperature change is not permanent, however; it is a temporary condition with the river water temperature gradually increasing and approaching what might

be called a natural water equilibrium temperature at some point downstream. This equilibrium temperature will prevail under natural conditions where heat losses due to evaporation, convection, and radiation will balance the heat gain from solar radiation. Computational methods employing energy budget relationships have been presented by Velz and Gannon(*1*) for determining this equilibrium water temperature, using the meteorological elements of air temperature, wind velocity, vapor pressure, and solar radiation.

The discharge of cool water and the resulting increase in water temperature until it approaches the natural equilibrium temperature is analogous to the condition where waste heat is discharged to a river, resulting in elevated river water temperatures with subsequent decrease toward the natural equilibrium temperature. Here, again, computational methods are available for defining either the heat gain or heat dissipation and the resulting water temperature profile, employing energy budget relationships and using the previously mentioned meteorological elements, together with the water surface area. If river channel characteristics are available relating surface area to distance, it then becomes possible to relate resulting river water temperature to specific downstream locations.

The methods employed by Velz and Gannon(*1*) use routine weather bureau data from nearby weather bureau stations, and are most applicable to average conditions for time periods of a week or possibly a month. Generally, they should not be applied to periods shorter than a week. Because many of the calculations are tedious to perform, a computer program has been written for the IBM 7090 employing the MAD computer language for both determination of equilibrium water temperature and also the resulting water temperature profile. As a result, many different conditions can be evaluated in a short period of time.

In summary, therefore, any temperature change resulting from the discharge of cool reservoir water is not a permanent downstream change, but rather a temporary one with the downstream river water eventually approaching natural equilibrium conditions. If resulting river-water-temperature profile information is needed for such purposes as evaluation of waste assimilation capacity, etc., it is possible to calculate this profile with reasonable accuracy.

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DISCUSSION FROM THE FLOOR

Mr. Churchill, Tennessee Valley Authority: This paper is an extension of Mr. Kittrell's fine paper yesterday, and of course the discussion of it by Dr. Harleman. I attempted to show actual instances

where reservoirs have affected — controlled, if you like — water temperatures downstream. We need to understand the magnitude of these changes in actual instances, and also to go into the mechanics a little bit more, into the reservoir hydraulics, if you please, because if you fail to understand the reservoir hydraulics picture, you fail to understand many of the impacts reservoirs have on water quality. The temperature is important because it controls the hydraulics and, therefore, it controls the effects produced; hence the emphasis on temperature in this symposium.

Mr. Coutant, Lehigh University: Mr. Churchill, in Figure 2b of your paper, the temperature values for water released from the dam in December, January, and February are apparently above the normal river temperatures. Are any data available to support the belief that this difference in temperature can be called insignificant, while the differences in temperature noted for May, June, and July can be considered significant, with regard to the ecological effects on the downstream areas?

Mr. Churchill: The dotted line is the temperature at elevation 866 in Norris Reservoir, the center line of the intake in the pool. The water in the river downstream is somewhat colder because of local inflow and is also more responsive to the seasonally colder air temperatures than the great mass of water in the reservoir. The trend of the temperature of elevation 866 is downward all through that period and hits a low point at about the middle of March.

Mr. Coutant: Perhaps my choice of your Figure 2b was unwise. The point I would like to make is that higher winter temperature is a very typical phenomenon of reservoir discharges. Especially in the higher latitudes, the water released from reservoirs having deep outlets tends to be considerably higher in temperature than the stream temperatures normally occurring in the area, which in the winter months may be zero degrees centigrade. I was wondering if you had reasons for not considering this temperature difference as significant as the summer temperature difference.

Mr. Churchill: Of course, the difference is not as large. I suppose that is the first reason I did not consider it. Also, when the water is that cold in the TVA area, a few degrees difference one way or another doesn't make too much difference, but if you are talking about 30 degrees difference in summer time, that does make a difference.

Something I did not bring out, but probably should, is that this cold water released from Norris is used at the Kingston steam plant, one of our own large steam electric power plants downstream near the mouth of the Emory River. Dr. Harleman, by the way, had something to do with the design of the skimmer wall that was built there to hold back the warm water in the surface layers and allow the cold water flowing down from Norris to be drawn underneath. The steam plant thus takes advantage of the cold water released from Norris some 80 miles upstream. Its use for cooling is a very important economic aspect.

Mr. Coutant: Well, I hope we agree that the microbiology of the stream is an important aspect of its quality — the plankton, periphyton organisms, plus the bacteria. In a number of cases, microbiological populations have been shown to be fairly responsive to temperature changes, and I wonder if the change in the winter temperature of the stream, such that the minimum temperatures do not get down to the freezing point, has changed the microbiology to a significant extent.

Mr. Churchill: The answer to that is easy: I don't know. I have no data on that.

Mr. Dougal, Iowa State University: Mr. Churchill, could you describe your program of temperature measurement? What size section do you use? What types of boats? How do you make the measurements, and do you take them every year at all of your reservoirs?

Mr. Churchill: In the early days we did observe temperatures in every reservoir every year, but we found, as you might suspect, that the temperature pictures repeated themselves so closely year after year that we no longer do this.

We have portable equipment and use thermisters, which are very easy to use, so it is simple to get a vertical traverse. It is a job that can be done very easily with a boat; we can survey a whole reservoir 50 miles long in less than a day. Data are easily and quickly collected.

Mr. Dougal: What is the last year for which you have taken measurements? I notice some of the charts extend through about '55 to '57.

Mr. Churchill: We observed temperatures on Watts Bar and Chickamauga Reservoirs just this last year, but not on any of the reservoirs shown on the figures. We are currently working on these, but do not attempt to keep records on all of the reservoirs each year. We do collect weekly samples of water from the outflow of each of our reservoirs, and the local collector observes water temperature at the time of collection. In that way we have a complete record of outflow temperature every week from each of our dams.

Mr. O'Connor, Manhattan College: Would you indicate, please, the inflow hydrograph to Cherokee Reservoir for the period June to October 1941, that coincides with the outflow hydrograph on your Figure 2b?

Mr. Churchill: That would depend upon the operation of reservoirs upstream, now. Before the upstream reservoirs were constructed, it would have been something like the hydrograph shown on Figure 2a for the Clinch River at Clinton below the Norris Reservoir site. Under natural conditions, summer time temperatures are higher and discharges are somewhat lower, but with the regulation going on upstream, this picture would be changed. I cannot give information, off-the-cuff, on the effect of current operation; I would be glad to send it to you.

Mr. O'Connor: I have noticed from your previous work that the minimum depth of reservoir that you dealt with was about 80 or 90 feet and that in all cases you had significant stratification.

Mr. Churchill: That is right.

Mr. O'Connor: At what depth of reservoir would you expect minimal stratification — at the 30-, 40-foot range?

Mr. Churchill: I do not know. Most of our pools are deeper than that, so any answer I would give would just be a guess. Your guess would be better than mine, I expect. Somebody else here may be able to answer your question.

Mr. Towne, U. S. Public Health Service: I have been listening to this discussion with considerable interest. I think we in the Columbia Basin are extremely interested in temperature and have done some work on the subject of predicting the temperature effect of reservoir releases for considerable distances downstream. Mr. Robert Jaske has been involved in the General Electric Hanford operation and will, I hope, give us a little bit of background on this. I think they have a considerable amount of information that would be very valuable.

Mr. Jaske, Hanford Atomic Products Operation: Our contract operation with the Atomic Energy Commission at Hanford involves the use of a tremendous amount of cooling water for the reactor operation at that site. We are interested in the optimum use of this water resource for our own cooling purposes, and also for the secondary purpose of minimizing the effects of our heat releases to the communities downstream.

We noted in the records, the development of a thermocline at Lake Roosevelt through the years much as Milo Churchill has shown; in fact, the data we collected could almost be superimposed on the Cherokee thermocline information in his figures. Consequently, we considered the possibility of using this cold water from Lake Roosevelt to our advantage and to the advantage of the downstream communities.

We started releasing cold water from the depths of Lake Roosevelt in 1958, originally on a daily cycle to counteract the diurnal cycle and later on a continuous basis to take care of the average effect on the river temperature. We have been successful in the past 5 years in reducing the average temperature of the Columbia River as much as 1.5 to 3 degrees centigrade through this process.

We are currently studying the heat budget associated with this release. Before we consider this, I should stress the size of this particular river. On the Columbia River, anything less than 30,000 cfs is considered drastically low flow. This is a large stream. The streamflow past the Hanford plant during the peak period is generally about 400,000 cfs; in some years, it has been as high as 800,000 cfs.

One lesson we have learned from our work there is the danger

of excessive generalizations from results in other areas. I note in this conference and in other discussions with people a tendency to take the experience of one particular region and to immediately apply it to every situation that comes to mind. For instance, the turbidity in the Columbia peaks at the period of high flow, which is just the opposite of what one would expect. Other changes associated with the annual and diurnal cycles in our area vary widely from what you would expect in some of the smaller rivers.

In our work on the heat budget, originally we followed the example of the people who worked on Lake Mead and then on Lake Hefner, and we attempted to correlate the factors in the heat budget with conditions that obtained downstream. We were not as successful as Milo Churchill in determining the fate of the cold water that was released from Lake Roosevelt, for two reasons: First, the volume of bank storage is very high in our area because a lot of porous gravel exists that is very permeable, resulting in the release of large quantities of water; second, we found to our dismay that we need a tremendous amount of micrometeorological data to correlate the heat transfer and radiation effects to the various temperature waters.

We do not have the equipment to conduct the extensive program needed to do a complete investigation. We have satisfied ourselves, however, that the temperature of the Columbia River can be regulated successfully for public purposes by the proper operation of the reservoirs. This proper operation, however, as noted by Murray Stein yesterday, does not always coincide with the most efficient use for power generation or for other purposes. Our own use of the river has been inadvertently compromised to some extent by the manipulation of reservoirs operated by the various agencies upstream.

One conclusion we have drawn from our entire work — and we drew this very reluctantly and in the face of some opinion to the contrary — is that the erection of dams and reservoirs on the main stem rivers in the Columbia Basin, notably the Columbia and the Snake Rivers, has served to increase the temperature of these rivers. This temperature increase we estimate in the range of 1 to 2 degrees centigrade for each major structure that has been erected. The fisheries biologists in the Pacific Northwest have been studying the incident of columnaris disease in salmon, and they note an exponential effect on the incidence of columnaris with increases in temperature above 70 degrees. For this reason, everyone out our way is concerned with temperatures of the river. We are hopeful more agencies will become interested in this particular facet of water quality as it relates to the erection of dams and storage reservoirs.

Mr. Kittrell, U. S. Public Health Service: I want to ask Milo about the two reservoirs where they have been practicing repumping during off-peak power periods. These were Hiwassee and Apalachia, were they not? Have you had an opportunity to observe any possible effects of this repumping on temperature or dissolved oxygen in these reservoirs?

Mr. Churchill: I believe the use of that equipment to pump water back upstream has been so intermittent and so infrequent that to attempt to find the effect would be straining at gnats. We have not tried to find it.

Dr. King, U. S. Fish and Wildlife Service: I am interested in Mr. Churchill's explanation of temperature conditions on the Cherokee, as I am sure all biologists are. There is one point I think would be well to mention to show the close relationship between temperature variations and the fishery. On his temperature chart for Cherokee Reservoir, the cold water is exhausted some time during the summer, certainly during August or by the first of September. The water is going down in elevation very rapidly during that period, too. About 9 months of the year the stream below Cherokee has temperatures in the mid-fifties and mid-sixties for 50 or 60 miles — it's a beautiful stream, ideal for boating and at that time of year good for trout. You can imagine, though, what happens when the cold water is exhausted and the temperature rises into the seventies during the late summer and early autumn. This is the problem the fishery managers face. After attempting to stock the stream with trout for several years with very little success, they investigated and found the temperature pattern mentioned here.

In this case, 9 months of the year a high recreational potential exists, but for 3 months the temperature conditions are such that the fishery disappears. The water is too cold to support warm-water fish most of the year since it does not permit spawning, but during late summer and fall it is unsuitable for trout. So it is impossible, with our present knowledge, to develop a useful fishery in this water.

Another instance of interest is Lake Mead below Hoover Dam. There are now 11 or 12 miles of excellent trout fishery below Hoover Dam that weren't there originally. There is also a good trout fishery below the thermocline in Lake Mohave. The Fish and Wildlife Service has just completed a new hatchery at a cost of over half a million dollars to supply trout to stock the water there. Here is a case where the temperature phenomena in reservoirs are contributing very materially to an excellent fishery, and we all expect it to continue.

Session 4

EFFECTS OF FLOW REGULATION ON WATER QUALITY (Part 2)

Moderator: **E. C. Hubbard**
North Carolina Department of Water Resources

THE EFFECTS OF NUTRIENTS ON PHOTOSYNTHETIC OXYGEN PRODUCTION IN LAKES AND RESERVOIRS

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A reservoir or lake is the settling basin of a drainage area. The potential productivity of a lake is determined to a great extent by the fertility of the land that drains into the lake and by the contributions of civilization. Biological activity within the lake influences such chemical parameters as dissolved oxygen, pH, carbon dioxide, iron, manganese, phosphorus, nitrate-nitrogen, etc.; it is governed by temperature and stimulated by nutrients (e.g., phosphorus and nitrogen). A lake's basin gives dimension to biological activity and may, because of unique physical characteristics, concentrate the nutrients it receives as well as the developing biomass.

BASIC NUTRIENT SUPPLIERS

Basic sources of nutrients to lakes and reservoirs are tributary streams and waste discharges, precipitation from the atmosphere, and the interchange of bottom sediments.

Sewage and sewage effluents enrich tributary streams. Rudolfs(*1*) studied the content of sewages from 12 separate sources and concluded that the annual per capita contribution of phosphorus ranged from 0.6 to 1.5 pounds. Studies of Wisconsin oxidation ponds indicate annual per capita contributions of 4.1 pounds of inorganic nitrogen and 1.1 pounds of soluble phosphorus(*2*). The secondary treatment effluent of the combined sewage and industrial wastes of Madison, Wisconsin, has an annual per capita contribution of 8.5 pounds of inorganic nitrogen and 2.8 to 3.7 pounds of soluble phosphorus. By diverting its treated sewage effluent around Lakes Waubesa and Kegonsa, this city reduced the inflow of nutrients into those waters by 3,143 pounds per day of inorganic nitrogen and 1,342 pounds per day of soluble phosphorus(*3*).

Lakes and reservoirs located on heavily used duck flyways receive "flying in" nutrients from a transient duck population. Sanderson(*4*) found the annual raw waste contribution of a domestic duck to be 2.1 pounds of total nitrogen and 0.9 pound of total phosphorus. Paloumpis and Starrett(*5*) applied a factor of 0.5 to these data and determined that the annual nutrient contribution to Lake Chautauqua, Illinois, from the wild duck population was 12.8 pounds of total nitrogen and 5.6 pounds of total phosphorus per acre.

Land runoff may often be the principal contributor of nutrients to the tributary stream. The annual loss per acre from a planting of

corn on a 20 percent slope of Miami silt loam was found to be 38 pounds of nitrogen and 1.8 pounds of phosphorus(*6*). On an 8 percent slope, the annual loss per acre was reduced to 18 pounds of nitrogen and 0.5 pound of phosphorus. In a study of the lower Madison lakes, Sawyer et al.(*7*) and Lackey and Sawyer(*8*) found the annual contribution of inorganic nitrogen per square mile of drainage area tributary to Lake Monona to be 2,800 pounds, to Lake Waubesa, 3,130 pounds, and to Lake Kegonsa, 4,100 pounds.

Lake Koshkonong, a 10,000-acre lake in southcentral Wisconsin, receives the Rock River and two minor tributaries. Based on calculated normal flows, Lake Koshkonong receives 91 pounds of inorganic nitrogen and 40 pounds of soluble phosphorus per acre per year. During high flows, the nutrient influx may reach as much as 8 pounds of inorganic nitrogen and 1 pound of soluble phosphorus per acre per day. Tributaries to the Rock River account for 64 percent of the drainage area to the outlet of Lake Koshkonong. Twelve monthly samples collected at the outlet in 1943-44 showed a mean total phosphorus concentration of 0.21 milligram per liter and an inorganic nitrogen concentration of 0.37 milligram per liter(*7*). These samplings were repeated in 1959-60. The mean total phosphorus concentration was doubled (0.42 mg/l); and the mean inorganic nitrogen concentration was more than tripled (1.36 mg/l). Total annual precipitation was 15 inches greater for the basin during 1959-60.

Inorganic nitrogen compounds are present in small amounts in rainwater where they are predominantly nitric acid and ammonia. These compounds come from the atmosphere and are the products of electrical discharges, terrestrial decomposition, and volcanic eruptions. If the concentrations quoted by Hutchinson(*9*) are used and a 30-inch annual precipitation is assumed, the contribution of ammonia and nitrate nitrogen in the temperate region would be 5.5 pounds per acre. In an 18-month investigation at Hamilton, Ontario, Matheson(*10*) determined the annual atmospheric nitrogen fall to be 5.8 pounds per acre. Sixty-one percent of the total nitrogen fell on 25 percent of the days when precipitation occurred, and the balance was attributed solely to the sedimentation of dust.

As nitrogen enters the reservoir it is incorporated in the biomass in the form of protein. Upon death or excretion, nitrogen is liberated for re-use. During this process some is lost (1) in the effluents, (2) by diffusion of volatile nitrogen compounds from surface water, (3) by denitrification in the lake, and (4) in the formation of permanent sediments.

Likewise, phosphorus is taken up in the web of life, is liberated for re-use upon death of the organism(*11*), may settle into the hypolimnion with the sedimentation of seston or in fecal pellets, and some may be released at the mud-water interface(*12*).

Sawyer et al.(*7*) found the nitrogen content of bottom muds in the Madison lakes to be 7,000 to 9,000 micrograms per gram (dry weight) and phosphorus, likewise, 1,070 to 1,200 micrograms per gram

(dry weight). Some of this is recirculated from the bottom ooze into the upper lake water by the movement of organisms, eddy diffusion, and the thorough mixing of the lake waters at the time of lake overturns.

NUTRIENT UTILIZATION

The principal factors affecting aquatic growths include temperature; sunlight; size, shape, and slope of lake basin; water quality, including water clarity and dissolved oxygen; and nutrients. The total supply of an available nutrient depends on the total volume of water, as well as on the concentrations of the element in the water. Gerloff and Skoog(*13*) determined in the laboratory that 5 units of nitrogen plus 0.08 unit of phosphorus — a ratio of 60:1 — will produce 100 units of algae. The N-P ratio, as it occurs in algae and submerged plants, is more nearly 10:1, and in sewage 8:1(*14*). Allen(*15*) found the maximum algal crop that can be grown on the nutrients present in domestic sewage to be 1 to 3 grams per liter (dry weight); to obtain any appreciable increase, it was necessary to supplement the sewage with nitrogen as well as carbon.

Sawyer(*16*) studied the southeastern Wisconsin lakes and concluded that 0.30 milligram of inorganic nitrogen per liter of water and 0.015 milligram of soluble phosphorus per liter at the start of the active growing season could produce nuisance blooms. Nitrogen appears to be the more critical factor limiting algal production in natural waters(*13*), since phosphorus is stored in plankton as excess and may approach 10 times the actual need.

A continued high rate of nutrient supply does not appear to be necessary for continued algal production. After an initial stimulus, the recycling of nutrients within the lake basin is sufficient to promote algal blooms for at least a number of years. The initial stimulus is most often supplied by dissolved phosphorus.

Studies of the standing crop of submerged aquatic plants in oligotrophic Green Lake and eutrophic Lake Mendota, Wisconsin(*17, 18*) indicated a wet weight of 14,000 pounds per acre and a dry weight of 1,800 pounds per acre. Harper and Daniel(*19*) found that submerged weeds were 12 percent dry matter and contained an average of 1.8 percent total nitrogen and 0.18 percent phosphorus. Birge and Juday (*20*) found the largest crop of spring plankton was approximately 360 pounds per acre on a dry weight basis (10 percent dry matter) and the largest crop of autumn plankton, 324 pounds per acre. The summer and winter minimums were 124 and 98 pounds per acre respectively. Blue-green algae are approximately 6.8 percent nitrogen and 0.69 percent phosphorus on a dry weight basis(*21*). These latter values are for growths occurring in a fertile lake that does not routinely produce nuisance blooms.

Based on the above computations, a standing crop of submerged aquatic plants in a fertile lake could contain, and liberate on decomposition, 32 pounds of nitrogen per acre and approximately one-tenth

as much phosphorus. Likewise, under similar circumstances an algal population could theoretically tie-up about 15 pounds of nitrogen and 1.5 pounds of phosphorus per acre, or approximately one-half of the nutrient components of a normal submerged weed population. An algal population often covers the entire lake; submerged plants are normally limited to that area where the depth is 20 feet or less.

PRODUCTION IN ABUNDANCE

The literature records many lakes capable of excessive algal production and as Hasler(*22*) states, "it is clear that any increase in the rate of eutrophy, even if this involves only the acceleration of a natural and inevitable process is, from a human point of view, thoroughly undesirable."

Anderson(*23*) discusses recent eutrophication of Lake Washington near Seattle. In 1950, the standing crop of phytoplankton was 0.6 parts per million (by volume); in 1955, 1.6; and in 1956, 4.2. The phosphate accumulation in the hypolimnion was 23 ppb in 1950, 89 ppb in 1957, and 74 ppb in 1958. These factors were correlated with changes in the flora, especially the initial observation in 1955 of *Oscillatoria rubescens*, "a notorious indicator of pollution in many lakes." Hasler(*22*) described eutrophication in the Zürichsee and Hallwilersee, Switzerland, in Lake Windermere, England, and in several other lakes. Phinney and Peek(*24*) discussed Klamath Lake, Oregon; and Benoit and Curry(*25*), Lake Zoar, Connecticut; Deevey and Bishop(*26*) found Linsley Pond to be the most biologically productive of 30 lakes studied in Connecticut. Here, again, evidence was found of rapid eutrophy in comparatively recent times.

Thirteen of the southeastern Wisconsin lakes studied by Sawyer et al.(*7*) were re-examined by this writer in 1959-60. Twelve to sixteen more inches of precipitation occurred during the latter study. With the exception of Lake Koshkonong (discussed earlier) and Lake Delevan, the chief difference noted was a significantly higher organic nitrogen concentration in six of the remaining eleven lakes. Total phosphorus, soluble phosphorus, organic nitrogen and inorganic nitrogen determinations of the lake effluents were made by the same chemist during both studies.

Lake Delevan, like Lake Koshkonong, is a flow-through lake with an area of 1,038 acres and a maximum depth of 52 feet. The resident population of its shores exceeds 1000 dwellings, and it receives additional treated sewage effluent from Elkhorn, Wisconsin (1960 pop., 3,586). When the 1959-60 monthly effluent-nutrient concentrations were compared with those found in the 1943-44 study, a 2-fold increase was noted in total phosphorus and organic nitrogen and a 2.7-fold increase in inorganic nitrogen. During the summer of 1948, this writer noted an abundance of higher aquatic plants such as pondweeds, coontail, wild celery, and water milfoil. The secchi disc visibility was 9 feet. Wisconsin Conservation Department records for August 16, 1951, again showed rooted aquatics abundant with a number of species present, and a secchi disc reading of 7.5 feet.

Another record for August 11, 1960, indicated the rooted vegetation scarce, the west shore devoid of plants, a dense algal growth, and a secchi disc visibility of 2.8 feet. In recent years, an accelerated algal control program, in which copper sulphate is used, has been established.

The parameters of eutrophication are many; most important to the layman on the scene are those that can be readily noted through visual inspection. The secchi disc is a more polished measure of visual inspection. The shape of vertical dissolved oxygen curves, the build up of nutrients in the hypolimnion, significant changes in the algal population and in the fishery are all factors closely correlated with enriched conditions in a lake basin.

PHOTOSYNTHETIC OXYGEN PRODUCTION

As early as 1931, Rudolfs and Huekelekian(27) noted the effects of sunlight and green organisms on the reaeration of streams and found that the dissolved oxygen in water containing large quantities of algae could be decreased from supersaturation to 17 percent saturation by placing the water in darkness, and could also be increased to 282 percent saturation by subjecting it to diffuse light.

In recent years, the measurement of primary production has stimulated interest among investigators(28). Several methods of determination are applicable in a situation in which the inflows of energy and material balance the outflows. These include the oxygen method (light-dark bottle, diurnal oxygen curve, and oxygen deficit in the hypolimnion); the carbon dioxide method; determinations with radioactive materials; and the chlorophyll method(29).

According to Dice(30), "the ultimate limit of productivity of a given ecosystem is governed by the total effective solar energy falling annually on the area, by the efficiency with which the plants in the ecosystem are able to transform this energy into organic compounds, and by those physical factors of the environment which affect the rate of photosynthesis."

Oswald and Gotaas(31) state that green algae utilizing energy from the sun produce carbohydrates from carbon dioxide and water, and then assimilate these carbohydrates together with the liberated ammonia and other essentials to produce additional algal cells. Quantitatively the growth of 1 pound of algae is usually accompanied by the production of a minimum of 1.6 pounds of molecular oxygen. In stabilization ponds it has been found that a photosynthetic efficiency of 1 percent is equivalent to the production of about 25 pounds of organic matter or the liberation of about 40 pounds of oxygen per acre per day. Photosynthetic efficiencies in pilot-plant sewage stabilization ponds have ranged from 2 to 9 percent under varying conditions of depth, detention time, recirculation time, and mixing.

The literature records many ways of expressing oxygen production, e.g., micromoles of O_2 per microliter of organisms per hour, millimoles per square meter per day, milligrams of carbon per square

meter per day, milligrams of O_2 per square centimeter per month, grams per square meter per day, pounds per acre per day, etc. This writer has taken the liberty of converting these data to pounds of oxygen per acre per unit of time and to parts per million, to permit rapid comparison.

Light-dark bottle data on sewage stabilization ponds in the Dakotas indicated gross oxygen production of 231 pounds per acre per day, respiration of 169 pounds per acre per day, or net oxygen production of 62 pounds per acre per day(*32*). Gross production was highest during mid-morning at Lemmon, South Dakota, (18.7 lb per acre per hr) and lowest during early evening (0.3 lb per acre per hr). Highest net oxygen production was 10.7 pounds per acre per hour. There is generally no measurable oxygen production during winter under ice in stabilization ponds.

In measuring *in situ* aeration of Wisconsin's sewage stabilization ponds, McNabb(*33*) found net oxygen production proceeding at a rapid rate in the morning, and oxygen consumption by biota exceeding production throughout most of the afternoon in spite of light intensities favorable for photosynthesis. Highest oxygen production was 21.4 pounds per acre per hour with a phytoplankton population of 178 parts per million (by volume) and a nutrient inflow of approximately 4.0 pounds per acre per day total nitrogen and 1.3 pounds per acre per day total phosphorus.

Verduin(34) summarized the literature on primary production in lakes and concluded that the net photosynthetic rate of autotrophic organisms under optimum light was 35×10^{-6} pounds of O_2 per milliliter of organisms per hour. Lakes with an epilimnion layer of the order of 1 meter are likely to have standing crops of autotrophic plants on the order of 50 parts per million (by volume), and lakes with an epilimnion depth of 10 meters are likely to have standing crops of about 5 parts per million (by volume).

Computations of photosynthetic oxygen production for several lakes yielded values lying mostly between 42 to 57 pounds per acre per day. A year-round study under completely natural conditions in western Lake Erie showed winter yields of about 11 pounds per acre per day and summer maxima of about 85 pounds per acre per day. The annual oxygen curve closely followed the solar radiation curve. Net oxygen photosynthesis in two Alaskan lakes ranged from 3.4 to 4.0 pounds per acre per day(*35*). The net oxygen production rate for East Okoboji Lake in Iowa, a producer of high plankton populations was found to be 79 pounds per acre per day, with production largely confined to the first 2 meters(*36*). Average gross photosynthesis for Grand Traverse Bay (Michigan) has been recorded at 10.8 pounds per acre per day and for Douglas Lake, 3.7 pounds per acre per day(37).

An increase in the hypolimnetic oxygen deficit has been taken as evidence of increased lake productivity. In Lake Washington, near Seattle, the hypolimnetic oxygen deficit was determined to be 105 pounds per acre per month in 1933, 178 pounds in 1950, and 279

pounds in 1955(*38*). The standing crop of phytoplankton in the top 20 meters of water in 1950 was 0.6 parts per million (by volume) and in 1955, 1.6 parts per million (by volume)(*23*).

As pointed out by Whipple et al.(*39*), supersaturation in the upper waters is not cumulative to a great extent because of the circulation that is maintained by wind action and convection currents, both of which promote contact of the water and the air with a consequent loss of oxygen. Highest saturation is frequently found in the upper region of the thermocline in oligotrophic lakes. Wind action seldom disturbs the water of this zone, convection currents are absent, and diffusion is a slow process. Chlorophyll-bearing organisms find an abundant supply of carbon dioxide and sufficient light in this area to promote photosynthesis, resulting in saturation values that may exceed 300 percent.

There is a need to relate photosynthetic oxygen production to (1) practical problems associated with lakes and streams, (2) some quantitative expression of phytoplankton, (3) nutrient balance, and (4) seasonal fluctuations and climatic phenomena.

THE PRICE OF EUTROPHY

The disadvantages of algae as a source of oxygen have been well summarized by Bartsch(*40*). Algae respond to complex, changing, unpredictable environmental factors including solar radiation, opacity of the medium, rate of bacterial activity, rise and fall of nutrients, climatic phenomena, and ecological succession. When algal cells die and sink to the hypolimnion, oxygen is used in decomposition. The stimulation of algal production by nutrients can lead to the formation of a mass of organic matter greater than that of the original waste course(*41*). In an enriched environment, algae respond so well to incoming nutrients that the oxygen required for the respiration of the resultant algal mass alone surpasses the BOD of the incoming food material. Lake Winnebago, Wisconsin, (area, 213 mi^2) produces heavy algal populations. In July, when the lower Fox River carried a heavy algal load from Lake Winnebago, the ultimate BOD in the river above the sources of industrial and municipal wastes ranged to 660,000 pounds of oxygen demand each day(*42*).

Enrichment often results in domination of the algal mass by a relatively small group of blue-green algae, which become well established. Indications are that many species of fresh water algae are capable of producing physiologically active metabolites that may function as toxins, growth inhibitors, or growth stimulators to themselves or to associated algae(*43*). Most of the adverse effects resulting from an algal mass occur when one species of algae dominates the population.

Fish kills have resulted from a supersaturation of oxygen(*44*), as well as a depletion of oxygen(*45*). An example of the latter occurred in October 1946 when tremendous quantities of *Aphanizomen flos aquae* entered the Yahara River from Lake Kegonsa near Mad-

ison, Wisconsin, decomposed in passing downstream, and caused oxygen depletion resulting in the death of tons of fish.

Provost(*46*) indicated that overproduction of chironomids (midge larvae or bloodworms) in lakes is caused by excessively nutritious waters. Midgeflies have become a nuisance in several areas where conditions are especially suitable for the concentration of a swarming mass of adults following an emergence (e.g., Clear Lake, California; Lake Winnebago, Wisconsin; and several lakes in Florida). Larval development is no doubt fostered by the deposition of the dead bodies of a rich plankton population on the bottom sediments.

Both weed and algal nuisances develop in enriched water. Fishing may be impaired; and bathing, boating and water skiing often become indefinitely postponed sports in waters that otherwise offer maximum multiple recreational use. Industrial or municipal water treatment is hampered or made inefficient by extensive aquatic growths; property values are lowered; and resort trade is often cancelled as a result of these nuisances.

Rapid decomposition of dense algal scums with associated organisms and debris gives rise to odors and hydrogen sulfide gas, which creates strong citizen disapproval and often stains the white paint on residences adjacent to the shore.

Controls are needed; these are feasible(47), but frequently are costly, time consuming, and offer only temporary relief. Long-term remedial measures can be focused on reducing the nutrient concentration in the troublesome area or on altering some aspect of the physical topography that concentrates or fosters the development of nuisance algae or aquatic weeds. These considerations often involve costly measures to correct existing conditions, and future planning to assure wise use of the natural aquatic resources of an area.

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DISCUSSION

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After the comprehensive discussion Mr. Mackenthun just presented, there is not too much left to say except perhaps to elaborate

around the fringes, emphasize some things, and note one or two places where I might disagree.

First, we are concerned, in the long run, with what is commonly called ecological control in the management of problems related to the superabundance of the algal forms we encounter in our aquatic areas. Let us look once again at the sources from which the nutrients come.

The air is one source we have generally ignored in the past. We can do very little about controlling contributions from the air. We cannot control the lightning, for example, or what comes down from the upper atmosphere, although sometimes we would like to. The people in Minnesota heard about the problem of water fowl contamination of lakes in Illinois, so they have been doing something about it by spilling soybean oil into their rivers with a tremendous kill of ducks in that area. I do not mean anything against the people in Minnesota, but I just thought you might be interested in what cooperation you sometimes get between States.

As to the land, the character of the soil is very important, of course, and the nutrients that reach our receiving waters depend both on the water that percolates through the soil and the surface runoff. We cannot do much about the nutrients that percolate through the soil because farmers are going to grow crops, fertilize the land, and so forth. An area in which we find tremendous amounts of nutrients in the receiving waters is in the development of peat lands. Peat bogs have very poor retentive capacity for nutrient materials and, furthermore, serve as tremendous nitrifying beds. I have seen small creeks coming from such beds that contained as much total nitrogen as an ordinary sewage treatment plant effluent. Not much can be done about this source of nutrients as the farmer is going to work these peat lands.

I have always been much concerned about the way farmers spread manure on the land. When they spread manure on frozen ground and it rains, what happens to the soluble fertilizing substances? They wash into the receiving stream; if the manure is spread on unfrozen land and it rains, the ammonia and phosphates are leached into the soil and held there by ion exchange. What can be done is to encourage county agents to educate the farmers to improve their practices in handling animal manures. We are all familiar with contour farming so I will not dwell on that.

The major source of nutrients in this modern age is our waste waters, particularly those of domestic origin. Mr. Mackenthun has given some information on per capita contributions of phosphorus and nitrogen. I would warn you about going back into the literature too far to find data on phosphorus, because the picture today is entirely different from what it was even 5 years ago and is certainly different from that 10 years ago. We used to think of domestic sewage as having a nitrogen to phosphorus ratio of 8 to 1. As a result of the use of synthetic detergents that are loaded down with complex phos-

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phates (they are often missed because we do not analyze for them), the nitrogen to phosphorus ratio in domestic sewage today is closer to 3 to 1. A total phosphorus concentration of 8 to 10 milligrams per liter is very common in domestic sewage today whereas prior to World War II it was on the order of 3 milligrams per liter. Tremendous quantities of this fertilizing element have been brought into the picture as a result of the development and widespread use of household detergents. This is an important consideration.

Many of our industrial wastes are very potent sources of nutrients — phosphorus, in particular. Great amounts of synthetic detergents are used in place of old-fashioned soap. Textile wastes are ordinarily rich in phosphorus; fortunately, they are deficient in nitrogen. Animal packing wastes are extremely rich in both nitrogen and phosphorus. Both of these are major sources of nutrient materials.

Mr. Mackenthun talked about the secondary effect of the cycling of nutrients between the water and the bottom deposits. Once you get the wheel turning, so to speak, algal blooms develop, the algae die, settle, and enrich the bottom, bacteria decompose the algae thus releasing the nutrients, and then there is a feedback from the bottom. This feedback from the bottom, or the hypolimnion, is extremely important; more important than is often realized. When a lake stratifies, stratification usually occurs at a depth somewhere around 20 feet, and whether the hypolimnion goes anaerobic or stays aerobic makes quite a difference in the feedback of nutrients.

Let us consider a lake that goes anaerobic. Tremendous amounts of ammonia nitrogen, phosphorus, and other nutrients come from the bottom that would normally be held there fairly tightly if the lake stayed aerobic from top to bottom. This feedback, then, is a source of nutrients throughout the summer months. The surface waters can be fairly well stripped of nutrient materials by early season blooms, but as wind on the lake surface sets up currents in the epilimnion, a reverse current is established in the hypolimnion. Transmission of energy through the thermocline sets up this lower circulation. Chemical data on hypolimnetic waters demonstrate that dispersion of nutrients from bottom muds is not dependent upon ordinary diffusion, but is due to circulation of the hypolimnion. Actually, analysis of the waters of the hypolimnion reveals that the nutrient content of the hypolimnion is more or less constant throughout its entire depth during the summer stagnation period.*

Mr. Churchill mentioned the lowering of the thermocline within stratified reservoirs as a result of the drawoff of cold waters from the hypolimnion. The thermocline will go down to some extent anyhow as the summer progresses, because of the mixing referred to above. Thus the depth of water in the epilimnion becomes greater and greater. As this takes place, of course, water keeps moving from the hypolimnion into the epilimnion, and this serves as a continuing supply of nutrient materials for the epilimnion.

*See Journal New England Water Works Association, 61, 122 (1947).

In regard to nutrient utilization, analyses of algae and rooted aquatics indicate that they take about 10 parts of nitrogen out of the water for every part of phosphorus. Although the work of Gerloff and Skoog that Mr. Mackenthun referred to indicates algal growth with a ratio of 60 to 1, this is very definitely a starvation diet; algae will grow, but the blooms will not be normal. This ratio of 10 to 1 is quite important. In the old days when domestic sewage had a ratio of nitrogen to phosphorus of 8 to 1, algae would grow and there was not much of an excess of phosphorus left in the water. Today, with a ratio of 3 parts of nitrogen to approximately 1 of phosphorus in wastes, and a ratio of approximately 10 to 1 in synthesized plant material, a great abundance of residual phosphorus is in the water.

In the Madison Lakes situation referred to, we often found the surface waters essentially stripped of nitrogen in the middle of the growing season, but 0.3 to 0.5 milligram per liter of phosphorus remained in the surface water after the nitrogen had been essentially all removed. I suspect if the municipal wastes were still reaching the lakes in the same way today they would show much higher levels of phosphorus.

How about lakes that are heavily fertilized with phosphorus? What does phosphorus mean to us. The important thing is that nitrogen in surface waters is not necessary to produce extensive algal blooms. The blue-green algae often come into the picture in late summer about the time the nitrogen is pretty well stripped from the surface waters. If there is sufficient phosphorus (and other necessary nutrients), extreme blooms of blue-green algae may occur. Therefore, we must consider both nitrogen and phosphorus in the nutrient problem.

I have searched and searched for a good definition of eutrophication. Mr. Mackenthun indicates it is based upon several parameters. This makes me feel better because here is a biologist who says more than one criterion must be used. The criteria I use are:

1. How far does light penetrate into the water? As productivity increases, algal blooms increase, so obviously the light will not penetrate so far. Shallow light penetration is therefore a major indicator.

2. In lakes that stratify, does the hypolimnion go anaerobic? If it goes anaerobic, I am sure it is a eutrophic lake. This is probably as important as any criteria and is the one I would use.

These are, in general, the major criteria.

The disappearance of rooted aquatics that Mr. Mackenthun referred to is a natural occurrence. We know we can control these growths if we can block out the light, but we generally do not build shelters over our reservoirs. The algae may do this, however, as far as the rooted aquatics are concerned. When a dense bloom of phyto-

plankton develops, they create a natural shade for the rooted aquatics, which, of course, do not survive.

Mr. Mackenthun discussed quite extensively the problems related to eutrophication in lakes; he also mentioned the problem that develops in the receiving stream when these accumulations of phytoplankton get loose and float down the receiving stream. If these algae would just keep their heads under water so they would not be concentrated by gentle breezes in coves or in the outlet river, they could be quite beneficial in many ways, But, they do accumulate in coves and they do go out the outlet and there they, of course, decompose and cause the algal nuisances to which Mackenthun referred.

There is one other aspect of this problem of the effluents from reservoirs or lakes, which is related to the nutrients themselves. In the Madison Lakes chain, the waters leaving Lake Waubesa were extremely nutritious. Rooted aquatics came into the picture in the relatively shallow river below there to such an extent that they restricted the flow of water down the river and raised the water level in the lake. The cottagers, of course, rebelled at that.

Another case is Spring Creek in Pennsylvania, a rich fishing stream. This is below a sewage treatment plant rather than an impoundment, but it illustrates the potential problem. The nutrients getting into this shallow stream have created a very extensive rooted-aquatic growth in the stream. These growths have two effects. In the daytime, of course, there is a diurnal effect that makes the DO go sky high. The water with its high oxygen concentration does not stay there, however; it moves on down the river, and when night comes fresh water that does not have the photosynthetically produced oxygen moves into the area where the rooted aquatics are, and the DO in the water flowing through the area is depressed. As you all know, it takes a little while for streams to recover, so that water with a low DO now goes downstream as a slug and produces some very serious fish kills.

There are many aspects of this problem to be considered. Before closing, I want to raise this question: How do we harness eutrophication to do us some good? My experience has been that we create these impoundments, everybody wants to use them as recreational areas and they do not want wastes discharged into them. Mr. Mackenthun has indicated we can expect to have 45 to 57 pounds of oxygen per acre per day that ought to be harnessed. We are living in a very affluent — I sometimes say, effluent — society and it is time we begin to think in terms of reserving some of these areas for industry, particularly the highly fertilized areas such as we are talking about here. We know industrial areas are going to develop and that they will probably become a nuisance to us; so why not plan to put them to work? We could encourage industries rather than cottagers with their speed boats to locate around the reservoirs that have high nutrient levels and thus assimilate considerable nutrient while reducing the potential adverse effects in other areas.

DISCUSSION FROM THE FLOOR

Mr. LeBosquet, U. S. Public Health Service: I wonder, Dr. Sawyer, if you could elaborate a little on corrective measures. I know that keeping nutrients out is a problem, but, when this has been accomplished, is it successful? In reclaiming some of these eutrophied lakes, how successful have you been in keeping the nutrients out, and how fast have the lakes come back?

Dr. Sawyer, Metcalf and Eddy: The classical example is Lake Waubesa at Madison, Wisconsin. I think Mr. Mackenthum is in a better position to discuss this than I am because he had it under surveillance after the diversion was put into operation.

Mr. Mackenthun, U. S. Public Health Service: As I recall, the Madison effluent was first diverted around the lower lakes December 1, 1958. Tests on nutrient content of the effluents of the lower lakes showed no great reduction during the first and second summers following diversion. The first winter following diversion there was a slight reduction in nitrogen, but no reduction in phosphorus. The second winter, however, there appeared to be a significant reduction in both nitrogen and phosphorus in the effluents as determined by weekly samples. Algal determinations were not made on these waters following diversion. Approximations were made, however, from the suspended solids and organic nitrogen and, as I recall, the algal population has been as high since diversion as before. There is some indication that the concentrations of nutrients are now going down.

Mr. Hester, U. S. Fish and Wildlife Service: Dr. Sawyer, you referred to the feedback, or recycling, of nutrients from the lower layer of the reservoir into the upper layer. I wonder if you would comment on whether bottom-level discharge or higher-level discharge would be more effective in increasing the concentration of these nutrients in a reservoir?

Dr. Sawyer: I would think that under summer conditions it would be better to discharge the surface waters rather than the lower waters because the lower waters ordinarily are quite a bit richer in nutrient materials. That has been my experience, anyhow.

HYDROLOGIC FACTS NEEDED FOR STUDIES OF FLOW REGULATION FOR STREAM QUALITY CONTROL

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This symposium has as one of its primary objectives a delineation of technical problems encountered in complying with Section 2b of Public Law 660, as amended, the segment of the Federal Water Pollution Control Act of 1961 having to do with streamflow regulation for purposes of water quality control. Discussion between agencies involved with water resource development will lead to mutual understanding and, we trust, to better advance planning for water quality management.

Some of the basic questions facing us today are:

How does the science and practice of hydrology enter these quality control studies? What are the specific questions that must be answered? Where are the principal deficiencies? Once we establish these basic points, we can then proceed to discuss the scope and limitations of flow regulation studies and ways for strengthening reports.

USES OF FLOW REGULATION FOR QUALITY CONTROL

Several relations between hydrologic and water quality parameters may be exploited by planned manipulation of streamflows. Under the general heading of storage and regulation, the within-reservoir relations must be considered as well as the downstream relations.

Regulation of streamflow below a reservoir might be used to control concentration by changing volume, to change time of passage for decay-type wastes, to improve reaeration and self-purification by increasing turbulence, or to prevent the alternating deposition and flush-out of taste- and odor-producing substances. These uses do not exhaust the possibilities, but represent the principal ones.

The volume-concentration relation is expressed as:

$$\text{Concentration} = \frac{\text{Pollution load}}{\text{Volume of flow}}$$

This simple dilution mechanism is applicable to control of almost all types of pollutants; however, it may not be the most effective or most efficient means in all cases.

Increasing the time of passage between a source of pollution and a downstream point of use may be more efficient than dilution for control of bacteria, radioactive wastes, and degradable organic wastes.

The generalized behavior of die-away pollutants is demonstrated by the equation:

$$C_t = C_o e^{-Kt}$$

where C_t is concentration at time t,
C_o is concentration at time o,
K is decay rate constant,
t is time.

Degradation of such pollutants through a stream reach might be enhanced by maintaining low flows and velocities. This time-of-passage relation is very important, too, within reservoirs.

When deoxygenating wastes (BOD) are involved, the oxygen deficit in the stream depends in part on the rate of reaeration (K_2), as described by Streeter and Phelps(*1*).

$$\frac{dD}{dt} = K_1L - K_2D$$

where D is dissolved oxygen deficit,
t is time,
L is residual BOD,
K_1 is the deoxygenation constant,
K_2 is the reaeration constant.

Turbulence and reaeration are related. To the degree that turbulence is a function of stream discharge and velocity, flow regulation provides a way to increase reaeration.

Fluvial sediment transport and the hydraulic variables affecting it can be important to taste and odor problems(*2*). Some taste- and odor-producing substances are readily adsorbed on sediment. Stream velocity may be manipulated in such a way as to preclude slow deposition and later batch flush-out of these sediments. Of course, sediment itself can be troublesome in a stream used for water supply.

Within reservoirs, storage tends to smooth out the peaks in concentration of inflow. Reservoirs also slow the time of travel and provide opportunity for decomposition of degradable soluble wastes. Sedimentation may provide relatively safe storage for some settleable materials while they decay. For example, uranium mill wastes deposited in Lake Mead probably will never be a threat below Hoover Dam. The surface exposure to air and sunlight afforded by reservoirs may also be conducive to water quality improvement.

THE ANALYTICAL PROBLEM

The hydrologic analysis for flow regulation studies is a four-step procedure that:

1. Describes the present annual streamflow and quality characteristics in terms of typical companion hydrographs having selected average recurrence intervals.

2. Projects the future streamflow and quality characteristics that would exist under projected water use and management in year(s) "X" without flow regulation.
3. Computes the regulated streamflow regimen needed in year(s) "X" to meet the quality objectives.
4. Schedules the flow regulation needs, including probable monthly distributions, over the life of the proposed structure.

A study of the needs of flow regulation is a forecast. It involves reservoirs *to be* built, water *to be* used, wastes *to be* discharged, and stream depletions *to be* experienced. The hydrologist has no choice but to accept this ground rule — projections into the future. History is essential to, but only a part of, projection. Statistical probability can be a very useful forecasting tool if the available data are amenable to statistical analysis. The method, therefore, dictates the kind of raw data needed.

A second ground rule is laid down in the law under which these studies are made. The responsibility assigned by the Congress is to control stream quality, not to maintain a streamflow. The two are entirely different entities. The law reads, in part, "— consideration shall be given to the inclusion of storage for regulation of streamflow for the purpose of water quality control,—." The term "regulation" was chosen advisedly. Pollution burdens imposed by nature and man on a stream are not constant. Hence, maintenance of a constant or minimum streamflow is not the most efficient answer to quality control.

Maximum regulation demands do not necessarily coincide in time with either minimum streamflows or maximum concentrations of pollutants. For example, the process of counteracting a BOD load imposed on a stream involves the oxygen concentration of receiving water, the reaction rate (deoxygenation), and reaeration factors. Each of these is temperature sensitive. Hence, the streamflow requirement is dependent, partially, on temperature. In mineral quality control the tons of mineral to be diluted may be much less at minimum flow, or maximum concentrations, than at some higher flow.

THE PRINCIPAL DEFICIENCIES

As is evident from the nature of the problem, its solution is approached through a chain of dependent sequential analytical treatments of facts and figures. The old cliche that "a chain is no stronger than its weakest link" is particularly appropriate here. Relative weaknesses exist both in the raw hydrologic data and in knowledge of how best to analyze and interpret these data. Only the four most significant deficiencies are considered in this paper.

1. Description of low-flow and quality characteristics of streams.
2. Obsolescence of data.
3. Hydrochemical dynamics of reservoirs.
4. Statistical treatment of multivariable systems.

These deficiencies are in no way peculiar to stream quality control. They are common to many other water resource functions. The concept of flow regulation for stream quality control does not generate a new set of problem areas, but rather adds impetus to the need for solving the "standard" ones.

Description of low-flow and quality characteristics of streams

Probably the most significant deficiency lies in the realm of interrelating water quality and streamflow. Stream quality and stream discharge are inseparable in these studies. For our purposes, each event in the past and future time series of events comprising stream behavior has two dimensions — quantity of flow and concurrent quality. The one objective of flow regulation for quality control is a satisfactory concentration of water-borne material; the mechanism involves manipulation of tonnages, which are the products of concurrent flow and concentration. Knowledge of streamflow characteristics is of little use unless it can be associated closely with attendant stream quality. The same is true of independent stream quality facts.

With respect to streamflow alone, information available on the low-flow characteristics is weak in both national coverage and validity. What are the problems in this area? First, real concern with low-flow characteristics of streams is relatively new in many parts of the country where water has been plentiful. Interest is accelerating but has not reached proportions necessary to meet the challenge of tomorrow's problems of water use and management. Second, there are technical problems that complicate and/or retard the effort. Low flows are extremely sensitive to the effects of geology, land use, and man's modification of the hydrologic regimen. Many measurements at specific sites are necessary. Interstation correlation and regional analyses, so useful in flood-frequency analysis, are of only limited use in low-flow studies.

Time-of-travel data and velocity profiles under low-flow conditions are needed to route pollution loads, to position oxygen sags along the stream, and to predict sludge deposition and scour. Such data are virtually non-existent nationwide.

To overcome these deficiencies will require increasing effort on the part of agencies that collect and summarize hydrologic data.

Obsolescence of data

As stated earlier, flow regulation studies are forecasts, and statistical treatments of data are useful tools. In statistical terms, the error of the estimate decreases as some function of the size of the sample drawn from a given population. In a time series, such as historic streamflow, the size of the sample may be equated to the number of years of record.

In theory then, the longer the period of record, the better is the estimate. In practice, this is not necessarily true because man is changing the statistical population from which the sample is drawn.

Regulation, diversion, and increasing consumptive use are continually changing the water quantity regimen of streams. The water quality regimen responds to changes in flow regimen and also to man's use of water to transport wastes. Data obsolescence is particularly pronounced in consideration of low flows.

This problem of obsolescence has several consequences in flow regulation studies. The hydrologist may be seriously misled by published low-flow frequency data compiled, unadjusted, from the historic record. Usually, such data require considerable reworking before they can be used with confidence. Then too, the analyst may be forced to base his predictions of streamflow and quality on a relatively short time series. Techniques are needed to improve the precision of estimates so based. Although not designed specifically for this purpose, the mathematical synthesis of streamflow sequences proposed by Thomas and Fiering(3) offers promise for both streamflow and stream quality investigations. Certainly, additional research and ingenuity in this field are needed.

Stream depletion is another very important aspect of obsolescence. To fulfill its responsibility in making recommendations to the Federal construction agencies, the Public Health Service must base its analysis of regulation needs on future depleted or modified streamflows. The flow to be augmented 20 or 50 years hence will not be the same as the flow measured now, but rather a stream flow depleted by the then existing water use and management. Hence, we need accurate projections of depletions and other modifications of stream flow. For some types of depletion projections, the Public Health Service turns to other agencies who are the responsible authorities.

In terms of national averages, consumptive loss by municipal use is about 10 percent of withdrawals; by industrial use (including cooling), about 2 percent; and by irrigation use, about 60 percent. In the current distribution of water by these major users 30 to 40 percent of the water withdrawn in the United States is lost from the supply. No stretch of the imagination is required to see that future depletions will make increasing inroads on the static available supply. National averages may be misleading, however, because both water supply and water users differ so widely from place to place.

Furthermore, streamflow may be lessened by factors other than municipal, industrial, and irrigation uses. How about stock ponds, phreatophytes, reservoir evaporation, and changes in land use? Some of these factors are particularly influential in low-flow and drought periods.

Concerted attention of several agencies to the over-all problem of projecting stream depletions will be required to strengthen this weak link in the chain of flow regulation studies.

Hydrochemical dynamics of reservoirs

If impounded water is to be used in the future to improve downstream quality, some method must be developed to predict more

accurately the quality of releases from reservoirs yet unbuilt. Both the importance of, and the deficiency in, this type of knowledge is attested by the number of papers in this symposium that relate to this facet. Consequently, I will not belabor the point other than to say that several groups are attacking this problem either from a theoretical or empirical angle.

The Division of Water Supply and Pollution Control is organizing a research project that hopefully will develop a scheme of prediction. This scheme would be based on measurements of existing environmental conditions and analytical tests that would show the potential for chemical and biological changes. Pollution from waste discharges and land drainage will be included in the study. Laboratory work has started, and sites for field studies are being solicited.

Statistics of multivariable systems

Even the simplest problem of flow regulation for quality control involves a hydrochemical system that contains several variables of quantity of water and quality of water. For example, the draw-down on a reservoir required at a given time in the future will depend on the quantity and quality of uncontrolled runoff, the quantity and quality of wastes, the quality of reservoir releases, and the streamflow depletions. Each of these variables has a probability distribution of occurrence. Suppose that one sets as a design objective the maintenance of acceptable stream quality 9 years out of 10. The problem is to interrelate the plausible combinations of the variables to compute volume of reservoir releases necessary to maintain quality at the design frequency.

The analysis would be straightforward if all of the variables were perfectly correlated. Similarly, if all of the variables were completely independent, a system analysis based on combinations of random values for each variable would be realistic. The fact is, of course, that neither extreme exists in any given drainage basin.

This problem provides a fruitful field for research and development in methodology. Particularly, it calls for experience and practical judgment in deciding those simplifying assumptions that can be tolerated while maintaining a precision of estimates commensurate with other aspects of flow regulation studies.

SUMMARY

The kinds of hydrologic data and techniques required in determining flow regulation needs are dictated by the unique nature of the analytical problem. Consequently, these requirements are rather specific and exacting.

Projections of flow regulation needed for water quality control can be improved through better raw data, increased knowledge of environmental processes, and improved methodology. In review, the major deficient areas are:

1. Description of low-flow and quality characteristics of streams.

2. Obsolescence of data.
3. Hydrochemical dynamics of reservoirs.
4. Statistical treatment of multivariable systems.

They cover a rather broad spectrum of topics. Likewise, a rather broad spectrum of effort — administrative, operational, and research — is required to overcome them.

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DISCUSSION

C. J. Velz

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Mr. Rainwater has laid the basis for a very wide discussion. In the brief time allocated I can but touch the high spots.

The synthesis of what we are after is the quantitative definition of the waste assimilation potential of each particular stream so that it can be intelligently utilized without waste or abuse. This synthesis I call the art and science of stream analysis.

Actually, the scientific tools are at hand to predict with reasonable reliability in advance of construction what can be expected in terms of stream quality under a range of streamflows, waste loads, and man-made river developments. With notable exceptions, what is generally lacking is the art of application — the rational process of thorough analysis preceding design. This has long been standard practice in many fields of engineering, yet in the field of pollution control (again with notable exceptions), designs, stream classifications, quality standards, and control procedures have been arbitrarily decided upon without benefit of rational stream analysis.

One need not be diverted by new names given to this old process such as "systems analysis," nor should one delay for the last scientific

refinement, or quibble about deficiencies in data. What is most pressingly needed is the application of the rational analysis process now.

A few comments about tools of analysis available today. Fortunately, in the United States there is a considerable body of hydrologic and climatogolical data available. True there are deficiencies and more and more manmade modifications are at play. I would not go so far as Mr. Rainwater, however, and say these records are "obsolete." Rather we must critically evaluate the data, make adjustments where called for, and exercise experienced judgment.

Hydrologic phenomena, while highly variable in time and place, are remarkably orderly, follow the laws of chance, and can be defined in statistical terms. The nature of variation can be reasonably defined from a 20- to 25-year record with sampling error well within the decision-making process of what probability to protect against or design for — the once in 5-, 10-, or 20-year occurrence. The important point is that statistical analysis provides the framework of probability of occurrence from which rational decisions as to level of utilization can be made.

Since the warm-weather low runoff season is generally critical, drought streamflow probability framework is of special importance as it provides the reference base from which the need for and the benefit of flow regulation are measured. We have found that the graphical adaptation of Gumbel's theory of extreme values is particularly useful in defining drought flow characteristics. Quite widely throughout the United States we find the distributions of drought flows are logarithmically extremal. Furthermore, indices can be derived from comprehensive basin or region studies that are useful in estimating drought severities at locations along the course of a river other than at the gaging stations.

Variations in monthly mean climatological measurements, such as air temperature, wind velocity, vapor pressure, and solar radiation, quite generally describe normal distributions from which seasonal patterns of most probable and expected confidence ranges can be readily constructed.

A segment of hydrologic data that too frequently is neglected both in collection and analysis is detailed characterization of the river channel. This is best fulfilled by channel cross-section soundings at intervals of approximately 500 feet along the course of the river by means of echo sound equipment. These provide a basis for obtaining reach by reach the occupied channel volume, surface area, effective depth, and accurate time of passage, the importance of which was so eloquently argued this morning. These are factors essential for refined computation of water quality profiles along the river course.

Incidentally, in computing water quality profiles the conventional oxygen sag equation as usually applied ignores these detailed channel factors and in our experience is inadequate to define the DO profile in all but the most elementary situations. The procedure we favor stems from Phelps' earlier work, in which deoxygenation and

reaeration are computed separately taking into account the measured channel factors reach by reach. This procedure, we believe, is essential if one is to evaluate adequately radical changes in channel induced by man-made river developments such as navigation works, dams, and flow augmentation and regulation. The computations are extensive but are greatly relieved by electronic computers. At this point, although the use of statistical methods is advocated, a word of caution. Statistical methods and modern computers are only tools — not substitutes — for thinking and experienced professional judgment. The machines do only what they are instructed. If you put in nonsense, out comes nonsense. There is presently a tendency to overwork data, particularly in multivariate analyses, with the danger of developing spurious correlations. Statistical analyses based solely on observed end results are no substitute for understanding of the fundamental mechanisms at play and identification of the controlling factors involved.

A few comments on flow regulation and the impact of multipurpose and hydropower developments: I have long been an advocate of low-flow augmentation. In studies of river basins throughout the United States, one is struck by the severity of drought flows relative to the average annual flow available and how depressing it is to gear community and industrial development to these minimal water resources.

In many instances a modest storage or multipurpose development can lift a river basin substantially above the restricting framework of natural unregulated drought flow. On the Savannah River, multipurpose developments with reregulation below the hydropower plant insures downstream flow completely above the normal and the severe drought levels.

In too many other instances, however, the potential benefits of multipurpose developments are not realized. For example, on the Chattahoochee River above Atlanta, Georgia, the multipurpose development provides storage that could easily assure flow three to four times the natural drought runoff. As initially constructed, however, no reregulator was provided to iron out diurnal pulses and weekend shutdowns and, as a result, off-peaking flow at Atlanta is no better than the natural unregulated drought runoff. I could cite a whole series of such cases.

One might ask, does hydropower plant practice have the right to inflict this waste of water resources on downstream users? Or should it be obligatory to provide reregulation below all hydropower developments? Granted, peaking practice is inherently essential in hydropower operation — but if we are to achieve the benefits of flow augmention, reregulation is also essential.

Returning to the stimulating argument of this morning, I would like to support Mr. Vanderhoof's position. I hope with all the special difficulties that have been cited you are not left with the impression that low flow augmentation is bad. Much depends upon where and how the augmented flow is added.

In detailed studies on the Miami River where the lower river from Dayton to the mouth is a continuous urban-industrial complex, we find that adding all the augmented flow from the headwaters is not the best solution. It corrects a serious oxygen depletion and a high temperature rise from steam power in the upper reach below Dayton, but it moves the residual waste loads downstream faster to create a secondary, though less critical, zone in the lower reach. This is similar to the situation Dr. Kaplovsky objects to on the Delaware. Splitting the augmentation, however, and introducing an increment also in the lower reach produces a greater overall stream improvement with less storage.

This only emphasizes the need for rigorous stream analysis. It also emphasizes the dangers of generalization and the need to consider each river basin individually.

Notwithstanding difficulties and problems, however, based upon my years of experience on rivers, I am convinced that low flow augmentation offers great opportunity for stream improvement.

In conclusion I wish to make a strong plea for rational administration of the 1961 Amendments to the Water Pollution Control Act. Section 2(b)(1) provides that in federal river development "consideration shall be given to inclusion of storage for regulation of streamflow for the purpose of water quality control, except that any such storage and water releases shall not be provided as a substitute for adequate treatment or other methods of controlling waste at the source." This was universally greeted with enthusiasm. There is growing concern, however, over the differences in opinion as to how this section is to be interpreted.

One rational view is expressed in the concept that reasonable treatment should be provided with additional benefits to be derived by augmenting low stream flow, utilizing the waste assimilation capacity of the stream. On the other hand, irrationally, there are those who feel that the highest degree of waste treatment possible should be enforced before any benefit to waste assimilation capacity can be considered from augmented stream flow. This is equivalent to saying that all community and industrial wastes must receive complete treatment and only then would consideration be given to low flow augmentation. To my thinking this will delay for years the benefits clearly intended in the Act and make difficult or impossible inclusion in current multipurpose river development of features that substantially increase waste assimilation capacity and other water-use benefits.

Also, this viewpoint would result in heavy excess expenditures for waste treatment plant construction and operating costs for degrees of treatment beyond what is "adequate" for current and reasonably foreseeable needs. With the pressures on the national economy and demands on the tax dollar, can we afford this kind of waste? I sincerely hope we shall proceed rationally and prudently. If we do not, Mr. Khrushchev may make good his threat to bury us.

DISCUSSION

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As a representative of the U. S. Weather Bureau in the Department of Commerce, it is an honor to participate with you in this inter-agency symposium on streamflow regulation for quality control. Some of you may not know that the Weather Bureau conducts a very up-to-date hydrologic service program that includes streamflow forecasting.

Mr. Rainwater, in his excellent paper, has delineated many of the technical problems that may be encountered, and has pointed out the kinds of factual hydrologic information needed for studies associated with streamflow regulation for quality control. But more than this, he has made some very profound statements that indicate a need to live more intimately with streamflow and quality control data. There is time for me to discuss only briefly a few highlights of his paper.

The role of streamflow regulation for quality control differs widely in season and location throughout the country because of many factors such as multiple water uses involved, increases and concentrations of population and industry in the watersheds, relative location upstream or downstream along the river systems, and ever-changing flow characteristics due to climatic variations and planned retention in reservoirs. It is no wonder that the obsolescence of flow data and quality information, as well as other weaknesses in factual materials, are considered by the author to be some of the principal deficiencies in regulation studies. Effective information on sampling or monitoring for quality would require almost continuous observation and daily analysis at representative points in the same manner that flow data are measured and reported automatically for immediate checking or processing into useful information for further study, planning, and operation. To us, this is called living with the river daily.

Mr. Rainwater's analysis for flow regulation by a four-step procedure is also very interesting because of his conclusion: "A study of the needs of flow regulation is a forecast . . . projections into the future. History is essential to, but only a part of, projection." This creates an enthusiastic response in the mind and heart of an old river forecaster who has been projecting for many years! Our forecasting procedures are based on published detailed streamflow records and stage-discharge rating curves furnished by the U. S. Geological Survey and the U. S. Corps of Engineers. To bring the procedures up to date and make them capable of handling ever-changing situations, we must incorporate current data and even anticipate forecasting problems and changing methods of reporting data. We must also meet changing conditions in quality control programs, such as Mr. Rainwater anticipates.

The ability to regulate streamflow for quality control or any type of control varies with the amount of reservoir inflow and storage capacity and also with the location of the impounding structures in the river system. In the Western States, regulating capacity with respect to total volume of streamflow is greater than in the middle and eastern sections of the country, because of a need to conserve the supply. The more humid climatic conditions and more abundant precipitation farther east account for greater annual streamflow volumes in the Mississippi River system and in the Gulf and Atlantic Coastal drainage areas. But there is one common denominator, which Mr. Rainwater points out, that applies to all within-reservoir relations as well as to all downstream relations. He labels this: "Volume of Flow." He mentions that the sample volume-concentration relation may be expressed as:

$$\text{Concentration} = \frac{\text{Pollution load}}{\text{Volume of flow}}$$

He stresses that although "this simple dilution mechanism is applicable to control of almost all types of pollutants . . . it may not be the most effective or most efficient means in all cases." It must be conceded, however, that no matter what the method or mechanism, flow information is a primary parameter for study purposes as well as for actual control activities whenever regulation is to be considered.

Mr. Rainwater's analysis of the deficiencies encountered in the use of hydrologic facts and figures is also of special interest. His conclusive statements are that "Knowledge of streamflow characteristics is of little use unless it can be associated closely with attendant stream quality," and "For our purposes, each event in the past and future time series of events comprising stream behavior has two dimensions — quantity of flow and concurrent quality." Then he makes a recommendation: "To overcome these deficiencies will require increasing effort on the part of agencies that collect and summarize hydrologic data."

The U. S. Weather Bureau is one of these responsible agencies. In addition to collecting, analyzing, and publishing basic data that may be used for hydrologic studies, we also furnish streamflow information and forecasts. Other types of forecasts include temperature and quantitative precipitation data.

Now, if a dynamic study program or operating activity requires that today's water quality conditions are to be correlated with today's streamflow information, the next step of planning or regulating for the improvement or maintenance of water quality for tomorrow must also be correlated with a specific, corresponding forecast of streamflow. In this program of furnishing specific hydrologic information for up-to-date, concurrent operations and studies, the U.S. Weather Bureau has made important advancements and contributions through their River Forecast Center public service programs.

The service furnished by the Weather Bureau River Forecast Center at Cincinnati has been described (*1*) and is summarized below.

Our hydrologic service program is similar to the programs conducted at 10 other centers in the United States. In the following discussion the application of streamflow forecasting as a tool in the quality management of water resources is emphasized. Examples of relatively low flow conditions are given rather than of the flood conditions that are also an important feature of the U. S. Weather Bureau's program.

Streamflow forecasting includes any of the predictable elements that make up streamflow conditions such as volume, discharge, stage, flood crests, temperature, velocity, and ice formation.

RIVER FORECASTING SERVICE DESCRIBED

The river forecasting service for the Ohio River and most of its tributaries is divided among three Weather Bureau forecasting centers; the Pittsburgh River District Office covering the Allegheny and the Monongahela Rivers and the Ohio River as far as McMechen, W. Va. (a main-stem distance of 96 miles); the River Forecast Center at Cincinnati, Ohio, covering the Ohio River with all the intervening tributaries between McMechen and Fords Ferry, Ky. (a main-stem distance of 781 miles); and the River Forecast Center at St. Louis, Mo., covering the rest of the Ohio River (a main-stem distance of 103 miles).

The service program at the Cincinnati River Forecast Center was established in September 1946 for the purpose of strengthening the river forecasting activities of the Weather Bureau in the Ohio River basin. The River Forecast Center works closely with and through eight River District Offices (Parkersburg and Huntington, W. Va.; Columbus and Cincinnati, Ohio; Louisville, Ky.; Indianapolis and Evansville, Ind.; and Nashville, Tenn.) that operate as collection and dissemination centers for their individual areas, and also provide some local river forecasting service.

COLLECTION OF DATA USED IN FORECASTING

The complex work of establishing and administering observational substations, selecting and training observers, collecting and distributing weather and river data, as needed for the hydrologic program in the Ohio River Valley, is a cooperative effort. It involves many federal, state, municipal, industrial, and private organizations. The Division and District Offices of the Corps of Engineers, the Geological Survey District Offices, and the Weather Bureau participate extensively in establishing, maintaining and financing this reporting network on which the river forecasting service is based. The main purpose is to provide current reports of precipitation and river conditions at specified times. The River District Offices of the Weather Bureau are chiefly responsible for collecting and relaying the reports to the River Forecast Center at Cincinnati. Reports from 575 stations are used to develop the forecasts for the Ohio River basin, a drainage area of 132,433 square miles; 352 stations report precipitation only, 200 stations report precipitation and river conditions, and 23 report river conditions only. Some of these are fringe stations outside the

drainage area. Many stations report once every 24 hours as of 7 a.m., but report more frequently on reaching prescribed criteria. Others report only on criteria. A very important group of 51 stations distributed over the basin report precipitation every 6 hours on a regular basis.

THE FORECASTING SERVICE AT THE RIVER FORECAST CENTER

The data received at the River Forecast Center are immediately processed through various procedures into discharge and stage forecasts. The precipitation reports include information on duration and amount of rainfall, amount of snowfall, snow depth on the ground and the water equivalent. Meteorological reports from first-order Weather Bureau stations include information on air temperatures, wind velocity, amount and types of clouds, and dew points. This information is used to estimate the volume of runoff to be expected, which is a fundamental problem in streamflow forecasting. The basic details of the procedures and techniques used to predict runoff from storm rainfall are discussed in Weather Bureau Research Paper No. 34(*2*). The unit hydrograph principle(*3*) is used for distributing the runoff and developing the forecast streamflow hydrograph for the 137 unit sub-areas that make up the total area served by the Cincinnati River Forecast Center. The river-stage reports are converted to discharge information by use of stage-discharge relationships most of which are developed and furnished by the U. S. Geological Survey. These discharge values together with reported reservoir releases are used to check the forecast hydrographs and as a basis for hydrograph adjustment. A combination of streamflow routing and unitgraph procedures produces the discharge hydrographs in successive reaches of the tributaries and main stem of the Ohio River. There are 145 points for which forecasts are made. The forecast messages are sent out immediately by TWX to the River District Offices, the U. S. Corps of Engineer Offices, the St. Louis River Forecast Center, and the Weather Bureau Central Office in Washington, D. C. Other forecast summaries and special data are sent on the inter-Weather Bureau nationwide teletype circuit called RAWARC. To accommodate other users of the reported information and river forecasts, the "Daily Ohio River Bulletin," Figure 1, is published and mailed daily, Monday through Friday. Monday's issue carries the Saturday and Sunday data to help recipients keep a continuous record, if desired.

A recent development in the forecasting service at the Cincinnati River Forecast Center is the velocity of flow forecasts furnished to the Ohio River Valley Water Sanitation Commission (ORSANCO).

USE OF STREAMFLOW FORECASTS IN QUANTITY MANAGEMENT

The varying stages and flow conditions that occur in the rivers and reservoirs of the Ohio River Valley affect the lives or property of a great many people in some way. When drouth or retention up-

U. S. DEPARTMENT OF COMMERCE - WEATHER BUREAU

719 POST OFFICE BLDG., CINCINNATI 2, OHIO

DATE: Nov. 8, 1963 (Friday)

DAILY OHIO RIVER BULLETIN

RIVERS AND STATIONS	FLOOD STAGE	STAGE TODAY	24-HR CHANGE		24-HR PCPN	SELECTED FORECASTS 9th	10th	11th	CREST FORECASTS STAGE	DATE HOUR
OHIO										
Pittsburgh	25	16.7P	-0.1		.57	Pool	Pool	Pool		
Dam No. 12	36	16.3P	-0.4		.02	P	P	P		
Dam No. 15	37	15.6P	-0.3		.02	P	P	P		
Parkersburg	36	10.8P	-0.4		T	P	P	P		
Dam No. 22	44	15.5P	-0.5		0	P	P	P		
Gallipolis Lower	50	13.2P	+0.7		T	P	P	P		
Greenup Lower	54	11.4P	-0.2		0	P	P	P		
Portsmouth	50	12.6P	-0.3		0	P	P	P		
Dam No. 33	50	15.9P	+0.3		T	P	P	P		
Cincinnati	52	26.1P	+0.2		0	P	P	P		
Markland Lower	51	12.6P	+0.3		0	P	P	P		
McAlpine Upper	28	17.0P	-0.2		-					
McAlpine Lower	55	9.5P	-0.2		0	P	P	P		
Dam No. 45	47	17.8P	+0.4		0	P	P	P		
Dam No. 46	41	19.1P	-0.3		0					
Evansville	42	8.8P	-0.4		0	P	P	P		
Mt. Vernon	35	12.5P	0.0		0					
Dam No. 49	37	19.0P	-0.3		0	P	P	P		
Dam No. 50	34	19.1P	+0.1		0	P	P	P		
Paducah	39	15.6P	-0.4		0					
Cairo	40	10.8	+1.8		0	10.3	9.4	9.9		
MISSISSIPPI										
St. Louis	30	-0.7F	-1.1		0	-0.7	-0.7	-0.8		
Memphis	34	-2.9F	-0.4		0					
Vicksburg	43	-3.6	0.0		0					
New Orleans	17	2.4F	-0.1		0					
TRIBUTARIES										
Franklin-Alleghany River	17	2.5R	+0.2		.37					
Lock No.7-Monongahela R.	37	13.7F	+2.6		.37					
McConnelsv.-Muskingum R.	11	M	M		-					
Kanawha Falls-Kanawha R.	25	3.2R	+3.0		-					
Charleston-Kanawha R.	34	-	-		.01	7.9	7.5	7.5		
Louisa-Sandy R.	45	M	M		-					
Piketon-Scioto R.	16	-0.1S	0.0		0					
Falmouth-Licking R.	28	0.6S	0.0		0					
Hamilton-Miami R.	17	0.7R	0.0		0					
Lock No. 4-Kentucky R.	31	6.8R	+0.2		0					
Bowling Green-Barren R.	28	-	-		0					
Lock No. 4-Green R.	33	6.9	0.0		0					
Lock No. 2-Green R.	23	9.9	0.0		0					
Mt. Carmel-Wabash R.	17	0.2	0.0		0	0.3	0.3	0.4		
Nashville-Cumberland R.	40	16.5P	0.0		0	17.0	17.0	17.0		
Clarksville-Cumberland R.	46	16.6P	+0.2		0	16.5	16.5	16.8		

As of 7 AM: Montgomery Dam, 1 ft. of gates open; Gallipolis Dam, 3.5 ft. of rollers up; Greenup Dam, 5 ft. of gates open; Markland Dam, 2 ft. of gates open, with 14 ft. of gates submerged; McAlpine Dam, No dam down, 3 units running. Ohio River water surface temperature: Markland Dam, 60°F.

Persistent rainfall yesterday over the upper Ohio tributaries, particularly the Kanawha and Monongahela, has increased streamflow substantially and will affect the entire Ohio River flow as the navigation dams pass the increase rapidly through their pools.

5-Day Outlook: Air temperatures will average about 6° above normal and rainfall will total 1/2 inch or more as occasional rain about the first of next week.

MEAN DAILY DISCHARGE FORECASTS in thousands of cubic feet per second:

Ohio R. Sta.	8th	9th	10th	11th	Trib. Sta.	8th	9th	10th	11th
Dam 15	6	16	23	17	Kanawha Falls	13	10	3	2
Huntington	15	24	28	23	Riverton,Ind.	1	2	2	2
Cincinnati	15	20	25	25	Charleroi,Pa.	11	18	10	
Louisville	15	15	22	26	Oakmont,Pa.	3	4	4	

Figure 1 — Typical river forecast bulletin.

stream reduces the quantity of flow to minimum ranges, hardship and damage may result. When excessive rains drench the drainage basins, the runoff may cause streams to overflow their banks, waste water resources, contaminate water supplies, endanger property, or even cause drownings and disaster. One way to lessen these extreme effects, or at least to moderate the problems that occur when streamflows are near extreme limits, is to give advance notice of their occurrence.

One of the most important uses for streamflow forecasts is in flood control management. The U. S. Corps of Engineers and others engaged in flood control in the Ohio River basin have worked out very effective manuals of operation that are put into action as soon as certain conditions of stage or discharge occur. Streamflow forecasts (some of which are made by their own organization) are part of the decisive information on which they base control measures or preparations to initiate such measures. The stage forecasts of the Cincinnati River Forecast Center provide official public information on what the streamflow conditions may be at critical points above or below the control areas. When criteria stages have been reached or may be anticipated with a high degree of certainty, the various systems of control are coordinated as needed to accomplish a desired objective as determined by the responsible authority. This action takes into account streamflow forecasts, weather forecasts, river conditions that influence downstream points, available control storage in reservoirs, probable flood damage in the reservoir areas if water levels are increased, probable damage at downstream points with various releases, and other significant factors. It is a complex problem of balancing damages and managing resources within limits of policy. The key to the final decision is what may be expected, based on forecasts for the immediate future and on studies of past records and seasonal patterns.

One of the obvious uses of streamflow forecasting as a tool in water resources management is in connection with water power production. Efficient utilization of available storage capacity depends upon accurate forecasts of inflow into the reservoirs. Where multipurpose projects are built using storage capacity for conservation of water resources, power operations, water supply, navigation, recreation, and flood control, proper and effective coordination of these operations depends upon reliable streamflow forecasts.

Another program in which forecasts of river conditions serve as an effective tool for management is in the obtaining of streamflow measurements. Receiving advance information about the possibilities of high water or crest stages on a given stream allows personnel and equipment to be dispatched in time to make valuable discharge measurements.

USE OF STREAMFLOW FORECASTS IN QUALITY MANAGEMENT

There are at least two phases of activity in the quality management program that are related to streamflow forecasting. The first

phase is when studies or plans are being made to develop an operating program. The second phase is the implementation of actual operations. These phases may be repeated frequently.

In the study or planning phase, management is watching and testing both river conditions and the forecasts, preparing operating criteria for future action. In connection with actual operation, if the river is falling and streamflow forecasts indicate a continued reduction of available dilution, management may hold back or reduce discharge of waste materials until the flow forecasts indicate an increasing quantity of dilution water will become available. Actual discharge of wastes will occur when flow information and forecasts assure adequate dilution to yield safe concentrations of the pollutants. It may be additional waste treatment will be provided. If management is concerned about concentrations of undesirable constituents that often occur in raw river water during the low flow and high temperature conditions, the forecast information will serve as a guide to when and for how long additional treatment is needed and will also help to govern the activities during the period of possible poor quality.

There are other situations that fit into this dual concept of using the streamflow forecasts subjectively while studies are made and objectively during control operations. It is well-known by the public as well as by sanitary engineers that quality conditions of the water supply change with the seasons and various other circumstances. The first period of runoff after a dry spell often brings substantial quantities of pollutants into streams. Industrial operations and associated waste discharges change according to the seasons and with fluctuations in business. Mining activities and resultant wastes vary. Climatic conditions of winter, spring, summer, and fall have characteristic effects on river flow and water temperature. Ice cover on a river may limit reaeration at times. The amount of navigation may influence quality, as may occasional accidental spills of deleterious materials. The composition of municipal sewage discharges is rather constant on a daily average basis, but the quantity and quality of the dilution water varies. The concentrations of population and industry as well as the available water supply differ along the river's course. This wide variety of circumstances that affect quality conditions in rivers suggests that during some periods certain operations in quality management may be relatively dormant, whereas during other periods expensive, active programs of sampling and treatment must be initiated to accomplish desired objectives in quality control. Sanitary engineers are well aware that throughout the year the problems of water quality in the Ohio River Valley change along with changes in flow conditions in the rivers. Streamflow forecasts, therefore, provide management with guidance and quantitative information that may be used in all phases of quality control activities.

Because the Ohio River drainage system is so vast and complex, quality- and pollution-control problems are complicated and create the need for broad control programs such as that undertaken in 1948 by ORSANCO under an eight-state compact. While considering a proposal to regulate discharge of chlorides and other pollutants into

the Ohio River and its tributaries, ORSANCO found that streamflow forecasts would be needed to accomplish their objectives in the planning phase as well as later in the operational phase. Arrangements were made with the Cincinnati River Forecast Center to furnish streamflow forecasts, Monday through Friday, in terms of mean daily discharge and average velocity of flow for a period of 3 to 4 days in advance for two tributary stations and four Ohio River stations.

At first the accuracy of the streamflow forecasts had to be established to determine whether they would be satisfactory to use as a basis for regulation and operation on a broad scale. A study as to how the forecast information could be coupled to current quality data was also made. With the recent establishment of robot-monitoring stations to appraise water quality conditions, the streamflow forecasts provided to ORSANCO have been expanded to cover 12 stations with 4-day forecasts. As the ORSANCO projects on quality control move toward operational programs, streamflow forecasts will be more significant and be given wider distribution.

The relative accuracy of the streamflow forecasts has been measured against the standard of mean daily discharges published by the Geological Survey for the same or nearby points. In Figure 2, data for the Ohio River at Gallipolis, Ohio, is compared with published data for the nearby station at Huntington, W. Va. (32 miles downstream), during low-water conditions in September 1960.

In an appraisal of the need for streamflow forecasts in quality management published in Public Works(*4*), Edward J. Cleary, Executive Director and Chief Engineer of ORSANCO, wrote "Knowledge of the availability of dilution water (streamflow) is fundamental to the practice of pollution control. But if we regard pollution-control practice as a dynamic exercise in the management of river quality, the need becomes apparent for daily information — and preferably advance forecasts — on the availability of dilution water."

CONCLUSION

Streamflow forecasting has been and will continue to be an important tool in quantity and quality management of water resources. There is need to get better acquainted with its possibilities and to extend this service. In the future, greater demands on our water resources will inevitably generate the development of a more complete program for supplying advance information of streamflow conditions.

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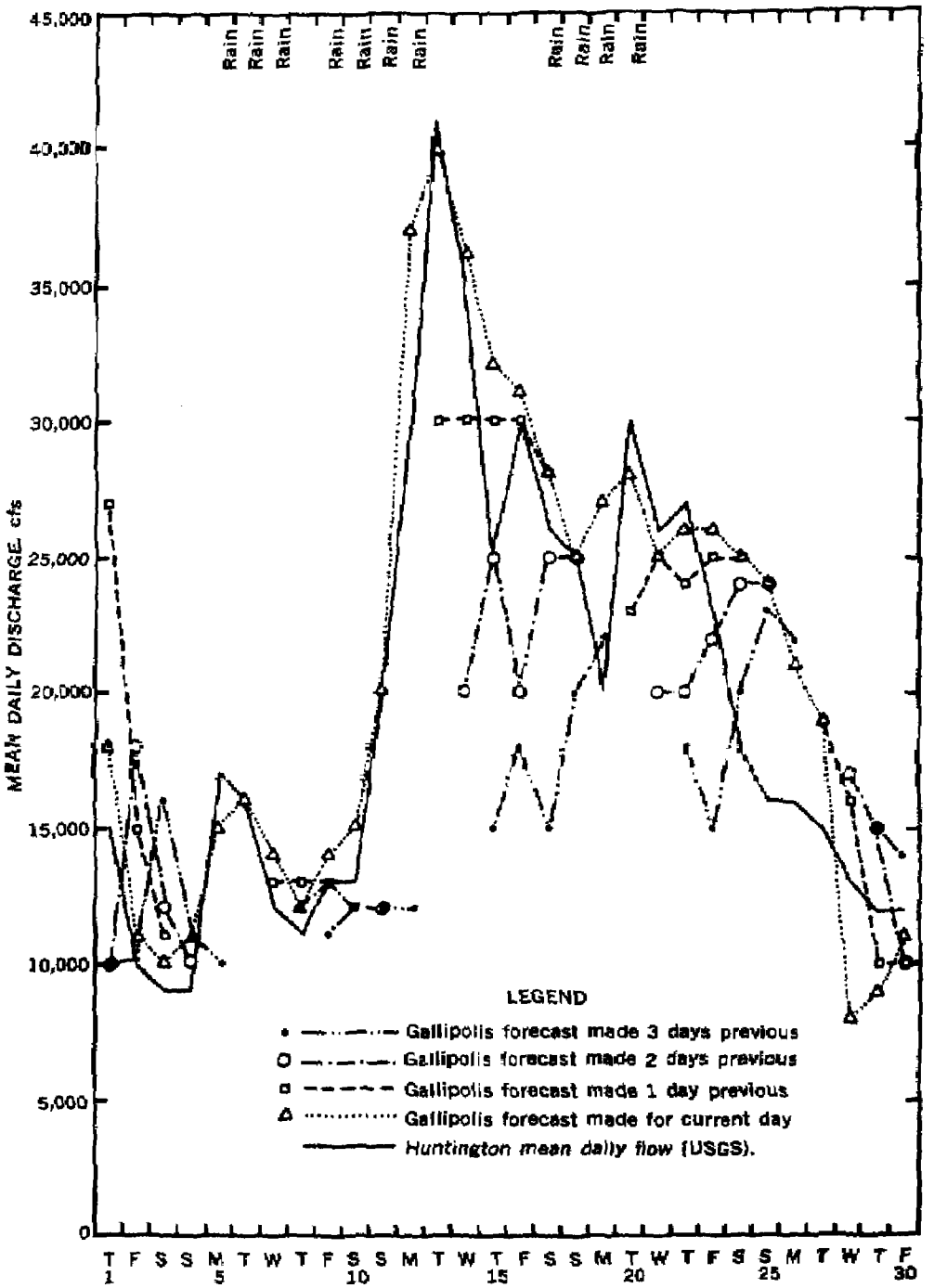

Figure 2 — U.S. Weather Bureau (Cincinnati) forecasts for Ohio River streamflow for September 1960 for Gallipolis, Ohio, lower gage, compared with published U.S.G.S. discharges at nearby Huntington, West Virginia (32 miles downstream).

DISCUSSION FROM THE FLOOR

Mr. Morriss, Atlanta Water Pollution Control: Dr. Velz, did I understand you to say that below the Buford Complex there are no reregulating facilities?

Dr. Velz, University of Michigan: That is my impression.

Mr. Morriss: On behalf of our taxpayers, I have to claim credit for a half million dollars worth of reregulation facilities in conjunction with an equal amount supplied by the Georgia Power Company. Our problem is not the lack of a facility. Perhaps it is not as big as it should be — it is only 3200 acre-feet — and its capability to meet dilution needs is not completely adequate — but this is not the real problem. The problem is getting enough water out of Buford Reservoir to operate the facility as it should be operated. This is a problem that will come more and more into play in the area of our discussion here. The question really is: Shouldn't reregulation facilities be considered in the economic justification of a peaking-power operation, particularly where there are strong pollution sources downstream including other steam-generation power facilities? And can't we make this consideration ex post facto; in other words, give us our money back and we will build a bigger one?

Dr. Velz: I tried to point out that we cannot put the hydropower people out of business. Production of peaking power, while carrying the base demand on steam plants, is the essence of the value of hydropower. But I maintain that by and large we have failed to recognize that peaking-power operations are creating some real havoc on our rivers, and I raise this issue here: Do the power people have the inherent right to do this? Or, isn't there an inherent obligation in hydro operation to equalize flow to iron out the hourly fluctuations, and more important, the shutdown of flows on weekends? There are many rivers in which for as long as 2½ to 3 days during the weekend shutdown, flow is below the once-in-10-year drought flow. Yet we invest large sums of public money, presumably in multipurpose developments, and we are no better off than we were under the natural drought condition. This is an issue I would like to see out on the table. I would hope that the Federal Power Commission might play a role in this by recognizing that in giving a license to build a dam, it should include reregulators as a basic part of the project.

Mr. Morriss: Thank you, Sir. This is my point. Don't let me give the impression that we are not satisfied with our reregulation. When this structure was built in 1957 it was to save "X" number of dollars; however, the industrial and population growth in the metropolitan area has made this a highly untenable statement today. We have to have more flow, but under the law we have to have complete treatment first. We have to get the treatment, then we have to go to Congress, and then we may get the flow. Now, this is "backwards."

Dr. Velz: You need water right now, I believe, for steam-power operation in Atlanta, don't you?

Mr. Morriss: That is generally true.

Dr. Velz: So it isn't only a matter of pollution alleviation. In the total power interest, reregulation would be a real asset and it ought to be considered as an integral part of the deal.

Mr. Morriss: That is my feeling.

Mr. Moore, U. S. Corps of Engineers: I want to comment with respect to Mr. Morriss' question. We are now designing and building reregulating structures in connection with four hydropower development projects in the Tulsa District. A part of the cost of these reregulating structures is included as a cost to power; a portion is assigned to water quality control. It is a federal expense and will be paid for by the federal government.

Mr. Wigglesworth, U. S. Department of Interior: I have some little knowledge about the operation of the Buford project. The operating schedule for Buford Reservoir includes a provision to provide a 650-cfs flow at Atlanta. The average critical-period flow at Atlanta is some 1200 cfs, so we are releasing a substantial part of the critical flow as a minimum flow release at Buford. The reason we have such a substantial minimum flow on the Savannah River is that it was planned as a navigation project. The Buford project was not planned for the purpose of providing navigation flows in the upper Chattahoochee River; it was planned primarily for flood control, power, and pollution abatement. The power operation pays a substantial part of the cost of the Buford Reservoir, and if we were not able to peak there, as we do, we would not be able to pay this cost.

THE NATURE OF THE STORAGE-YIELD RELATIONSHIP

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INTRODUCTION

The storage-yield relation is a traditional tool in water resource planning; it specifies the storage required to maintain a given flow, or conversely, the yield associated with a given reservoir size. This paper summarizes a technique for making more effective use of the historical flow sequence in developing the storage-yield relation(*1*).

The statistical consequence of the proposed analysis is more efficient utilization of the information inherent in the discharge record. The essential point of this paper is that the numerical values comprising the discharge record, and their particular permutation, identify but a single sample from the population of all possible records at the site; a different required storage can be evaluated as a function of each possible record. This study focuses on the distribution of the population of required storages, since any member of the population can be that storage required during the active economic life of the project. The selection of a design value from the population of storages must be made on the basis of certain criteria that encompass the objective function for the project.

This study treats a wide range of possible data combinations characterized by several inflow populations with different coefficients of skewness and serial correlation, by several levels of regulation, and by record lengths typical in hydrologic studies. Each combination of population, record length, and level of regulation defines a separate run; in all, 144 different runs were investigated. Without the aid of a high-speed digital computer this research could not be undertaken.

HISTORICAL SURVEY

Mass curve (or Rippl diagram) analysis was introduced in 1883(*2*). Observed flows at a proposed site are used in the mass curve analysis to determine the storage capacity required for any desired draft. For example, at 100 percent regulation (i.e., when the annual draft is a constant equal to the mean annual inflow), the associated "ultimate" storage is given as the range of the cumulative departures of the inflows from their sample mean. Graphical adaptations of this technique permit one to compute the storage required for any given level of regulation, or to evaluate the yield associated with any prescribed storage level. For 100 percent regulation, the ultimate storage is the storage that spills and goes dry only once during the active life of the structure.

H. E. Hurst(*3*), in his controversial paper in 1951, presented the

theory that gives the average or expected value of the range of cumulative departures of inflows from their sample mean. He showed that

$$E(R^*) = \sqrt{\frac{\pi}{2}}\,\sigma\,\sqrt{N} \sim 1.25\,\sigma\,\sqrt{N} \qquad \text{Eq. 1}$$

where σ is the standard deviation of annual inflows, N the length of record, and R^* the adjusted range (i.e., the departures measured from their sample mean). He examined an enormous number of natural phenomena, collecting data from tree rings, soil varves, and hydrologic records. Computations showed that the average range is proportional to the 0.72-power of the record length rather than the 0.5-power as postulated by Equation 1. He was unable to explain this apparent contradiction.

In 1951, William Feller(4) developed the variance associated with Hurst's statistic:

$$V(R^*) = \left(\frac{\pi^2}{6} - \frac{\pi}{2}\right)\sigma^2 N \sim 0.07414\,\sigma^2 N \qquad \text{Eq. 2}$$

whereupon the coefficient of variation of the range is 22 percent. Feller also found that for the asymptotic distribution of the unadjusted range, the expected value is

$$E(R) = \sqrt{\frac{8}{\pi}}\,\sigma\,\sqrt{N} \sim 1.59\,\sigma\,\sqrt{N} \qquad \text{Eq. 3}$$

and the variance is

$$V(R) = 4\,\sigma^2\left[ln\,2 - \frac{2}{\pi}\right] \sim 0.218\,\sigma^2 N \qquad \text{Eq. 4}$$

From these last results, the coefficient of variation of the unadjusted range is 29 percent. It was Feller's hypothesis that the discrepancy between Hurst's data and theory could be attributed to the serial correlation inherent in many natural processes, among them those from which Hurst derived his data. Feller never proved this assertion, and the matter is still unresolved.

Other writers (Anis and Lloyd(5) and Yevdjevich(6)) have dealt with the problem of the distribution of the range, particularly for small values of N; none have added significantly to Feller's work in that the effects of non-normal distributions, non-zero serial correlation, and regulations less than 100 percent have not been investigated. This paper builds upon Feller's results by investigating the effects of skewness and serial correlation, and by evaluating varying time periods and low levels of development.

THE HYDROLOGIC MODEL

The strategy of this analysis requires the generation of a large number of replicate sets of synthetic hydrologic data from which we impute the characteristics of the distribution of the required storage. The synthetic data are generated by a mathematical representation of the relationship between flows in successive time periods.

We postulate a linear regression model (Figure 1) of lag one; that is, the flow in any season is a linear function of the flow in the preceding season. Thus,

$$Q_{i+1} = \overline{Q}_{j+1} + \beta_j (Q_i - \overline{Q}_j) \qquad \text{Eq. 5}$$

wherein Q_{i+1} and Q_i are the discharges during the $(i+1)^{st}$ and i^{th} season, respectively, reckoned from the start of the synthesized sequence; $\overline{Q}_{j+1}$ and $\overline{Q}_j$ are the mean seasonal discharges during the $(j+1)^{st}$ and j^{th} season, respectively, within a repetitive annual cycle of seasons; and β_j is the least-squares regression coefficient for estimating the flow in the $(j+1)^{st}$ from the j^{th} season. *Season* is used here to define any convenient subdivision of a year — months, weeks, days, etc.

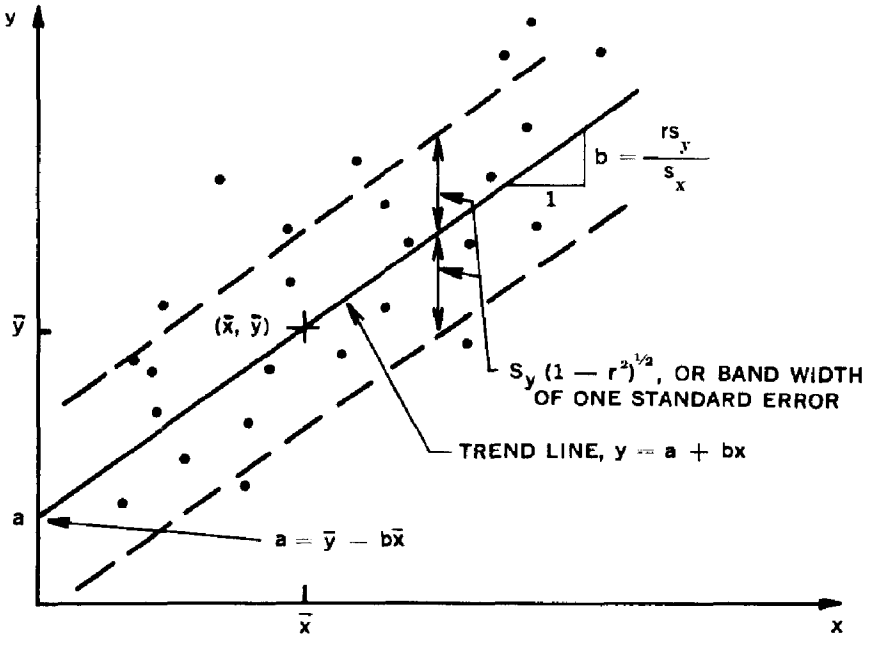

Figure 1 — General linear regression model.

The expected value of Q_{i+1}, written $E(Q_{i+1})$, is $\overline{Q}_{j+1}$, thus the first moment of the distribution of historical flows is preserved by the model in Equation 5. It can be shown, however, that the variance $V(Q_{i+1}) = \rho_j^2 \sigma_{j+1}^2$. In this formulation, σ_{j+1}^2 is the variance of discharges during the $(j+1)^{st}$ season and ρ_j is the serial correlation coefficient between flows in the j^{th} and $(j+1)^{st}$ season. The model in Equation 5 does not preserve the variance of the historical flows unless $\rho_j = \pm 1$; hence, some modification is necessary.

If t_i is a standardized random variate, the recursion relation

$$Q_{i+1} = \overline{Q}_{j+1} + \beta_j (Q_i - \overline{Q}_j) + t_i \sigma_{j+1} (1 - \rho_j^2)^{1/2} \qquad \text{Eq. 6}$$

preserves the mean and variance of historical flows. Equation 6 entails the deterministic, or trend line, estimate defined by the linear

relation of Equation 5 and a stochastic, or random, component proportional to the standard error of estimate $\sigma_{j+1}\ (1 - \rho_j^2)^{1/2}$. We can envision band widths of 1, 2,....., n $[\sigma_{j+1}\ (1 - \rho_j^2)^{1/2}]$, which contain a corresponding proportion of all the points in the bivariate distribution of Q_j and Q_{j+1}; the evaluation of these proportions depends on the distribution of seasonal flows.

If a normal distribution is postulated, Equation 6 is a sufficient algorithm, since the first two moments are preserved. In this case, the t_i are normally distributed. If the flows are characterized by the gamma distribution, three parameters must be preserved and the distribution of t_i must reflect γ_j, the skewness of the seasonal inflows.

It can be shown that, in order to preserve the skewness of the distribution of historical flows, the skewness of the random variate t_i is

$$\gamma_t = \frac{\gamma_{j+1} - \rho_j^3 \gamma_j}{(1-\rho_j^2)^{3/2}} \qquad \text{Eq. 7}$$

If t_N is a standardized normal variate, t_γ can be computed from the transform

$$t_\gamma = \frac{2}{\gamma_t}\left[1 + \frac{\gamma_t t_N}{6} - \frac{\gamma_t^2}{36}\right]^3 - \frac{2}{\gamma_t} \qquad \text{Eq. 8}$$

It is interesting to note that more skewness must be built into the gamma variate, t_γ, than exists in the original record.

If the historical record were characterized by a distribution requiring four or more parameters, the kurtosis and higher moments of the synthetic data could be preserved by further manipulation of the distribution of t_i.

The computation can be summarized as follows:

1. Analyze the historical data and compute the constants $\overline{Q}_j$, β_j, σ_j, ρ_j, γ_j for each season.
2. Specify the distribution to be maintained.
3. Synthesize a flow sequence of desired length.
4. Examine the moments of the synthesized data to ascertain that the model faithfully, but not necessarily exactly, reproduces the given moments.

The essential property of every generated sequence is that, based on all statistical tests of significance, the generated sequence cannot be distinguished from the original historical record. If the synthetic generating scheme contained in Equation 6 is valid, any sequence generated therefrom defines a sample that might be drawn from the total population of all possible records characterized by the moments of the observed sequence. Moreover, the storage required in any one synthetically generated sequence is just as likely to be the storage required during the active life of the project as that associated with any other generated sequence, including the storage

computed from the historical record. That is, the historical record defines a single storage that is but one member of the population of all possible storages. If a large number of replicate sets of synthetic data are generated, e.g. 100, the 100 resulting storages define a distribution that is an approximation to the distribution of all storages. When 100 sets are generated and analyzed, the first two moments of the distribution of required storage appear to be fairly reliable; the third and higher moments of the distribution are not well defined.

Let us summarize the analysis. From any of the 144 combinations of streamflow population, serial correlation, length of record, and degree of regulation, 100 replicate sets of synthetic flow data are generated. For each set, we compute the storage required to meet the specified draft; this value is a member of a sample of size 100 taken from the population of all possible required storages. The sample is used to deduce the distribution (i.e., the moments) of the required storage corresponding to the given combination of parameters.

COMPUTER STUDIES

We consider four streamflow distributions, four record lengths, three levels of annual serial correlation, and three degrees of regulation. Since the number of parameter combinations increases in a multiplicative fashion, 144 combinations define the sample space for this investigation. In each instance, the annual flows are assumed to be derived from a population with a mean of 1.0 and a standard deviation of 0.25; the resulting coefficient of variation, 25 percent, is typical for streams in several regions of the United States. The computer is coded to generate a variable number of replicate sets of synthetic data; we choose 100 for each combination. Thus, 14,400 sets of hydrology are generated and analyzed by the computer program within a few minutes. The parameters assigned in the computation are:

Populations

Normal
Gamma with skewness —0.5
Gamma with skewness 0.5
Gamma with skewness 1.0

Record lengths

10, 25, 50, and 100 years

Annual serial correlations

0.0, 0.1, and 0.2

Degrees of regulation

100%, 90%, and 80%

A one-season model is utilized in these runs to minimize the effects of within-year storage. The computer generates a synthetic

flow sequence of given length from which the mean annual inflow is computed. The annual draft is computed from the sample mean (i.e., mean annual inflow) whereupon the required storage is determined. The technique for evaluating the required storage is applicable to any annual draft pattern and any degree of regulation; it is a generalization of the mass-curve analysis and is called the *sequent-peak* method.

The program computes and reports the mean and standard deviation for each sample of size 100 of the required storage. These results are summarized in Tables 1 and 2 and in Figures 2, 3, 4, and 5.

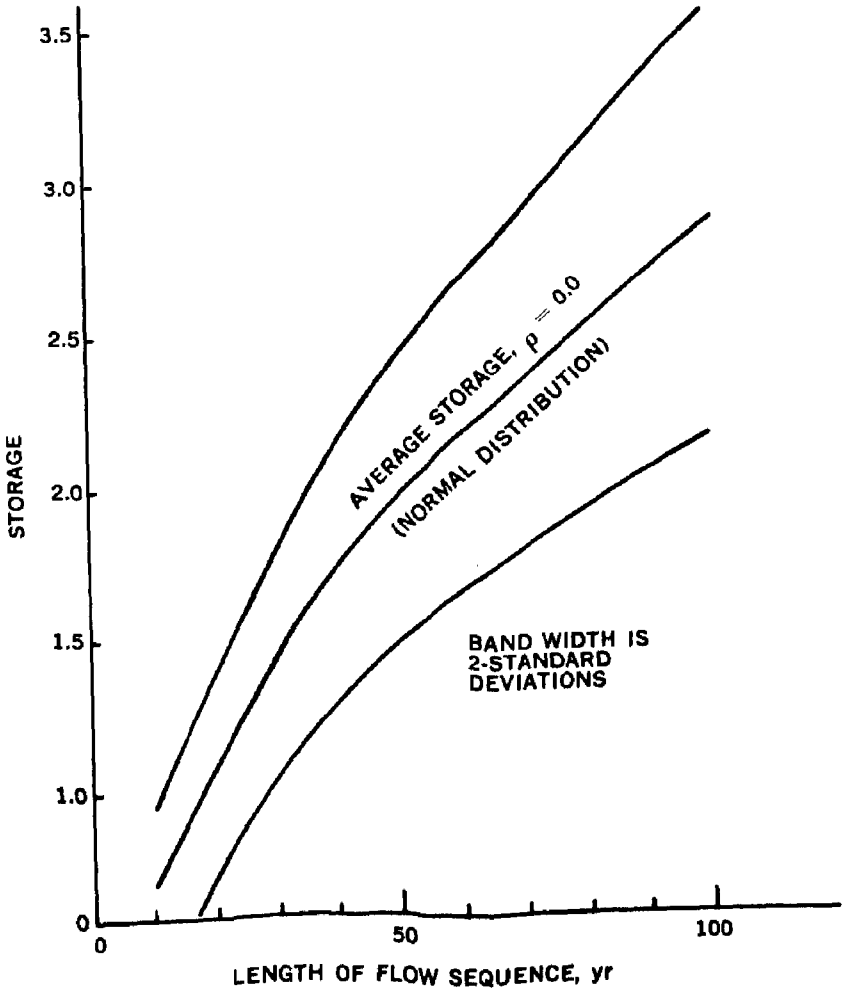

Figure 2 — Required storage vs length of record, 100% regulation.

GPO 821-740-9

TABLE 1. MEAN AND STANDARD DEVIATION OF REQUIRED STORAGE [a]

Population	ρ	N, yr	Regulation, %		
			100	90	80
Normal	0.0	10	0.7 (.23)	0.4 (.17)	0.2 (.17)
		25	1.2 (.35)	0.6 (.22)	0.4 (.18)
		50	2.0 (.47)	0.8 (.28)	0.5 (.18)
		100	2.9 (.70)	1.0 (.25)	0.6 (.19)
	0.1	10	0.7 (.24)	0.4 (.18)	0.2 (.17)
		25	1.3 (.37)	0.6 (.25)	0.4 (.20)
		50	2.1 (.54)	0.9 (.33)	0.5 (.21)
		100	3.2 (.74)	1.1 (.36)	0.6 (.22)
	0.2	10	0.7 (.29)	0.4 (.20)	0.2 (.18)
		25	1.4 (.43)	0.7 (.29)	0.4 (.21)
		50	2.2 (.53)	1.0 (.39)	0.5 (.24)
		100	3.2 (.74)	1.3 (.44)	0.7 (.24)
Gamma (γ=+0.5)	0.0	10	0.7 (.23)	0.3 (.16)	0.2 (.13)
		25	1.2 (.35)	0.5 (.20)	0.3 (.14)
		50	1.9 (.46)	0.7 (.25)	0.4 (.13)
		100	2.9 (.73)	0.9 (.23)	0.5 (.14)
	0.1	10	0.7 (.24)	0.3 (.17)	0.2 (.14)
		25	1.3 (.39)	0.6 (.23)	0.3 (.16)
		50	2.1 (.55)	0.8 (.29)	0.4 (.16)
		100	3.2 (.75)	1.0 (.32)	0.5 (.17)
	0.2	10	0.7 (.30)	0.3 (.18)	0.2 (.15)
		25	1.4 (.44)	0.6 (.26)	0.3 (.17)
		50	2.2 (.54)	0.9 (.35)	0.4 (.19)
		100	3.2 (.75)	1.2 (.40)	0.5 (.19)
Gamma (γ= −0.5)	0.0	10	0.7 (.24)	0.4 (.20)	0.2 (.17)
		25	1.2 (.36)	0.6 (.24)	0.4 (.23)
		50	2.0 (.49)	0.9 (.31)	0.6 (.24)
		100	2.9 (.68)	1.1 (.29)	0.7 (.24)
	0.1	10	0.7 (.27)	0.4 (.20)	0.2 (.17)
		25	1.3 (.37)	0.7 (.29)	0.5 (.25)
		50	2.1 (.52)	1.0 (.37)	0.6 (.27)
		100	3.2 (.74)	1.2 (.41)	0.8 (.27)
	0.2	10	0.7 (.29)	0.4 (.27)	0.2 (.22)
		25	1.4 (.44)	0.7 (.32)	0.4 (.26)
		50	2.2 (.56)	1.0 (.43)	0.7 (.29)
		100	3.2 (.72)	1.4 (.48)	0.8 (.29)
Gamma (γ=+1.0)	0.0	10	0.7 (.24)	0.3 (.17)	0.1 (.10)
		25	1.2 (.36)	0.5 (.19)	0.2 (.10)
		50	1.9 (.46)	0.6 (.22)	0.3 (.09)
		100	2.9 (.78)	0.8 (.20)	0.3 (.10)
	0.1	10	0.7 (.26)	0.3 (.18)	0.1 (.11)
		25	1.3 (.41)	0.5 (.22)	0.2 (.12)
		50	2.1 (.58)	0.7 (.26)	0.3 (.11)
		100	3.2 (.78)	0.9 (.30)	0.4 (.13)
	0.2	10	0.7 (.32)	0.3 (.19)	0.1 (.14)
		25	1.5 (.47)	0.5 (.24)	0.2 (.14)
		50	2.2 (.57)	0.8 (.31)	0.3 (.16)
		100	3.3 (.78)	1.0 (.37)	0.4 (.15)

[a] Entries in the body of the table are the average storages, based on a sample of 100; the associated standard deviation is in parenthesis.

TABLE 2. COMPARISON OF THEORETICAL AND MEASURED STORAGE [a]

N, yr	E(storage) $=1.25\sigma\sqrt{N}$	Range of calculated average storage	Range of calculated C_v, %
10	0.99	0.7 — 0.7	33 — 36
25	1.56	1.2 — 1.5	28 — 32
50	2.22	1.9 — 2.2	23 — 27
100	3.13	2.9 — 3.3	23 — 27

[a] 100% regulation; 100 replicate sets.

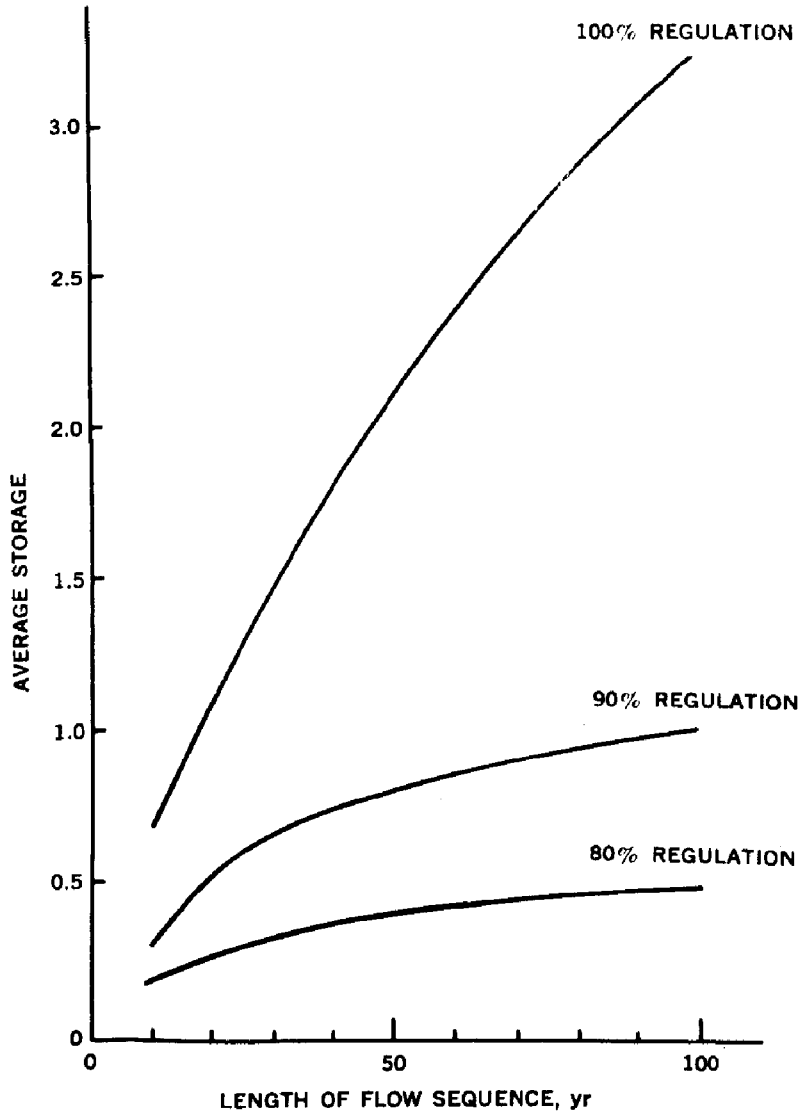

Figure 3 — Average required storage vs length of record, $\rho = 0.1$, gamma distribution ($\gamma = 0.5$).

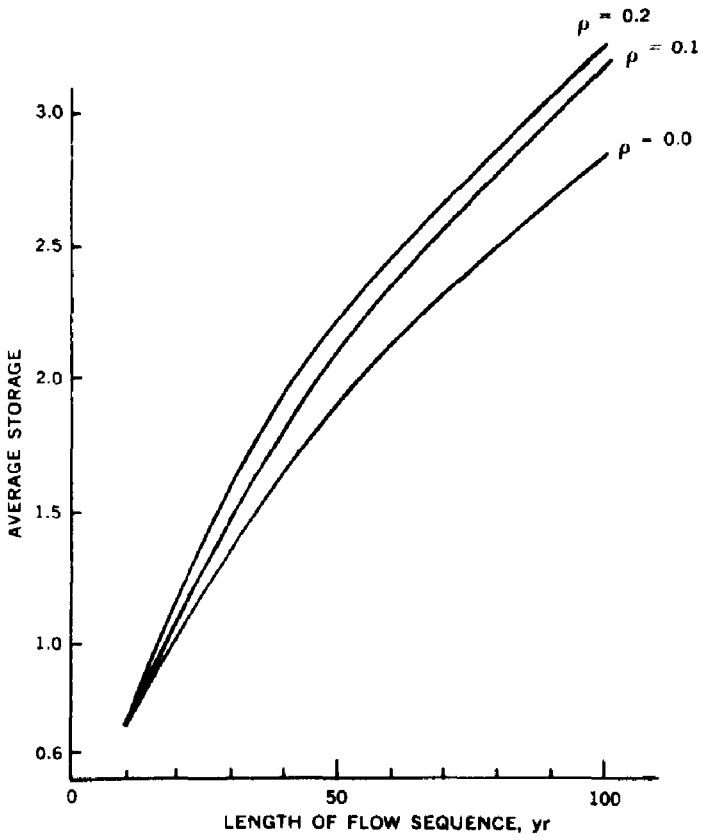

Figure 4 — Average required storage vs length of record, gamma distribution ($\gamma = 1.0$), 100% regulation.

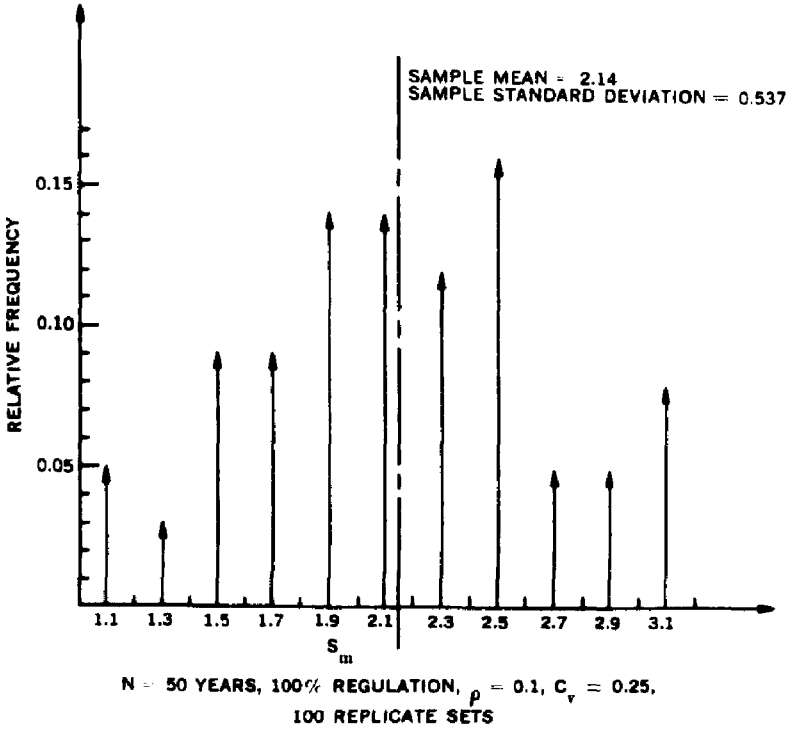

Figure 5 — Distribution of required storage.

CONCLUSIONS

The principal results can be stated as follows:

1. The work of Hurst and Feller is verified. Skewness of the data is far less important than the standard deviation in determining the mean range. Agreement between theoretical and measured values improves as N increases.

2. The effects of low values of the annual serial correlation on the range are pronounced; presumably more substantial variations (i.e., larger storages) would arise for higher values of ρ.

3. The effects of small reductions in the yield are very marked.

4. It is manifest that use of the ultimate storage, or any other storage computed from a mass-curve analysis of the historic flow sequence, is fraught with risk because of the high degree of instability inherent in the statistic. The use of synthetic sequences to define the sampling distribution of the range is proposed as an alternative design technique.

FUTURE WORK

Employing the statistical consequences of the distribution of the range to forge a union between engineering and economics, which is tantamount to writing an unambiguous objective function, we are currently studying techniques to further the scope of rational decision making in engineering design. Work on the theory of the distribution of the range is an essential link in the process of providing rational designs to satisfy man's needs.

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DISCUSSION

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Dr. Fiering has done an excellent job of honoring Rippl and castigating his diagram. This paper points up very clearly the weakness of the practice of basing reservoir designs on studies that consider only the single historic trace of a streamflow record. The use of the statistical methods outlined by Dr. Fiering in this and in other papers can give the designer a much clearer insight into how the reservoir he is designing is likely to function in meeting the demands made upon it.

These studies emphasize that reservoir yield needs to be looked upon as a statistical variate. This fact is probably appreciated intuitively by most engineers and hydrologists engaged in water resource design, but the implications of the fact have not been very deeply explored. Neither was there any good information on the variance of our estimates of storage requirements for a given yield prior to this paper. I doubt that many would have believed that these estimates would have a coefficient of variation of more than 20 percent, as Dr. Fiering's studies show. Although the variance of these estimates decreases as the percentage of the mean annual flow developed decreases, the coefficient of variation is even greater. Some of the figures in Table 1 indicate coefficients of variation greater than one.

As Dr. Fiering points out in his final paragraph, the obvious lesson from this is that the common design practice of selecting a target demand for some use such as water supply and determining the storage required to meet the demand leaves something to be desired. Nevertheless, it is necessary to set some storage for design purposes. Since there is some finite probability that this fixed storage will fail to meet the target demand, we need to be able to estimate the losses such failure will entail. This procedure is not uncommon in the case of storage for power generation or for irrigation, but as yet it has not been used in the case of storage for municipal or industrial water supply. We need to develop the background information necessary to make such estimates realistically.

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DISCUSSION

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One of the important implications of Dr. Fiering's paper is that the natural streamflow that we can expect to have in the future will at times reach new minima that will be lower than any experienced historically. Obviously the reason for this is that precipitation in some years or seasons will be less at times than for similar periods experienced in the past. The methods used by Dr. Fiering(*1*) can be applied directly to precipitation data to give us an idea of the potential severity of future precipitation droughts over any period of time, in a stochastic sense.

The low flow portion of the streamflow distribution can be considered the result of the interaction of (1) a stochastic precipitation element, having a low serial correlation coefficient, and (2) a deterministic ground-water element, dependent upon the characteristics of all the aquifers in the stream basin. Any stream basin can be represented as an aquifer system, and the ground-water outflow that sustains the perennial streams can be predicted from the time-dependent boundary conditions imposed by precipitation, infiltration capacities, direct runoff, and man's activities(*2*).

"Streamflow regulation for quality control," the title of this Symposium, is needed principally during the times when natural streamflow is entirely from ground-water sources. Therefore the problem at hand is essentially a ground-water problem, not a surface-water problem and should be called "base-flow augmentation" to keep our thinking clear. Heretofore the approach to regulation has been from the surface-water point of view alone. In many stream basins, however, manipulation of ground-water storage in extensive aquifers or systems of aquifers can provide a significant degree of regulation for quality control and other purposes. This method of streamflow regulation can be called "internal base-flow augmentation," in contrast to the "external base-flow augmentation" achieved by the use of surface reservoir storage.

Now, two of the four symposium objectives, quoted from our program, are:

1. Review available knowledge on the effects of streamflow regulation on water quality.
2. Explore research needs in the field of streamflow regulation for quality control.

In regard to the first of these two objectives, it should be emphasized that we already have a vast store of knowledge of theoretical and field data on ground water that relates to base-flow augmenta-

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tion; the important feature that is lacking is a general understanding of what is already in the literature and in the files of public agencies. Thus, the second objective can be translated to:

2a. Explore methods of dissemination of knowledge of the importance of *ground water* to streamflow regulation for quality control.

There is more usable ground water in storage than exists in all the surface reservoirs ever built. Nearly every large stream basis has at least one important aquifer, if not a whole system of interrelated aquifers. Every stream on the Atlantic coast has not *one,* but *two* major aquifer systems (one for the proponents of upstream control, and one for the proponents of downstream control). These aquifer systems are, respectively, (1) the belt of limestone forming the Great Valley in Pennsylvania, Maryland, and Virginia, and extending as far south as Georgia and Alabama; and (2) the coastal plain sediments that extend all the way to Florida and the Gulf Coast as well. In general, current development of the ground water alone is resulting in stream depletion rather than augmentation, but if wells are located properly with respect to the streams and if recharge facilities are constructed, ground-water utilization and base-flow augmentation can be achieved simultaneously.

Current investigations of quality control, using the Lehigh River in Pennsylvania as an example, lead to the conclusion that groundwater storage in the limestone belt of the Lehigh Valley (an extension of the Great Valley) can be manipulated to increase base flow, decrease stream temperature, and neutralize acid mine drainage more effectively than any surface reservoir plan now under consideration.

A few figures will illustrate. The historical minimum flow of the lower Lehigh River near Allentown has been less than 700 cfs and can be expected to be much lower in the future, as has been implied earlier. River temperatures currently go to more than 75°F and can be expected to go even higher in the future. Surface reservoir sites are too far upstream to be effective in lowering stream temperatures in the lower Lehigh River. Installation of a system of injection (from surplus winter flow) and production wells in the Lehigh Valley, however, can furnish 416 cfs of water at a temperature of about 54°F in the immediate area during the low-flow summer season when base-flow augmentation is needed most.

A similar solution is possible in the Potomac and Susquehanna Rivers and in fact in every stream basin in which the limestone aquifer is present. Other aquifers can be utilized similarly, although artificial recharge may be more difficult and hence more costly. Nevertheless, large-scale aquifer management schemes may be more economical than surface reservoirs in many areas.

Now back to the generalities. Some of you may conclude that I came up here to present a concept of multipurpose water resource design based on aquifer storage manipulation, rather than on surface reservoir regulation. Well, this is in fact my aim. Current concepts

of multipurpose use of surface reservoirs have developed principally from the need to add new functions that give additional economic benefits, real or otherwise, to projects that were not justifiable for the primary function alone. The same logic can be applied to the planning of water resource control systems based primarily on aquifer storage manipulation. Floodplain clearing to provide additional natural or artificial recharge facilities has the additional benefits of flood stage and damage reduction, open space for recreational and aesthetic uses, or space for waste treatment facilities. Replacement of fixed channel obstructions with pump diversions or flexible dams can provide flood stage and damage reduction benefits as well as channel and watercourse aquifer storage manipulation. Well fields can be constructed in parks or along "green strips" and boulevards, and water can be distributed in landscaped open channels for some injection or water supply purposes. Fountains can provide aesthetic benefits as well as water aeration, public benefits that were perhaps first provided on a large scale by the ancient Romans. Many other examples of the multipurpose benefits of the extensive use of ground water can be cited, but only one more will be given, in order to return to specific discussion of Dr. Fiering's paper.

It is apparent from Dr. Fiering's Figure 3 that the average storage required increases very rapidly in order to achieve increasingly greater degrees of streamflow regulation above 80 percent control of the total runoff. This means that tremendous capital investments must be made if maximum utilization of basin water yield is to be achieved by the construction of surface reservoirs alone. In view of the uncertainty in the accuracy of projections of future demand for stream regulation, such large capital expenditures may not be economically justifiable. However, ground-water developments can be used to provide water for various purposes by well-by-well or field-by-field construction at much less risk of capital (hence with greatly reduced interest payments). Floodplain zoning, flood warning, and channel and floodplain rehabilitation can usually provide all the benefits allocated to reservoir detention, frequently at lower cost.

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DISCUSSION FROM THE FLOOR

Dr. Yevdjevich, Colorado State University: There are three groups around the world actively studying the storage-yield problem.

One is the Harvard group of which Dr. Fiering is a part, the second is the Australian group with Statistician Professor Moran and Hydrologist Alexander, and the third is the Moscow group with Professor Kritskiy and Academician Menkel. Each of the three has a different approach to the storage problem.

The Harvard approach is generally called the "synthethic hydrology method." Another approach, called the "probability method," uses stochastic processes in describing hydrologic sequences.

Dr. Fiering noted the work on the expected value of the range of cumulative departures of streamflow from the sample mean by Hurst in Great Britain and by Feller in this country. It should be pointed out that they were concerned with the asymptotic distribution of the range of storage needed, i.e., with very large n. A substantial contribution in this field was made by Annis when he computed the theoretical moments of the range of the cumulative departure from the mean (or the necessary storage) for normal independent variables. Dr. Fiering might be interested in comparing his results with those derived by Annis. On general inspection of presented data, it seems to me that Annis' values are higher, and that there might be some differences in definition of the mean range.

The Australian group has been working very actively the last couple of years to obtain a theoretical solution for the range of the departure of independent flows having gamma distribution when the mean annual flows are asymetrically distributed, or to find the probability that a given amount of storage is required to regulate flows over periods of several years.

These two approaches, one using computer simulation that is now well advanced by the Harvard group, and the other that is purely theoretical, are a good combination.

Professor Feller has indicated that it is practically impossible to compute the exact distribution of the range of required storage even for 3, 4, or 5 years. We have succeeded in the last few years in developing expressions for exact distribution up to $n = 4$. It would be a good contribution to the solution of storage problems if the exact distributions of the range could be developed for $n = 5$ to $n = 10$.

In Fiering's approach, the first serial correlation coefficient is used for the correlation of successive seasons or periods. It is known that the St. Lawrence River, for example, has a carryover of approximately 8 to 10 years, so that a wet year affects flows during the next 8 to 10 years. It might be useful to extend the correlation approach to rivers that have long carryover periods, or for which the first order or the second order linear autoregressive schemes may be applied. Dr. Fiering's statement about the average values of first serial correlation coefficients is correct. In a recent study that I did with 446 river gaging stations in the Western United States and Canada, I found that the average first serial correlation coefficient

was 0.20; this might now be taken as an expected value for river gaging stations and annual river flows.

By using these new techniques described by Dr. Fiering, we may soon be able to describe river flows by stochastic hydrologic processes. These hydrologic processes have a structural part (seasonal fluctuations that are cyclic) and a random part, while water carryover from month to month and year to year may be considered by a moving average model.

It should also be possible to describe water quality by similar mathematical processes, so that in the future it can be described in much the same way as we are now attempting to describe the flow sequence.

Dr. Fiering, Harvard University: I would like to comment on one of Dr. Yevdjevich's points. The gentlemen from Russia have requested permission to come to Harvard next year; I am going to Australia in the year following. So we hope to get a fairly comprehensive look at all the attacks on this matter.

One other point is that in instances with long carryovers, such as the St. Lawrence River, you don't really have much of a design problem simply because the flows are, by definition, so nearly uniform that extending autoregressive schemes to such long lags is, at least from a design point of view, not a terribly useful practice.

Mr. Deininger, Northwestern University: Dr. Fiering, you are synthesizing these streamflows from equation 6. Since equation 6 has a random term at the end, when you start synthesizing over a number of years you are bound to get negative flows. What do you do in this instance?

Dr. Fiering: You are quite right. In the actual simulation runs that we studied in detail we did get negative flows. Let me answer the question first by making the simple assumption that all the data might be log transforms: then the negative values will cause no trouble. In the more general case in which there is no log transform, we made a study of exactly how much error is involved in truncating the distribution at zero and throwing away all the negative values. It turned out to be less than one-tenth of one percent, so that for the particular values of mean and standard deviation that we encountered this was not a damaging practice. But you are quite right, this is a conceptual difficulty with the model, particularly since one must admit that the normal distribution goes to infinity at both ends and can generate negative results.

Mr. Deininger: Well, if you truncate these low flows, you could truncate some of the high flows, too.

Dr. Fiering: We tried that.

Mr. Deininger: The question is, how accurate is this means of forecasting? I think you are really back to the old technique of shuffling cards.

Dr. Fiering: We tried that, too. But when you shuffle cards. you are constrained to getting the same numbers again and again and you can never get anything lower than an ace or higher than a king. The definitive answer for the very difficult problem of how to reproduce, or synthesize, possible sequences from any distribution that has extremes higher or lower than the recorded values has never been found. I am merely suggesting this as a possibility, and an empirical study of the errors introduced by truncation indicates that our errors are extremely small. We wish we had the answer to the general case.

OBJECTIVES AND CRITERIA FOR WATER POLLUTION CONTROL

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Because water is a universal solvent, *in situ* it always contains impurities. An impurity is a pollutant when it becomes objectionable or in any other way interferes with man's use of water. Pollutants may be physical, chemical, or biological; and they may stem from manmade or natural sources. The Federal Water Pollution Control Program is directed to the elimination of pollution and the maintenance of surface and ground water in an unpolluted condition.

For the discussion that follows, a distinction is made between water quality objectives and water quality criteria. Water quality objectives are goals that take the form of statements of intent to protect water uses and preserve the enjoyment of clean water. Contrary to thinking in technical circles, the objectives of the Federal program are established by the Congress in response to the desires of the voting public. Some of the objectives are expressed as public wants and transcend economic analysis or professional preference.

The Federal Water Pollution Control Act contains the objectives of the Federal program, and it is clear that instream as well as withdrawal uses are to be protected. Instream uses include recreation, propagation of fish and wildlife, and preservation of the natural appeal of the stream. Benefits resulting from instream uses are sometimes intangible from the dollar-value standpoint, but they are nonetheless legitimate objectives with high priority in a water quality management program. It is not uncommon that quality objectives established to protect instream uses will be higher than those required to protect withdrawal uses. For instance, the bacterial quality required of water for swimming is higher than that for a raw drinking water supply.

Withdrawal uses include domestic supply, industrial processing cooling, irrigation, and all other uses for which water is taken from the stream. Withdrawal uses generally have an associated return flow with altered quality characteristics.

Water quality objectives must be reduced to an operational program; and, for that purpose, criteria are established. At times criteria and objectives are synonymous but more frequently a criterion can be measured while an objective represents a general condition. A criterion should provide one connecting link between water uses and the control of pollution. It should be operational in the sense that a change in the criterion will produce a predictable change in opportunity or cost of water use.

Unlike objectives, water quality criteria are established by water pollution control administrators and their technically trained staffs.

The profession must be constantly aware of two charges. First, quality criteria must reflect the intent of water quality objectives; and second, a cost-benefit ratio is imputed when a water quality criterion is established(*1*).

Water quality criteria are commonly selected through one of three processes: edict, judgment, or (not so commonly) systems analysis. Edicts follow clearly expressed public wants stemming from widespread desires or fears. Fish kills are unacceptable; therefore, materials toxic to fish are banned without hesitancy. Propagation of fish and a healthy fish environment are expressed as public wants, and desirable levels of beneficial substances as well as tolerable limits for potentially harmful substances are established. Unfavorable community reaction to visual evidence of human contamination results in edicts prohibiting floating refuse or recognizable objects of human origin. Fear of death or disease is an over-riding motivation that takes the form of highly restrictive criteria that limit concentrations of toxic substances or other materials suspected of being a threat to public health. Oil slicks, floating scums, and color- or odor-producing compounds are usually controlled by edict, although the same results might be indicated by economic analysis.

Judgment is by far the most common mechanism in current use for establishing water quality criteria. In arriving at a particular criterion, many things are considered. First of all, the water uses that might be affected are identified and then the effect on each use is examined. A search is made for existing information, and studies are made to determine the threshold concentration at which the contamination interferes with the water use under consideration. The investigation is then extended to determine how frequently interference with the use will be tolerated and the nature of damages that will result as the period of substandard conditions is lengthened.

With these factors in mind, the examination turns to the possibilities for control or treatment. Often the criteria are established from a judgment of what can reasonably be expected in the way of control. For instance, it is known that uranium in drinking water is harmful to humans in any concentration. Therefore, water pollution control agencies attempt to keep uranium in drinking water supplies at the lowest practicable level. The extensive investigations of the Public Health Service undertaken as an enforcement action at the request of, and in cooperation with, the seven States of the Colorado River Basin revealed that proper control measures at uranium milling plants would keep the radioactivity from radium-226 in the Colorado River and its tributaries below 1 micromicrocurie per liter. Even though the previously accepted level was 3 micromicrocuries per liter, the seven States, the Atomic Energy Commission, and the Public Health Service agreed to the limit of 1 micromicrocurie per liter because in their judgment that level could be obtained without undue penalty to the uranium milling industry.

Another example is that of pathogenic organisms. Without arguing the merits of the relationship, if one accepts the philosophy that

indicator organisms are a parametric measure of the density of pathogenic organisms, the risk to public health is reduced as the density of coliform organisms is decreased. Water pollution authorities attempt to maintain a low coliform density at bathing beaches. A density of 1000 per 100 milliliters is commonly accepted because judgment has demonstrated that this level can be met and that the public health hazard is not too great at that level. However, few health authorities would fail to require a higher quality and thus secure greater protection if it were practical and possible to do so. In effect, the quality criterion is established from a judgment of levels that can be obtained through reasonable control measures.

Summarizing, the judgment process includes the effect of a contaminant on water use, the frequency of occurrence of substandard conditions that will be tolerated, and the length or duration of any one substandard period that can be tolerated without severe penalty. This knowledge is balanced against a consideration of the effectiveness and cost of practical control measures. Thus, a criterion for chlorides might be expressed as a concentration no greater than 100 milligrams per liter, not to be permitted for a period longer than 7 consecutive days, with an expected occurrence interval of no less than once in 10 years. The prudent water pollution control authority would assure himself that the criterion was reasonable and could be met without excessive cost before he would attempt to put it into effect.

It was stated earlier that a cost-benefit ratio is imputed when a water quality criterion is established. Thomas(*1*) illustrated this important fact in an analogy using an "Animal Farm." In that illustration, the farmer's daughter solved her father's dilemma — to treat or not to treat — by deriving the equation:

$$X_c = \frac{V}{KBNU}$$

Where:

X_c is the critical concentration (quality criterion).

V is the cost of treatment.

K is an infectivity parameter.

B is the discounting function used to bring a series of future benefits to a present value.

N is the number of animals.

U is the profit per animal.

In the right hand member of the equation, the numerator is the cost and the denominator is the benefit. The equation is general and applies to a wide range of water quality decisions.

When an administrator uses judgment to establish a water quality criterion, he intuitively balances the reduction in damages against the cost of preventing damages. Systems analysis provides a methodology for quantitating the decision-making process. By skillful analysis, the administrator can arrive at the optimum set of criteria for increasing regional income gains, and he can demonstrate the

penalty of choosing something less than optimum to satisfy another community objective.

Before a general procedure is described for a systems approach to the selection of water quality criteria, some general comments are in order. First, the technique for analysis need not be more refined than the data going into the analysis; but, conversely, an outline and general formulation of the systems calculations will show the type of data needed, and, therefore, the kind of studies required. This point is of special importance to the State and Federal agencies entrusted with public funds to develop effective comprehensive water pollution control programs. A large part of that effort should go into studies to obtain the operational data needed for systems analysis.

Another consideration is that the systems approach will fall into disrepute (as well it should) if instream uses and intangible benefits are ignored. Because these uses and benefits are difficult to measure, there may be a tendency for the analyst to pay them lip service and base his calculations and final conclusion on the easier-to-measure withdrawal uses and other tangible benefits. One way to avoid this is to accept quality standards that will protect the propagation of fish and wildlife and other instream uses as constraints on the system. Another way is to expend more energy in water quality studies to arrive at a good means of ascribing "shadow costs" or in some other way of measuring the utility of intangible benefits.

One final note — the external economies and diseconomies of changes in water quality are diffused and ill-defined. Effects on a specific manufacturing process or a municipal water supply are often apparent; but effects on, say, hot water heaters in tens of thousands of homes may go virtually unnoticed. The effect on any individual home owner might be small, but the multiplication factor is very large. Furthermore, water quality changes affect the community of water users as a whole. Because of the community nature of the market, marketplace concepts — specifically the willingness to pay — cannot be relied on as a method for establishing relative values.

The foregoing comments might lead to the conclusion that the problem is so ill-defined and so full of imponderables that experience and skilled judgment will never be replaced by systems analysis. This is true; skillful analysis can only complement experience and judgment. On the other hand, systems analysis is the only means for quantitatively forecasting the changes in regional income gains that will be brought about by changes in the selection of water quality criteria.

The selection of a water quality criterion through systems analysis is a joint economics-engineering venture. The pattern is the same countrywide, but the specifics can only be supplied with reference to place, time, and season in a particular river basin. The steps are:

1. Determine potential water uses.
2. Construct a use-concentration spectrum.

3. Construct a net benefit - concentration chart.
4. Determine the marginal loss function.
5. Construct a cost of quality improvement-concentration chart.
6. Determine the marginal cost of quality improvement.
7. Determine concentration where marginal loss and marginal cost are equal, i.e., indicated quality criterion.
8. Compare indicated criterion with constraint level and select the one representing the better quality of water.

The determination of potential water uses is made after an evaluation of resources and other economic factors. The economic study required to determine the potential for present and future water uses is beyond the scope of this paper.

The use-concentration spectrum may be shown in tabular form, but it is often convenient to show it on semilogarithmic graph paper. Concentration is marked off so that it increases from left to right. Each water use that is influenced by the contaminant is shown above the concentration where the use first becomes practical. Thus, all uses to the right of any point on the spectrum can be served by the quality at that point.

The net benefit - concentration chart is constructed by moving from right to left on the use-concentration spectrum and plotting the cumulative net income increase above each use. The technique of determining gains in net benefits is beyond the scope of this paper, but a general discussion may be helpful.

One consideration is the scarcity of suitable quality water. For instance, as an extreme example, consider an area with underdeveloped resources in a good economic location. Water is plentiful but so highly saline that economic development is stymied. In this case, the analyst is justified in adding total net benefits after adjustment for opportunity shifts as he considers each new use moving from right to left on the use-concentration spectrum. In the more common situation where alternative sources of good water are available, he may take credit only for increments of net benefits added by increased opportunity for instream uses and for savings that will result from using the improved water rather than water from an alternate source.

The cumulative net benefits at the left of the net benefit - concentration chart show the benefits that will accrue as water quality is made very good with respect to the contaminant under consideration. The difference between the maximum level of benefits and the level of benefits at increasing concentrations represents a penalty or loss that the community suffers as a result of poor quality water. On this basis an overall loss function can be derived. The difference between the cumulative net benefits at any concentration and the total benefits at the left of the chart is plotted at each concentration. This will result in a curve showing small losses for good quality water and increasing losses as the quality of water deteriorates.

The marginal loss function may be defined as the first derivative of the net benefit curve with a change of sign. A generalized equation can be fitted to the loss function and its first derivative plotted, or the change in loss, $\frac{\Delta \text{ Loss}}{\Delta \text{ Concentration}}$, can be picked off the loss curve at a number of concentrations and plotted above the concentration to give the locus of a curve.

The cost of quality improvement - concentration curve is based on engineering estimates of the effectiveness and cost of control measures needed to bring water from the quality in the stream to a target quality. The analysis is not concerned with the one control measure that will provide the highest quality of water. Rather it is concerned with the optimum combination of feasible control measures that will produce the target quality with minimum total cost. Cost-concentration curves require investigation and analysis with respect to a particular year, season, and place in a specific river system.

Within the scope of the Federal Water Pollution Control program, there are three basic measures for water pollution control: in-plant modifications to keep waste out of water or to regulate the flow of waste waters, collection and treatment of waste waters to remove pollutants, and the regulation of stream flow for quality control. To this list must be added a fourth possibility for cost studies, treatment of water taken from the stream to make it suitable for a specific use. Each of these has associated initial, operational, maintenance, and replacement costs. The optimum arrangement for a given quality objective is the combination that will give the smallest sum of the present values of all costs.

The Federal Water Pollution Control Act places a constraint on the use of flow regulation. The Act stipulates that storage in Federal reservoirs for streamflow regulation for quality control will not be provided as a substitute for adequate treatment at the source. This restriction is in keeping with public policy recorded at the President's Conference on Water Pollution Control(2). Many comments have been made regarding the economic inefficiency of the constraint; however, it remains to be seen whether the constraint is inefficient. In the first place, streamflow regulation is a costly control measure that is most effective at low flows. The stream flow must be doubled to halve the concentration of a stable pollutant. Furthermore, the ground rule that each water user bear his own costs by providing treatment before discharging waste water makes more than a little sense from the cost distribution standpoint.

Under the Federal program the following scheme is used to arrive at a combination of control measures. Treatment at the source and in-plant modifications are required to the extent of the polluter's ability to control pollution. Streamflow regulation is provided from storage in Federal reservoirs to obtain further improvement if needed. Process water drawn from the stream is treated to meet the specifications for a particular withdrawal use.

Within this scheme the cost of the optimum arrangement is found

by identifying the combination that will give the minimum total cost to bring the water to a target quality. The total cost is the sum of the initial cost, all recurring annual maintenance and operating costs, and periodic replacement costs, all discounted to a present value.

$$C_T = C_i + C_a \left[\frac{1 - (1+r)^{-T}}{r}\right] + C_r$$

where:

C_T is the present value of all costs during time T.
C_i is the initial cost.
C_a is the recurring annual maintenance and operating costs.
r is the discount rate.
T is the economic time horizon.
C_r is the present value of periodic equipment and replacement costs.

The cost of quality improvement - concentration curve starts at zero at the concentration of the pollutant that would be found in the raw river water if no control measures were applied. The locus of the cost - concentration curve is established as the optimum cost of control is found for each target quality level. The marginal cost curve is the first derivative of the cost - concentration curve.

The marginal loss function and the marginal cost of optimum measures for controlling pollution are compared to arrive at the indicated water quality criterion. The indicated criterion is the concentration where the added cost of another increment of improvement would not provide an equal amount of additional net benefits, but a reduction in cost of treatment would result in a loss in net benefits greater than the reduction in cost. This is the quality where the first derivatives of cost and benefits are equal.

The indicated criterion is then compared with the concentration needed to protect instream uses or other intangible conditions that have been established as public wants. The criterion representing the higher quality is selected. If the constraint placed on the system by public wants results in an economic penalty, the analyst must accept the fact that optimizing net benefits may not be the over-riding objective. He is, however, in an excellent position to demonstrate to the public the cost of satisfying its stated want.

Thus far, the return period and the intensity and duration of adverse conditions have not been brought into the picture. These facets are considered in arriving at optimum costs of treatment, especially with respect to streamflow regulation. The return period, intensity, and duration of adverse conditions are related to water uses. Their selection will depend somewhat on the severity of the penalty when the water quality objective is violated. For instance, it might take years for a stream to recover from a violation that caused a general fish kill and destruction of other aquatic life. This event would be assigned a much longer return interval than an event

that would cause a slight nuisance of short duration. Similarly, if the damages were imposed on a larger city or industrial complex, a longer return interval would be assigned than if the affected reach of the stream were used less intensively.

In summary, the elements of investigation and analysis required to establish a criterion to maximize net benefits have been briefly described. It should be evident that some of the short paragraphs contained in this paper can be expanded into chapters for a textbook. Establishing criteria that will maximize net benefits and reflect the objectives of a water pollution control program is a highly complex undertaking that requires careful investigation and skillful analysis. Experience and judgment must be fortified with decision-making models and systems-type analyses that recognize the restraints of public wants and include both tangible and intangible benefits in an operational manner. A large part of the effort going into current water pollution control studies should be devoted to assembly of data and perfection of analysis techniques that can be used by State and interstate administrators to establish cost-benefit ratios, i.e., water quality criteria.

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DISCUSSION

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How to quantify a decision affecting public policy is a question that often plagues those charged with administration of public affairs. The problem is particularly difficult when unanswered questions of public health — present and future — are involved. Several comments relative to the points made by the author, and brief reference to certain concepts not detailed in his discussion, are presented herein in the belief that they are pertinent to the subject of this meeting.

The 1961 amendments to the Federal Water Pollution Control Act require that, in the planning of any reservoirs by any federal agency, "consideration shall be given to inclusion of storage for regulation of streamflow for the purpose of water quality control, . . ." The amended Act includes the constraint noted by the author, "such storage and water releases shall not be provided as a substitute for ade-

quate treatment or other methods of controlling waste at the source." It also requires that the value of the storage for such purposes be determined and be taken into account in appraising the economic value of the entire project, and in the functional allocation of project costs. Finally, the Act states that the beneficiaries of such flow augmentation storage are to be identified, and "if the benefits are widespread or national in scope, the costs of such features shall be nonreimbursable." These several provisions have led to increased interest in a quantitative approach to water quality control criteria.

The policy decisions posed can be divided into three major categories, each of which involves a number of associated economic and socio-political questions. They are: a need to define adequate treatment; a need to develop a basic engineering-economic procedure for appraising the amount of storage required and the value of the storage; and a need to define what constitutes widespread or national benefits. The decision made in each of these areas, regardless of the process followed, represents a value judgment and hence influences the cost-benefit ratio. The available options are many if not innumerable. This situation leads to the general theme of the author's remarks — that the best administrative tool in sight for quantifying this value judgment is that offered by systems analysis.

Although one should never fail to accept the opportunity to embrace utopia, some of the qualifications noted in the author's paper should be emphasized. The first such qualification is that experience and skilled judgment will never be replaced by systems analysis. One should hope that this statement will be as true 50 years from now as it is today.

The necessity for supplementing the type of systems analysis outlined results from the very "nature of the beast." The point was made by the author that "marketplace concepts — specifically the willingness to pay — cannot be relied on as a method for establishing relative values {of changes in water quality}" since "water quality changes affect the community of water users as a whole." The proposed solution, however, would utilize a criterion based on determination of that point where the added cost of increment of improvement would not provide an equal increase in net benefits. This is the type of criterion that is assumed to produce an efficient use of a resource in a highly competitive market, but it is difficult to visualize its equal applicability to the determination of water policy criteria unless all water-using facilities are controlled by a single individual, agency, or corporation. Hopefully, this situation will not occur. This, of course, means that whereas a systems analysis approach may serve as a guide, it will not always produce answers acceptable as public policy.

It is quite conceivable that the best possible analytical solution would indicate that the cost of satisfying a specific public want is apparently prohibitive, and yet the public might reaffirm its desire to have that want fulfilled. In such cases one must conclude that either the analyst failed to communicate adequately the significance of his study, or that the value society places on that particular service

is much higher than the analyst can comprehend. This is one way of saying that enactment of laws in a free society represents one type of systems analysis.

Similarly, analysis might show that optimum development is considerably beyond the level of development that the public subsequently supports. Such a situation may not mean the analysis is wrong or that society disagrees with the solution. Society may, however, be forced to settle for something less than optimum water control, or change the time scale for achieving optimum control, because it must forever grapple with the problem of optimizing its capital resources among many needs of which water is but one.

These remarks are not offered to oppose the author's plea for quantitative analysis or to deny the potential advantages that systems analysis may one day give to the administrator in this field. They are intended to strike a word of caution. We must always remember that the high-speed computer can only search out the best solution based on the many human and often nebulous value judgments that were inserted as input data.

This leads to the second important qualification cited by the author. There is need for a great deal of research effort before reliably useful solutions can be developed. Recitation of just four of the factors needed in the way of input (whether based on educated guestimate, factual knowledge, or hope) to perform the analysis outlined by the author will illustrate:

1. Prediction of the water-use pattern.
2. Determination of the benefits that accrue from each use category.
3. Establishment of the cost of improvements needed (in turn dependent on the appraisal of the future use pattern).
4. Assignment of a time scale to each of the foregoing items.

Based on a recognition that there is still ample opportunity for disagreement on such questions as the rate of population growth to be expected in a given area, that shifts in employment opportunity will take place with changing technology, and that advancements will be made in waste treatment technology, the problem is rather awesome. It becomes extremely sticky and shot with fantasy when we face the question of project analysis based on a 100-year life expectancy. As an academic venture the problem is most intriguing, but until research improves present knowledge and techniques appreciably, application of systems analysis to such policy decisions as allocation of storage and assignment of financial responsibility remains highly dangerous.

Recognition of this situation provides little satisfaction to the administrator who must make decisions today within the framework of existing statutes. He has to establish some sort of perspective as to the long-range objectives of the program he is administering. Moreover, he has a responsibility to develop administrative policies

and procedures that will lead toward attainment of these objectives, but not to premature consecration of policy decisions in areas where current appraisal is most problematical.

Perhaps this is an appropriate place to summarize the possible role of dilution in waste disposal. Adequate treatment for degradable wastes should be viewed with respect to downstream water uses. If, for example, the objective is a low coliform count in the receiving water, secondary treatment followed by chlorination will achieve this goal at much less cost than will dilution.

If oxygen balance is the critical factor, it seems doubtful whether any water should be released to add oxygen until all wastes have received treatment to remove at least 90 to 95 percent of the BOD.

Dilution water can be most easily justified where it is used to dilute dissolved minerals. Constituents such as nitrates, boron, chlorides, sulfates, phosphates, and carbonates may come from either natural sources or manmade pollution. To an appreciable degree they can be controlled at the point of origin in man's activities, but contributions of these constituents from natural sources are often very costly if not impossible to keep out of streams.

Also, mention should be made that one of the more recent measures of pollution is given by carbon filter chloroform and alcohol extracts. These substances have a high taste and odor potential and some may be carcinogenic in concentrated form. They represent a class of toxic and organoleptic substances, and include such compounds as the organic pesticides, waste components from organic manufacturing processes, and some organolytics of natural origin. These substances are not removed by conventional waste treatment processes. Until better methods are developed for determining their actual nature, and until processes are designed to remove them from waste streams, dilution may be the only practical solution to the problem of keeping levels reasonably low in areas of high chemical manufacturing intensity.

How do the objectives of the 1961 amendments of the Federal Water Pollution Control Act compare with this general physical outlook? I have no way of knowing the exact objectives the drafters of the 1961 amendments had in mind. My interpretation of the significance of these amendments in terms of a public statement of wants is as follows. Water quality control is of sufficient importance that some of the available water of good quality and some of the potential storage resources in this country should be allocated to flow supplementation needs in the interest of (1) achieving improved water quality, (2) ensuring full development of the limited available supplies of good water and effective reservoir sites, (3) determining the economic feasibility of multipurpose reservoir projects, and (4) establishing an additional basis for public investment in water resources development programs. Each of these may prove to be a most desirable social objective if comprehensive development of the water resources of this country is to be achieved. It is inconceivable, however, that anyone can comprehend what the ultimate cost of fulfilling

these wants will be or what adjustments their fulfillment will require in both intra- and inter-governmental institutional arrangements regarding the control and use of water. However, if the implementation of the Act is to be based on an objective of optimum economic return as outlined by Mr. Coulter, if the restraint that dilution shall not be a substitute for treatment is to be retained, if reasonable equity among water users is to prevail, and if today's actions are to stand the test of time, one can visualize the desirability of some rather conservative approaches to initial policies. Some thoughts that come to mind are as follows:

1. Adequate treatment for degradable wastes should be dependent on stream uses, but the use of water for dilution of such wastes should not be required until at least 90 percent BOD reduction is achieved. How much additional treatment is required should be dependent on analysis of treatment costs versus storage costs.

2. Recommendations for the development of flow augmentation storage on a nonreimbursable basis for the dilution of inorganic or nondegradable wastes should be limited to that amount of storage needed to dilute natural pollutants plus 50 percent of the manmade contributions. (The 50 percent is arbitrarily chosen, the point being that some sort of limitation is needed if reasonable equity is to be secured among water users in different geographic areas and if the use of storage as a substitute for treatment or other management techniques is not to be abused. Note should also be made that such a policy would require concurrent action under the enforcement authorities of state and federal pollution control laws.)

3. Projects recommended for construction when their benefit-cost ratio, in the absence of flow augmentation benefits, is less than unity should be assigned a priority in keeping with their relative need for flow augmentation.

4. Whenever conservation storage is provided in a reservoir, whether it be for flow augmentation or for other purposes, such storage should be developed, within the physical limitations of the site, to the point where the marginal cost per unit of yield is no longer competitive with the average of alternative storage opportunities in the same general region.

5. Any authorization of storage for future flow augmentation purposes should carry the provision that the storage may be reallocated to other water uses provided such reallocation will not adversely affect water quality and provided the users thereof agree to repay appropriate portions of the storage cost. Concurrently, all water users would have to be prohibited from using releases made for flow augmentation purposes unless they had assumed a proportionate share of the storage costs.

Some of these suggestions may be highly unpopular with the public and some may even be contrary to the objectives of the 1961 Act. They are mentioned, however, to point up some of the ramifications of streamflow regulation for quality control that have not been discussed at this meeting. They also suggest one way of seeking a quantitative evaluation (in the democratic sense) of the public's desire for flow augmentation. Their adoption would minimize the need for compromising professional judgment and would help provide opportunity to conduct the research needed to bridge some of the present gaps in knowledge.

DISCUSSION FROM THE FLOOR

Mr. Lebosquet, U. S. Public Health Service: I thought I might mention a few things to back up Jim Coulter in this particular approach. This is perhaps not as new as some of you might think. We have been writing reports and estimating economic benefits from flow augmentation since about 1936. The first report was in connection with the Allegheny Reservoir, which finally is about to be built. That report was signed by Streeter, Hoskins, and Crohurst — the only document I have ever seen that was signed by these three eminent engineers in the Public Health Service. From around 1941 until P. L. 87-88 was passed, probably a hundred reports were written. Since then very, very many reports have been made. So, there is quite a lot of background.

I would like to second Jim Coulter's remark that low-flow regulation is a very expensive method of correcting pollution, even when the cost of this water is based on the most economical project. Even if there are 10 sources of pollution in a row so that 10 cities benefit, it is still very expensive. In all of these analyses, water quality is always considered with other multipurpose features. There might be, for instance, a power development; we would be interested in whether there is enough water from this power development for pollution control. Perhaps reregulation would be needed; the cost of reregulation would be only a small part of the overall project cost.

While many of the projects that have been built were partly justified by this low-flow augmentation, they have depended largely on these other benefits for the basic justification. Nevertheless, low-flow augmentation may add just that little bit the Corps of Engineers or the Bureau of Reclamation might need to push a project over the 1:1 benefit:cost ratio that Congress thinks we should have on these water resources projects. You should understand we are not trying to justify projects for low-flow augmentation alone; there are generally many purposes. I think the project that came closest to being strictly for low-flow regulation was Berlin Reservoir on the Mahoning River in Ohio. This project was built during World War II. We needed steel, and Youngstown needed cooling water to operate at full capacity; so we were, what I call, sharpening the pencil. There were

benefits from cleanliness, from hardness and acid reduction, from cooling water use — this was the big point — and finally, from organic pollution abatement.

These evaluations have become very complex. We have been struggling with them for a long time, and have used various formulas. Now we have a mathematical model — new words, but pretty much the same story. Sometimes the computations can get quite complex, and I am happy to turn over the future computations in this field to younger people who understand computers.

Mr. Stoevener, Oregon State University: I would like to make one brief comment on the model outlined by Mr. Coulter. I think the difficulties with it, which were pointed out earlier by Prof. Velz and now by Mr. Coulter and Prof. Smith, perhaps originate from the lack of making one distinction. This model as it is outlined here has one objective, that is, maximizing net benefits or, from a general economic point of view, maximizing income. It does not make any allowances for something else, which is very dear to most of our hearts, and that is income distribution, which means, who is paying for what, and who, in particular, is getting the benefits?

This also underlies the difficulties and the paradox pointed out by Prof. Velz this morning in the Federal Water Pollution Control Act. It is a part of the institutional framework under which we operate and should not be confused with the objectives that a model like this may point out. At best, if we disregard the institutional framework, we can only come up with some opportunity cost of fulfilling some of these criteria that may have been set.

Dr. Velz, University of Michigan: I want to make two very brief statements. First, we can never charge all the costs of low-flow regulation against waste treatment responsibilities. A lot of other benefits accrue from flow regulation, and if we try to justify flow regulation on the benefits of reduced treatment alone, we never will get it. I firmly believe there are broad benefits to flow regulation. If we can get around the dollar sign with which people insist on evaluating these things, we will get out of this box. For the last 50 years we have been living under the bushel of natural drought conditions and making all human activity adhere to the least flow that goes down the river.

The second point concerns the four approaches suggested by Mr. Coulter. I agree with every one of them, but I don't agree with putting them into effect in layers. Let us put these together and consider all possible ways of solution to arrive at the best combination of waste control at the source, waste treatment, flow regulation, and water treatment for specific uses. It seems to me this is where we fall down in our system analysis approach. The cross combinations of these things must be brought into play; not one versus the other, but rather an intelligent give and take among all of the practical ways of getting at this problem. Let's not go whole hog in any one direction, but see what we can get the most out of for the least number of dollars.

Mr. Smith, University of Kansas: I agree wholeheartedly with some of the concepts outlined by Prof. Velz. I might point out that this situation has existed in the State of Kansas in very recent years. Since 1958 we have amended our State constitution to allow the State to be a partner to development. As a result of a mathematical model and analysis of flow considerations, we decided that we did need much flow supplementation. We also concluded that this was not a cost we could pinpoint too well, so it became a question, a broader question, of political economy. We subsequently recommended to the State legislature that the State take an initial hand in this, and by concurrent resolution 2 years ago they indicated their desire to proceed. This past year a law was finally enacted to allow the Kansas Water Resources Board to begin negotiation of contracts with Federal agencies.

Session 5

MEASURES FOR IMPROVING THE QUALITY OF RESERVOIR DISCHARGES

Moderator: **R. S. Ingols**
Georgia Institute of Technology

IMPROVEMENT OF THE QUALITY OF RESERVOIR DISCHARGES THROUGH CONTROL OF DISCHARGE ELEVATION

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Next to the air we breathe, water is the most important substance that we use. All plant and animal life is sustained by it. Men have fought and died for water; civilizations have perished for lack of it.

Man's demands for water have increased as our civilization has progressed. Per capita use of water in 1900 was 50 gallons per day; by 1940 it was 122 gallons per day; and by 1960, 150 gallons per day. The use of water by agriculture and industry has increased at a more rapid rate. Yet man's total supply of water is a relatively fixed quantity.

The growing demand for water has directed more and more attention to its conservation. One obvious means of stretching the available supply is to prevent its waste during periods of high runoff by storing it in reservoirs. The idea of storage is, of course, far from new; however, the use of reservoirs as a means of conserving water is certain to increase in the future.

The increased use of electric power has already resulted in many of our rivers being developed to their potential for the production of hydroelectric power. Reservoirs for flood control and low-flow augmentation have been constructed and others are being planned.

Intelligent planning of water resources conservation and development requires that releases from reservoirs be adequate in both quantity and quality to serve essential uses.

When water is stored in reservoirs, changes take place in practically all aspects of its quality. Fortunately, most of these changes result in improvements in quality. For some uses, however, the changes are detrimental.

The effects of storage on water quality have been the subject of much study by Federal and State agencies. Thermal stratification of lakes has been recognized by man since he first dived into a lake and found the water near the bottom colder than that at the surface. Likewise, the fact that at times water near the bottom of a reservoir contains little, if any, dissolved oxygen has long been known. Studies of the concentration of dissolved oxygen in water discharged from reservoirs indicate that during the critical summer period, dams with deep intakes discharged water of very low dissolved oxygen content, dams with intermediate intakes discharged water of higher dissolved oxygen content, and dams with high-level intakes discharged water with even higher dissolved oxygen content.

One of the major uses of our streams is the carriage and absorption of wastewater. This must remain a principal function of streams, but if the fullest development of the water resources is to be made while adequate water quality is maintained, the degree of waste carriage and absorption must be reduced through waste treatment.

Of the many and often conflicting uses made of our streams, only two, the discharge of water from deep reservoirs through low-level intakes and the absorption of municipal and industrial wastewater, exert any significantly detrimental effects on the dissolved oxygen assets of streams. Waste absorption requires the presence of dissolved oxygen in the stream water, whereas the discharge of water from reservoirs through low-level intakes reduces the quantity of dissolved oxygen available for the absorption of wastes. From the standpoint of effects on dissolved oxygen assets, reservoirs that discharge water low in dissolved oxygen are similar to sources of organic pollution.

There are many well-established principles and practices, resulting from years of study and experience, that may be employed to reduce the oxygen demand of organic wastes. In the case of a reservoir used to produce hydroelectric power, however, efficiency of operation requires that water enter the turbines from the lowest possible level. Unfortunately, there are no well-established procedures, resulting from years of experience, for restoring the dissolved oxygen content of the discharge immediately downstream from the dam. It is possible, however, to discharge water relatively high in dissolved oxygen content by controlling the level from which water is selected for discharge without at the same time producing appreciable head loss.

The Roanoke River in North Carolina has been developed to its potential for the production of hydroelectric power. The river also serves as the source of water supply for municipalities and industries throughout its length. It is the vehicle for the disposal of municipal and industrial wastes. It is an important fishing stream used extensively by sport and commercial fishermen and is the principal spawning ground for striped bass (Figure 1).

In 1952, the John H. Kerr Reservoir was completed and power production was begun in November. Kerr Reservoir, a Corps of Engineers development located in Virginia 18 miles above the North Carolina State Line at river mile 179, is a multipurpose project that operates primarily for flood control and peaking-power production. At maximum power pool elevation (300 feet), the lake is 100 feet deep at the dam and has a surface area of 48,900 acres. Turbine intakes for the six generating units are from elevation 204.5 to elevation 265. The project is also responsible for maintaining a schedule of minimum flows during off-peak hours (Figure 2).

Even though thermal stratification occurred during summer months, resulting in the discharge of water low in dissolved oxygen, reaeration over some 44 miles of natural stream bed resulted in water approximately 90 percent saturated with dissolved oxygen at the first point of organic wastes discharge.

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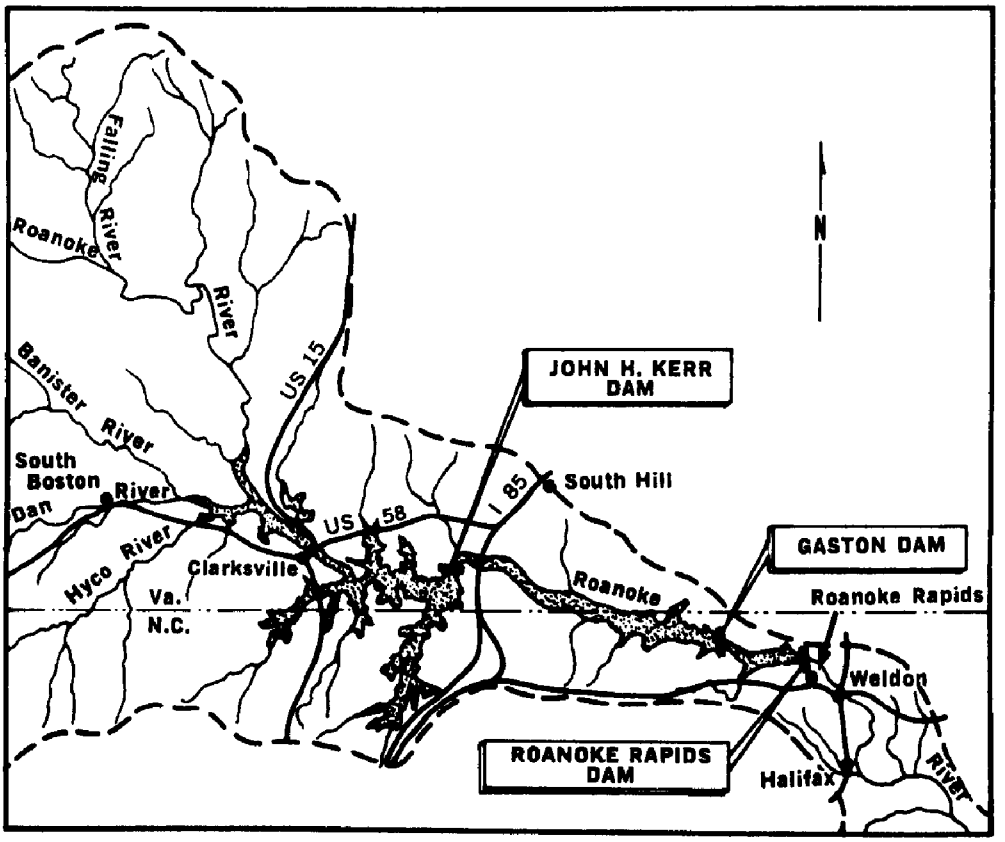

Figure 1 — Lower Roanoke River.

In 1953, in keeping with provisions of the North Carolina law relating to stream sanitation (enacted in 1951), studies were conducted and stream classifications were assigned. The organic waste assimilative capacity of the segment of the river receiving organic wastes was calculated based on an upstream dissolved oxygen concentration of 90 percent of saturation at 25°C and the weekday minimum flow of 2000 cfs as set forth in the minimum flow schedule governing the operation of the Kerr project.

The waste assimilative capacity was allocated to the various polluters and a comprehensive plan was developed for the abatement of pollution in the lower river.

In 1955, the Virginia Electric and Power Company placed its Roanoke Rapids project in operation (at river mile 137), and the Company's application for a license to construct the Gaston Dam (at river mile 146) was pending action by the Federal Power Commission. The schedule for minimum flow releases from the Roanoke Rapids Dam was the same as that for the John H. Kerr Reservoir.

Unlike the John H. Kerr Reservoir, the Roanoke Rapids Reservoir is relatively small. The dam, which is located just upstream from the town of Roanoke Rapids, creates a lake approximately 9 miles long with a surface area of about 4900 acres at normal full-power pool (elevation 132). The reservoir is approximately 62 feet deep near the dam.

As in Kerr Reservoir, dissolved oxygen deficiencies developed in the lower depths of the Roanoke Rapids Reservoir during summer months. The discharge of water through the low-level turbine intakes resulted in a significant reduction and substantial variations in dissolved oxygen concentrations downstream from the dam. Studies conducted during the summer of 1955 and 1956 indicated that the dissolved oxygen content of the discharge water (measured at the highway bridge approximately 1 mile downstream from the dam) fell as low as 3.2 milligrams per liter. The average of the dissolved oxygen data collected over the period was 5.4 milligrams per liter or 65 percent of saturation at 25°C.

The reduction in dissolved oxygen reduced the waste assimilative capacity below that which had been available at the license flows prior to the construction of the Roanoke Rapids Dam. The effects of the reservoir on downstream water quality raised serious questions regarding the further effects of another hydroelectric project on water quality. The importance of dissolved oxygen to downstream users caused the State agencies concerned with maintenance of water quality, preservation of fish and wildlife, and industrial interest dependent on dissolved oxygen to satisfy the oxygen demand of its wastes to intervene before the Federal Power Commission against the license requested by the Company for the construction of its Gaston project. The purpose of the intervention was to delay issuance of the license until the probable effects of further impoundments could be more adequately investigated and effective measures could be incorporated

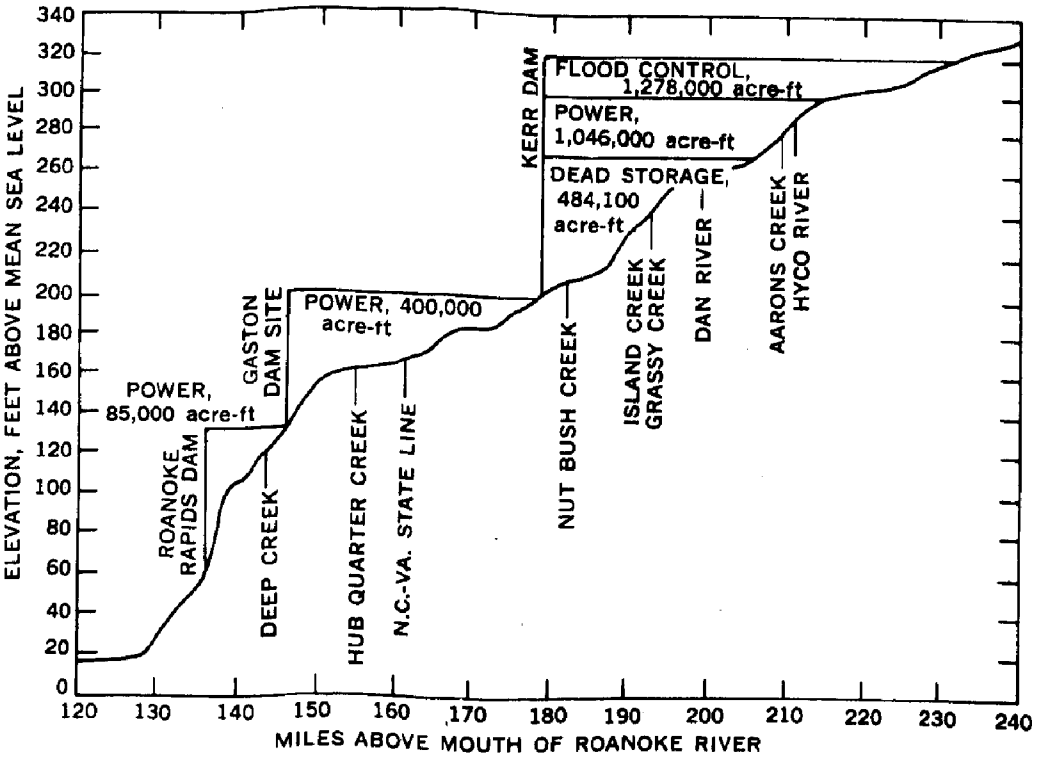

Figure 2 — Condensed profile of Lower Roanoke River.

in the license to assure that further reduction in the dissolved oxygen in the discharge from the lower reservoir would not occur.

After considerable investigation of possible methods of remedying the detrimental effects of impoundments on dissolved oxygen resources, the Virginia Electric and Power Company proposed to construct a submerged weir around the Gaston turbine intakes as a solution to the problem of low dissolved oxygen discharge from low-level intakes. The submerged weir would form an underwater barrier to obstruct passage of deep water into the turbines so that water would be selected for discharge from levels above the crest of the weir and thereby act as the equivalent of a high-level intake.

Since the concept of a submerged weir to act as a high-level intake was new, it was believed that the performance of such a device should be verified. In order to determine the effectiveness of the submerged weir in improving the dissolved oxygen discharged, Virginia Electric and Power Company constructed a submerged weir around the turbine intakes in the Roanoke Rapids Reservoir in the summer of 1957.

The weir has two sides extending perpendicular to the face of the dam for a distance of about 275 feet connected by an upstream side about 525 feet in length; thus an enclosed forebay is formed around the turbine intakes. The weir, constructed of crushed stone, extends upward to within 25 feet of the surface and in effect is an integral part of the intake system (Figures 3 and 4).

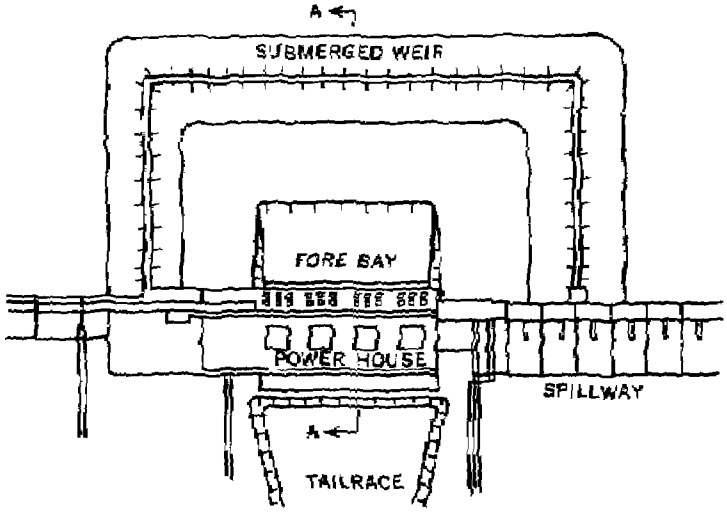

Figure 3 — Plan of submerged weir — Roanoke Rapids hydroelectric station.

A comprehensive survey was planned jointly by the interested State and Federal agencies (Steering Committee for Roanoke River Studies) and the Virginia Electric and Power Company and carried out during late summer and early fall of 1957. This was one of the most intensive limnological studies ever performed anywhere; it in-

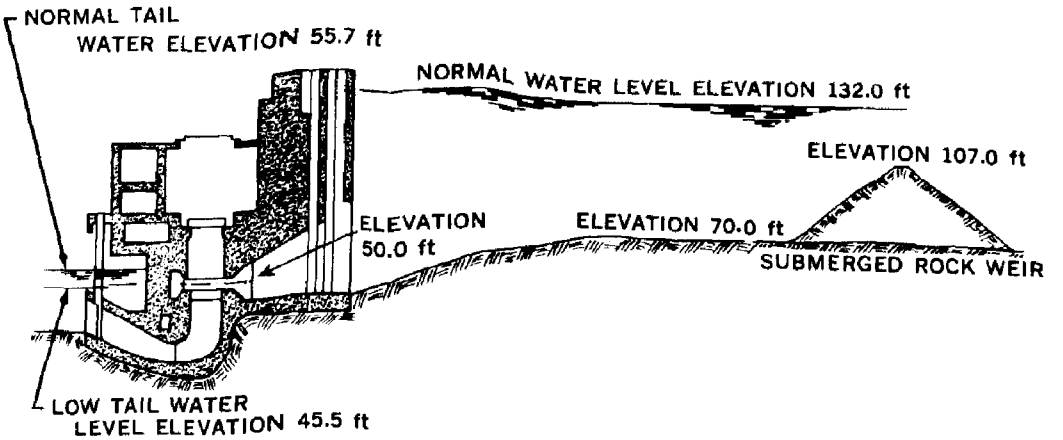

Figure 4 — Profile of submerged weir — Roanoke Rapids hydroelectric station.

volved more than 20 engineers, chemist, biologists, limnologist, and samplers representing State and Federal agencies as well as two industries.

The study program included the collection and analysis of samples at stations located to determine (1) the quality of Kerr Reservoir discharge, (2) reaeration over the reach of river bed between Kerr Dam and Roanoke Rapids Reservoir, (3) the quality of water entering Roanoke Rapids Reservoir, (4) dissolved oxygen and temperature patterns and water movement in Roanoke Rapids Reservoir, (5) the quality of water in the Roanoke Rapids powerhouse tailrace, and (6) the quality of water at Highway 48 bridge.

Upwards of 15,000 separate chemical and physical measurements of water quality were made, consuming several thousands of man-hours. No effort will be made here to present or summarize all of the data obtained during the study. Only a part of the more pertinent data will be discussed.

In order to understand the performance of the submerged weir in Roanoke Rapids Reservoir, it is necessary to understand the effects of upstream factors. For this reason, this discussion will begin with a summary of water quality in the Kerr Reservoir discharge.

Kerr Reservoir is a large deep impoundment exhibiting all the characteristics of such bodies of water, including thermal stratification and resulting low dissolved oxygen in the deeper portion. The water discharged from the reservoir is drawn primarily from the hypolimnion. This water is very low in dissolved oxygen and relatively low in temperature. Table 1 shows the average and ranges of values measured in the tailrace near the dam during the survey period.

Data obtained from sampling at the Gaston Dam site (river mile 146) 33 miles downstream represents the quality of water entering the Roanoke Rapids Reservoir. Table 2 shows the averages and ranges of values observed during the survey period.

TABLE 1. SUMMARY OF DISSOLVED OXYGEN AND TEMPERATURE SAMPLES AT KERR RESERVOIR TAILRACE

	Dissolved oxygen, mg/l	Temperature, °F
Maximum	4.7	76.3
Upper quartile	3.0	72.6
Weighted average	2.5	71.9
Median	2.3	71.3
Lower quartile	1.7	69.5
Minimum	0.3	64.0
Number of samples	323	318

TABLE. 2. SUMMARY OF DISSOLVED OXYGEN AND TEMPERATURE SAMPLES AT GASTON DAM SITE

	Dissolved oxygen, mg/l	Temperature, °F
Maximum	8.2	87.0
Upper quartile	7.1	75.7
Arithmetic average	6.6	74.4
Median	6.8	73.9
Lower quartile	6.0	72.9
Minimum	5.2	68.4
Number of samples	303	307

Water entering the headwaters of Roanoke Rapids Reservoir varies considerably in quality, as observed at the Gaston Dam site sampling station. Compared to the surface water in the reservoir, the inflow water is relatively cool, especially during periods following heavy discharges from Kerr Reservoir. In the extreme upper reaches of the reservoir, high velocities and the resulting turbulence prevent stratification. Eventually, the inflow reaches wider and deeper sections of the reservoir of such cross-sectional area that turbulence is no longer sufficient to prevent stratification between the cool inflow and the warmer surface waters in the reservoir. The cool water then sinks beneath the surface and becomes a density underflow.

The inflow continues downstream as a density underflow until it reaches its own density level, which varies in elevation, depending on the temperature of the reservoir as well as the thermal structure within the reservoir. Joining its density layer, the new inflow becomes the tail end of that layer. The hydrostatic head of the extreme upstream end of the inflow, which is at a higher elevation, tends to compress and thicken the downstream portion, displacing the warmer waters above upward.

The volume of water that can be discharged from Kerr Reservoir in a single peaking-power period is large compared to the volume of Roanoke Rapids Reservoir; therefore, the vertical displacement of warmer water immediately above the stratum corresponding to a cool inflow is considerable. Water thus displaced upward may be low in dissolved oxygen, since it may have been stored at the intermediate depth for a considerable time with little chance for reaeration. When water with such low dissolved oxygen is raised to the elevation of the weir crest or above, it may be withdrawn alone or mixed with other water from above and below, depending primarily on the Roanoke Rapids discharge rate. This fact accounts for the occasional observed periods of relatively low dissolved oxygen in the Roanoke Rapids Reservoir discharge.

The hydraulic performance of the submerged weir was a subject of considerable study. This work, conducted by Dr. D. W. Pritchard and J. H. Carpenter of the Chesapeake Bay Oceanographic Institute, included measurements of the water movement in the vicinity of the weir and lower reservoir. Four methods of direct measurement were employed: (1) Gurley Current Meter, (2) confined drags, (3) free-drifting drogues, and (4) fluorescent dye tracer.

Data from all four techniques of observing the pattern of water movement were combined and velocity-versus-depth curves for various locations and discharge rates were determined. On the basis of these curves, the percentage contribution from each 5-foot layer to the discharge was determined. Table 3, taken from Special Report No. 1, Roanoke River Studies — A Report of a Study of the Effects of a Submerged Weir in the Roanoke Rapids Reservoir Upon Downstream Water Quality, shows the percent contribution of each 5-foot layer of the reservoir 500 yards upstream from the weir at the discharge rates shown.

TABLE 3. PERCENT OF DISCHARGE CONTRIBUTED BY EACH 5-FOOT LAYER IN ROANOKE RAPIDS RESERVOIR

Depth interval, ft	Discharge rate, cfs		
	2,000	6,000	12,000
0-5	0.0	5.0	9.4
5-10	0.0	14.8	21.0
10-15	7.5	23.8	21.3
15-20	32.8	23.8	18.0
20-25	34.3	17.4	13.9
25-30	17.9	9.9	9.4
30-35	6.0	4.2	4.6
35-40	1.5	1.0	1.7
40-45	0.0	0.0	0.7

These data show (1) only a small percent of the flow originates at depths below 35 feet; (2) the layer from which the maximum contribution to the flow originates increases in depth with decreasing

flow, for 12,000 cfs it is centered at 10 feet, for 6,000 cfs it is centered at 15 feet, and for 2,000 cfs it is centered at 20 feet; and (3) there is no significant change in percent contribution with flow for the layers below 35 feet, but there is a marked increase in percent contribution for the upper 5 feet with increasing flow.

The final check on the efficiency of the submerged weir in the Roanoke Rapids Reservoir is provided by the data collected below the impoundment at the bridge crossing Roanoke River at Highway 48 bridge. During the survey period, this station was sampled a total of 1092 times, usually for dissolved oxygen, temperature, and turbidity. The results for temperature and dissolved oxygen are summarized in Table 4.

TABLE 4. SUMMARY OF DISSOLVED OXYGEN AND TEMPERATURE SAMPLES AT HIGHWAY 48 BRIDGE

	Dissolved oxygen, mg/l	Temperature, °F
Maximum	8.6	84.2
Arithmetic average	6.3	76.2
Minimum	2.7	71.0
Number of samples	1092	1082

These data show water of relatively good average quality, but with a wide range of values separating the maximums and minimums, especially with respect to dissolved oxygen.

An analysis of the data shows that the dissolved oxygen content of the waters selected by the weir for discharge from the reservoir is closely related to the rate of discharge from the reservoir. At low discharge rates, the dissolved oxygen in the discharge is less, other contributing factors being equal, than for high discharge rates. This is in keeping with the velocity-versus-depth curves. Under conditions of minimum discharge at Roanoke Rapids Dam (2000 cfs), water is selected from a narrow range of elevations (centers at 20 feet below surface) immediately above the weir crest, with little mixing with the surface layers. The quality of water at this elevation is influenced by several factors, including the rate of discharge from Kerr Dam for the preceding several days, the rate of wind mixing and reaeration in Roanoke Rapids Reservoir in the preceding several days, the rate of discharge from Roanoke Rapids Dam for several preceding days, and the degree of thermal stratification above the weir-crest elevation at the time of discharge. The minimum dissolved oxygen values observed at Highway 48 bridge represented the worst combination of these factors.

As another measure of the effectiveness of the submerged weir in selecting water of relatively good quality from the impoundment, the data obtained at Highway 48 bridge during the study can be compared with data collected prior to the installation of the weir. Available data are summarized in Table 5.

TABLE 5. COMPARISON OF ROANOKE RIVER WATER QUALITY AT HIGHWAY 48 BRIDGE FOR 1953, 1956, AND 1957

	Dissolved oxygen, mg/l			Temperature, °F		
	1953	1956	1957	1953	1956	1957
Maximum	9.0	6.5	8.6	84.2	77.0	84.2
Upper quartile	8.2	6.0	6.9	78.8	75.2	77.8
Arithmetic average	7.9	5.4	6.3	77.9	73.4	76.2
Median	7.9	5.6	6.3	78.8	73.4	76.1
Lower quartile	7.5	4.7	5.7	77.0	71.6	74.3
Minimum	7.0	3.2	2.7	73.4	71.6	71.0
Number of samples	47	21	1092	45	21	1082

The 1953 data were collected during the period August 9 through August 31; the 1956 data during the period August 28 through September 21; and the 1957 data during the period July 15 through September 13.

Comparison of the dissolved oxygen data shows all 1957 dissolved oxygen values except the minimum are significantly higher than the corresponding 1956 values, but lower than the 1953 values. These data show a significant improvement in dissolved oxygen concentration below the Roanoke Rapids Dam over the post-dam but pre-weir period. The improvement can be attributed to the submerged weir surrounding the turbine intakes and providing the equivalent of a high-level intake. The survey resulted in the following conclusions:

1. The submerged weir in Roanoke Rapids Reservoir is hydraulically effective in selecting, for discharge from the reservoir, water primarily from the layers above the crest of the weir.
2. The weir causes a significant improvement in average water quality. Because of the relatively small storage capacity of the Roanoke Rapids Reservoir compared to the large releases from Kerr Dam, however, such releases cause occasional displacement of low-quality water from intermediate levels upward into the layers above the level of the weir. The water thus displaced upward then becomes available for withdrawal over the weir. Water thus selected may at times be of undesirably low dissolved oxygen content.
3. The submerged weir has effectively solved the problem of water quality at high flows below Roanoke Rapids Dam.
4. Based on observations in Roanoke Rapids Reservoir, the weir in the proposed Gaston Reservoir should be redesigned to extend upward to within 15 feet of the surface, instead of 25 feet as originally planned.

The proposed Gaston Reservoir (being constructed at river mile 146) will create a lake 34 miles long from the head of Roanoke Rapids Reservoir to the toe of John H. Kerr Dam. The surface of the normal full-power pool will be at elevation 200 and will have an area of 20,300 acres. Storage capacity of the power pool will be approximately 400,000 acre feet. The Gaston Reservoir will have a volume approximately 5.8 times that of Roanoke Rapids Reservoir.

Flow releases from Gaston Dam will be controlled by peaking-power operation with no requirements for minimum flows and will be discharged directly into Roanoke Rapids Reservoir. Under normal operating conditions, the Gaston Reservoir level will vary less than 1 foot.

After Gaston is constructed with a submerged weir extending to within 15 feet of the surface, water entering Roanoke Rapids Reservoir is expected to be of better quality than that available during the study. With a higher level weir in Gaston Reservoir than in Roanoke Rapids Reservoir, the quality of the discharge is expected to be better than that presently observed below Roanoke Rapids Dam. Should the quality of the discharge from Gaston Dam be no better than the average observed below Roanoke Rapids Dam, however, this would mean that water entering Roanoke Rapids Reservoir would be at a temperature of about 75°F and would have a dissolved oxygen content of about 6.0 milligrams per liter. Under these conditions, the problem of poor-quality water being discharged from Roanoke Rapids as a result of a large discharge of cool water from Kerr Reservoir should be greatly reduced. After these facts were considered, it was concluded that "the dissolved oxygen content in the waters released from Roanoke Rapids will be at least 6.0 mg/l, and in most cases higher."

Upon completion of the study, consideration was given provisions that might be included in the Gaston Project license relating to minimum flows and minimum water quality. Provisions acceptable to the Virginia Electric and Power Company and the agencies concerned were finally agreed upon. Upon reviewing the Gaston Project, the Federal Power Commission concluded that "the proposed Gaston development and the constructed Roanoke Rapids development shall be considered as units of one complete project." The license for the Roanoke Rapids Project was amended to include Gaston Dam with a submerged weir. This license is unique in that it not only established a schedule of minimum flows to be maintained downstream from Roanoke Rapids Dam, it also specified minimum water quality in terms of minimum pounds of dissolved oxygen to be discharged per day.

The Gaston Dam has been completed, and power production will start during the Spring of 1963. For this reason, it is too early to draw conclusions concerning the effectiveness of the two submerged weirs on water quality downstream from the Roanoke Rapids Dam. Needless to say, this will be the subject of considerable study during the coming summer.

The dissolved oxygen content of the discharge from the Roanoke Rapids Reservoir has been monitored since 1960. In June 1960, a Hays dissolved oxygen analyzer was installed on the river at Highway 48 bridge, and a continuous record of dissolved oxygen was obtained until the analyzer was removed in December. During this period the minimum dissolved oxygen concentration obtained was 5.6 milligrams per liter. The power company installed an analyzer in the tailrace and has a continuous record of dissolved oxygen concentration since the summer of 1960. These records indicate that density currents resulting from large discharges from Kerr Reservoir continue to result in occasional low dissolved oxygen concentration in the discharge from Roanoke Rapids Dam. On occasions when the dissolved oxygen drops below 6.0 milligrams per liter during periods of minimum flow, the Company splits the flow through two turbines and aerates the water through its vacuum breakers. Consequently, through the effects of the submerged weir and "split-wheel" operation, the dissolved oxygen content of the discharge seldom drops much below 6.0 milligrams per liter for extended periods of time. It is expected that with Gaston in operation, with its high-level weir selecting warmer water with a higher dissolved oxygen content, the quality of water discharged from the Roanoke Rapids Reservoir will be at least as good as that required by the license.

Since completion of the Roanoke River study, a similar study was conducted on Catawba River by the Duke Power Company. This study concluded that a submerged weir is equivalent to a high-level intake. Accordingly, the Company's license for its Cowans Ford project includes a provision that a submerged weir be constructed around the turbine intakes.

In order that storage reservoirs may truly serve as a means of conserving water, it is essential that consideration be given to methods of ensuring that the quality of the discharge is adequate to meet the needs of downstream users. From the standpoint of conserving dissolved oxygen assets, a submerged weir is an effective device.

DISCUSSION

John M. Hester*
U. S. Fish and Wildlife Service, Atlanta, Georgia

HIGHLIGHTS

Mr. Knight has presented a valuable, informative paper on one method of obtaining desired water quality below a thermally stratified reservoir with low-level outlets. His paper on the hydraulic per-

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formance of the submerged weir should serve as a useful basis for future planning of projects.

Although it is evident the dissolved oxygen levels of the inflows to Roanoke Rapids Reservoir are reduced within the reservoir, it is also evident the top layers of the reservoir are capable of restoring almost an equivalent amount through reaeration and photosynthetic activity of phytoplankton. Based on this apparent situation and a submerged weir that selectively discharges certain layers of the reservoir, the dissolved oxygen content of the discharges is adequately maintained when higher discharge rates prevail.

It is interesting to compare the percentage of flow contributed by each 5-foot layer of the reservoir under various rates of discharge. Even though the Roanoke Rapids weir has not entirely overcome all the dissolved oxygen deficiencies below the reservoir, the data indicate the principle has merit in improving the dissolved oxygen content of waters discharged from certain types of thermally stratified reservoirs. It shows considerable promise for other reservoirs that will have limited water level fluctuation and relatively shallow depth. The same principle will be employed in the newer Gaston Reservoir, now under construction. The weir will, however, be raised to within 15 feet of the surface to ensure better water quality.

In the selection of the features for controlling the dissolved oxygen content, the design and operations of the project were basic considerations. I believe it is recognized that the engineering design and operations of reservoirs limit the type of control features that would be adaptable. In these two reservoirs, it was determined that the most feasible means of providing releases with high dissolved oxygen content was by a submerged weir surrounding the penstocks. Hull(*1*) has made a review of the potential corrective measures that have been used at other projects to remedy poor quality water resulting from impoundment.

Based on the findings presented, the submerged weir becomes less effective in assuring a satisfactory dissolved oxygen content when the magnitude and/or duration of cold inflows are increased. This suggests that further increases in the volume of this type of water entering the reservoir would increase the period of poor-quality releases below Roanoke Rapids Dam. This illustrates the necessity of providing means for water quality control at each development unit added within the drainage system. The lack of means to control water quality at an upstream project could tend to obscure the effectiveness of a control device located in a downstream unit.

On the other hand, the downstream device may be made more effective because of controls installed in a new unit. It is predicted that this will occur below Roanoke Rapids Reservoir as the result of the Gaston weir.

TRENDS IN WATER USE DEVELOPMENT

The recent report of the Senate Select Committee on National Water Resources(*2*) indicates that by 1980 we will need to double

the facilities we now have for conservation and use of water. Based on this prediction, the Corps of Engineers, one of several planning agencies for water use development, has recently formulated 20-year estimates for their portion of the national program(3). The Corps envisions the need of some 320 million acre-feet of storage in more than 300 new reservoirs, plus inland waterways, harbors, levees, flood walls, channel improvement, and recreational facilities to accommodate perhaps 300 million visitors annually at the projects involved. Fox(4) has pointed out that waste disposal and outdoor recreation, two old uses of water resources, are growing with unusual rapidity. He predicts in many parts of the country these two uses will tend to dominate water management in future years. Recently, Congress has given expanded recognition to the need of additional outdoor recreation areas and the need of water quality control.

With this magnitude of reservoir development in prospect and with increased competition by water users, it is of great concern that adequate means be devised to provide optimum water quality control for the entire stream system.

NEED FOR FLEXIBILITY TO ACHIEVE WATER QUALITY CONTROL

The Bureau of Sport Fisheries and Wildlife, in carrying out its responsibilities of studying and reporting on water use projects, recognizes the importance of maintaining water quality control for effective management of the fisheries affected. Since water quality is subjected to detrimental changes because of impoundment, means are sought whereby both the reservoir and downstream area can be managed effectively under the changing conditions.

The Bureau is aware of the current limits of definitive knowledge on precise management of water quality at individual units as well as on total drainage system plans. Accordingly, our approach to date has been to provide for as much flexibility as is feasible so that future knowledge and understanding can be implemented as a management tool without costly project modification. It should be emphasized here that more future attention must be given to the total effects within a drainage system.

A means that provides for some flexibility in management of affected fisheries has been included in certain projects that have either recently been placed in operation or under construction by the Corps of Engineers(5). These projects generally provide for flood control, low-flow augmentation, and raised water levels during the recreational season. In providing for these purposes, the water levels of the reservoir will be widely fluctuated.

Because the reservoirs will have widely fluctuating water levels, multiple openings, such as are shown in Figure 1, are necessary to provide for various levels of discharge so that the desired water can be selected under the various conditions that occur as a result of changing water levels. Although the dissolved oxygen content must

be sufficient, it is also vital to the fishery that a favorable annual pattern of water temperatures be maintained. The flexibility in selecting water temperatures afforded by the multilevel openings provides opportunity for maintaining the desired temperature pattern (Figure 2).

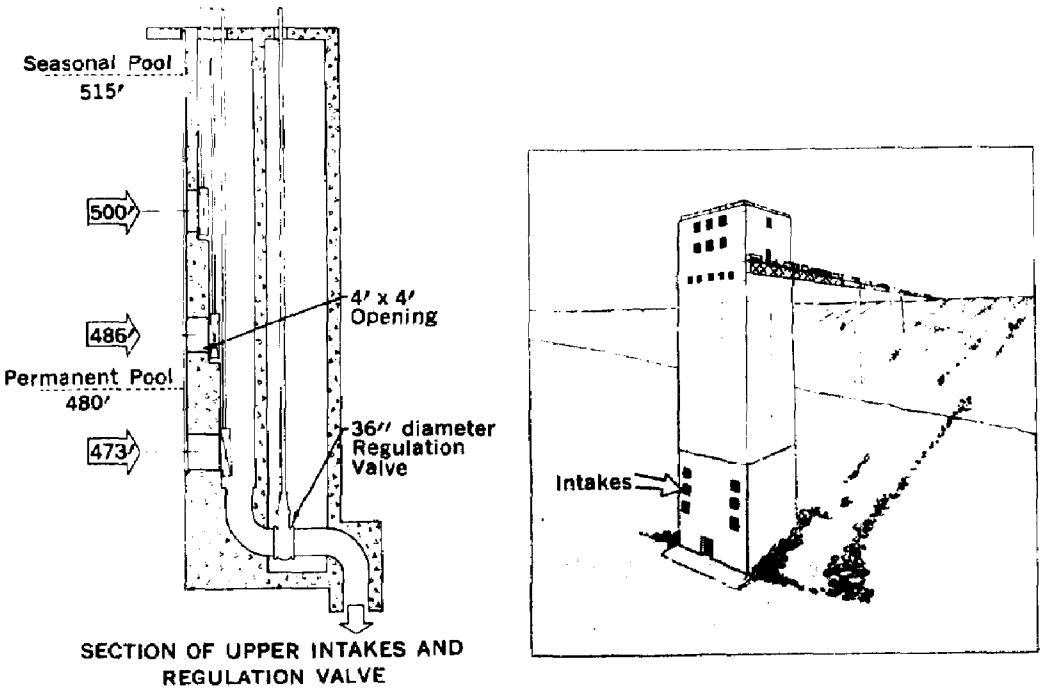

Figure 1 — Multiple level intakes gated for selective withdrawal of water.

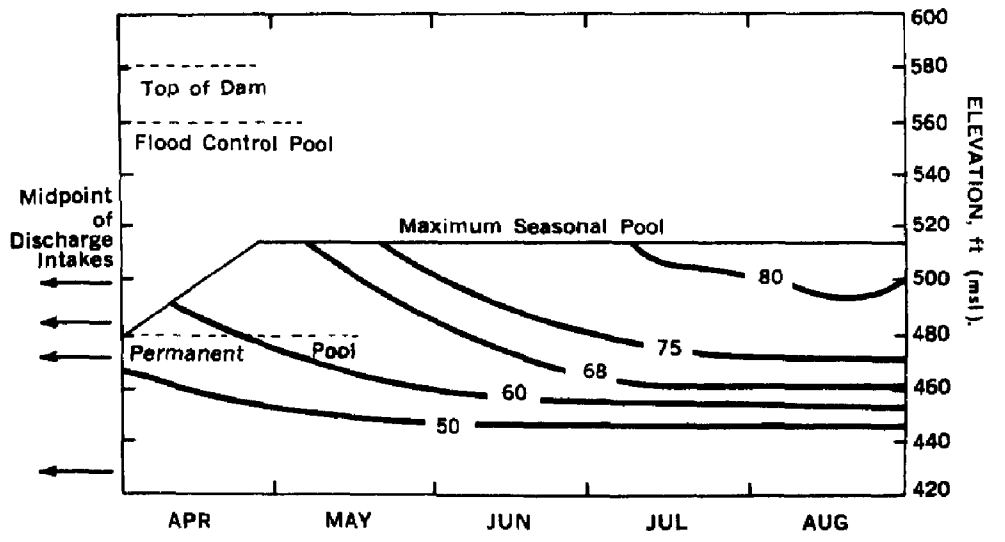

Figure 2 — Hypothetical temperature patterns with multiple level intakes (Nolin Reservoir, Kentucky).

The use of multilevel openings will permit greater latitude in managing the fisheries downstream. With this control provided, the downstream area can be managed for the optimum fishery permitted within limitations of other physical factors. Studies are being made by the Kentucky Department of Fish and Wildlife Resources to evaluate the effectiveness of the multilevel openings for management of the downstream fisheries(*6*).

Concern has been expressed by some workers as to the effect different levels of discharges will have on production and utilization of the reservoir fishery(*7*). The most effective management of both the reservoir and the downstream area should be the objective. For now, there is need for flexibility of plant operations and basin studies to resolve differences and develop best management plans.

Mr. Knight has presented information on a technique that offers a great deal of promise as a means of providing water quality control when adapted to a set of conditions whereby the submerged weir can effectively function. Although its limitations are recognized, the findings reported provide useful information. From the fishery manager's standpoint, means are needed to provide sufficient latitude in selecting levels of discharge so that the greatest benefits can be achieved from management of both the reservoir and the downstream area. Additional research is needed to determine the effects that various levels of discharges will have on reservoir fish populations and to explore potentials for development of highly specialized fisheries below a dam.

In devising structural means to control the quality of water discharged from reservoirs, it is necessary that project design and operations for other purposes be recognized. Consequently, because of the imposed limitations, each reservoir requires planning on an individual basis.

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DISCUSSION FROM THE FLOOR

Mr. Coutant, Lehigh University: Mr. Knight, would you please defend your reliance upon average dissolved oxygen values when it is rather well known that the only datum of real significance to the physiology of organisms is the oxygen minimum?

Mr. Knight, North Carolina Dept. of Water Resources: Apparently I did not make myself clear. I thought I said it was the minimum dissolved oxygen values that the people in the water pollution control business had to concern themselves with, and that the minimum values observed in this situation were the ones that required some action for improvement. Under minimum flow conditions, when dissolved oxygen values fall to below 6, I believe it is, the power company splits the minimum flow between two of its turbines to provide additional oxygen.

Of course, the circumstances that bring about these lower dissolved oxygen concentrations at minimum flow conditions should be largely if not completely eliminated after the Gaston weir is in operation, since the density underflow conditions that occurred in the system during the period of study and produced the observed low dissolved oxygen values should be largely eliminated.

Mr. Gellman, National Council for Stream Improvement: Mr. Knight, first, to what extent might the ability of the submerged weir to select water from various levels be a function of its porosity?

Second, I note in your paper that the operating range of Roanoke Rapids Reservoir is about 3 feet. From your studies do you have any indication as to how much the effectiveness of this structure might be increased by raising the elevation of the weir crest closer to the surface than the present 25 feet?

Mr. Knight: We have not investigated the effect of the porosity of the weir on the quality of the discharged water. It is my opinon, however, that since the hydrostatic pressures on both sides of the weir are approximately the same, the porosity of the weir will not have a serious adverse effect on the quality of the water that is discharged.

Regarding the second question, the effectiveness of the weir in improving water quality might be increased by raising the crest to a higher elevation. This installation was constructed, however, to

form a basis for predicting what should be done at the Gaston Project. The 25-foot submergence at Roanoke Rapids was arbitrarily selected for its use as an experimental unit. The higher the weir, the higher the velocity across the top of the weir and, from the standpoint of power production, the greater the head loss. Perhaps some of the engineers in the audience can contribute more on this point.

Mr. Peters, Virginia Electric and Power Company: I might be able to add a little to the answers to both of these questions. While studying the weir during the 1957 survey that Mr. Knight speaks of, we made very careful temperature measurements on the inside face of the weir, using a very sensitive thermometer. Since there was a temperature differential in the water on the two sides of the weir at the lower depths, we would have been able to pick up a lowering of the temperature on the inside if there was any leakage. At no place did we find any evidence of seepage through the weir.

In addition to this, a comparison of the contribution at various levels (for which the temperature and dissolved oxygen were known) with the temperature and dissolved oxygen of the water in the tailrace also showed that there was no seepage of water through the weir.

On the question of the submergence of the weir, the Gaston weir is being built to within 15 feet of the surface. Based on the head loss across the weir, the length of the weir required at Gaston Dam is just about 1,000 feet.

Mr. Ragone, Virginia Electric and Power Company: Figures 4 and 5 in our paper show the construction of the Roanoke Rapids weir. The weir was actually installed in the old Coffer Dam area after the reservoir was filled. The height was limited by the construction method. It had to be rock fill because of the economic problem of keeping the plant in operation. We could not lengthen the weir and still stay on the Coffer Dam area. The base was such that 25 feet was as close as we could come to the surface and not have excessive head loss over the short length of weir.

Dr. Harleman, California Institute of Technology:* From my experience with structures for control of stratified flow, the weir is a very effective device. We have done some testing for TVA on another type of structure you may be interested in seeing very briefly.

I think it may reinforce your confidence in this control of stratified flow. In connection with the planning of a fairly large steam power plant, an intake channel and outlet channel were to be constructed on a section of a river. As you well know, when you pass a portion of the water through a condenser you raise the temperature, which results in a temperature stratification in the river. The condenser return will move upstream, especially if the quantity of water used is large compared to streamflow. Therefore, we planned a skimmer wall structure, which is just the upside-down part of the structure Mr. Knight discussed. This was, in effect, a submerged sluice gate

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*Now with Massachusetts Institute of Technology.

that held back the warm water so that the cold water could be taken through. The water on the downstream side was essentially the same level (very slight head loss), but the submerged sluice has been very effective in preventing a thermal recirculation.

We conducted experiments to determine what maximum rate of flow per unit width could be allowed for a given elevation of the cold water without taking in the warm water above. Probably the most interesting thing about the submerged weir is that one can analyze it as a problem of critical flow analogous to surface flow. It looks just like a flow over a weir in air, the difference being that the effect of gravity is greatly reduced as a result of the reduced density difference. This type of flow, which is analogous to free surface flow, takes place in relatively slow motion. This is a further example of selective withdrawal and the ability to control flows in stratified water having very small density differences. The density difference between two layers is about one-third of 1 percent when the temperature difference is about 10 degrees Fahrenheit.

This type of structure can obviously also be used if the river in which the diversion is to occur is already stratified due to, let us say, deep releases from a reservoir upstream.

Mr. Kittrell, U. S. Public Health Service: Dr. Harleman, what velocities were used in your experiments?

Dr. Harleman: The velocities were about half a foot a second in the model.

Mr. McLean, U. S. Public Health Service: Mr. Churchill, in one of your recent papers you showed a graph of the annual change in dissolved oxygen in the discharge from a reservoir that had a pronounced dip in September or October. I think the outlet from this structure was at an intermediate level in a deep reservoir. Do you think that this could be explained in terms of a density underflow of colder fall flows that came into the reservoir and raised the hypolimnetic water, which earlier was below the level of the outlet, into the area of the outlet? This would suggest another reason for having multilevel outlets.

Mr. Churchill, Tennessee Valley Authority: I could not say. Each situation must be analyzed by itself. I would need to know more about the situation before I would want to comment on it.

IMPROVEMENT OF THE QUALITY OF RESERVOIR DISCHARGES THROUGH TURBINE OR TAILRACE AERATION

Theodore F. Wisniewski

Director, Wisconsin Committee on Water Pollution, Madison

Control of water pollution requires a continuing search for new, practical methods of treating wastewater. The development and installation of processes capable of removing 90 to 95 percent of the oxygen demanding components of sanitary and of industrial wastewaters prior to discharge remains a necessary first objective in every water pollution control program. But the tonnages of residual oxygen demanding components from even these high efficiency processes add to the ever increasing loading placed on the receiving waters of rivers, lakes, and streams.

More than 20 years ago Tyler(*1*) suggested that practical means of aeration might be developed to increase the natural treatment capacity of a body of water. Stream studies have demonstrated repeatedly that moderately sized rivers have a large and important working capacity for self-purification, which may involve the processing of hundreds of tons of natural and man-made organic waste matter in a relatively short stretch of the stream. Artificial reaeration may often be required, however, to facilitate these treatment processes in natural waters and to aid in rapid recovery to clean stream conditions. The early concepts of stream reaeration processes are now attaining the status of practical and workable auxiliary methods of waste treatment of growing importance to the overall objective of water pollution control. Reaeration of quiescent waters in lakes and bays has received less study, but could be a promising area for further research.

Development of methods for reaeration of rivers has been a subject for continuing study by several cooperating organizations in Wisconsin since 1943. Various aspects of this continuing state and industry study have been published in a series of seven papers(*2-8*). Hydroturbine aeration at power dams has been especially successful as a practical method for introducing air into the water for large-scale reoxygenation of waters depleted in dissolved oxygen. As of October 1961, 18 different dams on the Flambeau, Wisconsin, and Fox Rivers have been equipped for hydroturbine aeration. Several power dams are also known to have been equipped for aeration in neighboring states. Other installations have been under consideration or are being tested on a preliminary basis.

Experience with hydroturbine aeration of rivers at some of these installations covers 5 years or more, and many have had at least 3 years of operation during critical periods of dissolved oxygen depletion in these rivers. Basic principles for successful operation of stream reaeration are becoming established, and the limitations of methods are becoming known. This paper is intended to review the present

status of commercial-scale stream aeration as a means for accelerating the recovery of oxygen depleted waters and of increasing the working capacity of rivers subjected to heavy loadings of biochemical and chemical oxygen demand.

DISSOLVED OXYGEN TENSION

There is a limitation on the efficiency and practical value of reaeration in that the rates of solution for oxygenation become very slow at the higher levels of oxygen saturation in water and at higher temperatures. During summertime critical periods of low stream flow and high temperature, it is seldom practical to try and reaerate waters when the dissolved oxygen saturation exceeds 40 percent.

As a result of this limitation, it is usual to find that warm water operations start at any given reaeration facility when the dissolved oxygen level declines to 3 milligrams per liter or less, and reaeration is maintained until the dissolved oxygen level again reaches 3 milligrams per liter or more.

Figure 1 graphically presents the relationship between dissolved oxygen saturation and dissolved oxygen absorption as determined in waters of the Flambeau River at the Pixley Dam hydroturbine installation. Very high rates of increase in the dissolved oxygen level were accomplished under conditions of low dissolved oxygen saturation of 10 percent or less, but as the degree of dissolved oxygen saturation increased to the 50-percent level, the rate of dissolved oxygen increase dropped rapidly to less than 10 percent. The temperature of the water materially affects the degree of saturation and thus the rate and efficiency of dissolved oxygen absorption. At temperatures approaching the freezing point of water, the absorption of oxygen may be highly efficient, even when the dissolved oxygen level exceeds 6.0 milligrams per liter. On the other hand, at temperatures around 25°C it may be difficult to obtain solution of appreciable amounts of newly introduced oxygen even at reduced levels of dissolved oxygen in the range of 3 milligrams per liter. It is, therefore, important that the degree of dissolved oxygen saturation be considered in establishing the level at which reaeration should be undertaken.

AERATION EXPERIENCE IN WISCONSIN

Flambeau River

Experience with river reaeration on the Flambeau River extends back over an 18-year period of study and evaluation. Pixley Dam is located just upstream from the location of the summertime zone of accelerated reaction rates and at the upper end of the critical zone of depleted dissolved oxygen levels for the particular stretch of the river that extends downstream from the City of Park Falls where a pulp and paper mill is located.

The earliest work on this stream undertook the introduction of air through a bed of diffuser plates that extended across the bottom

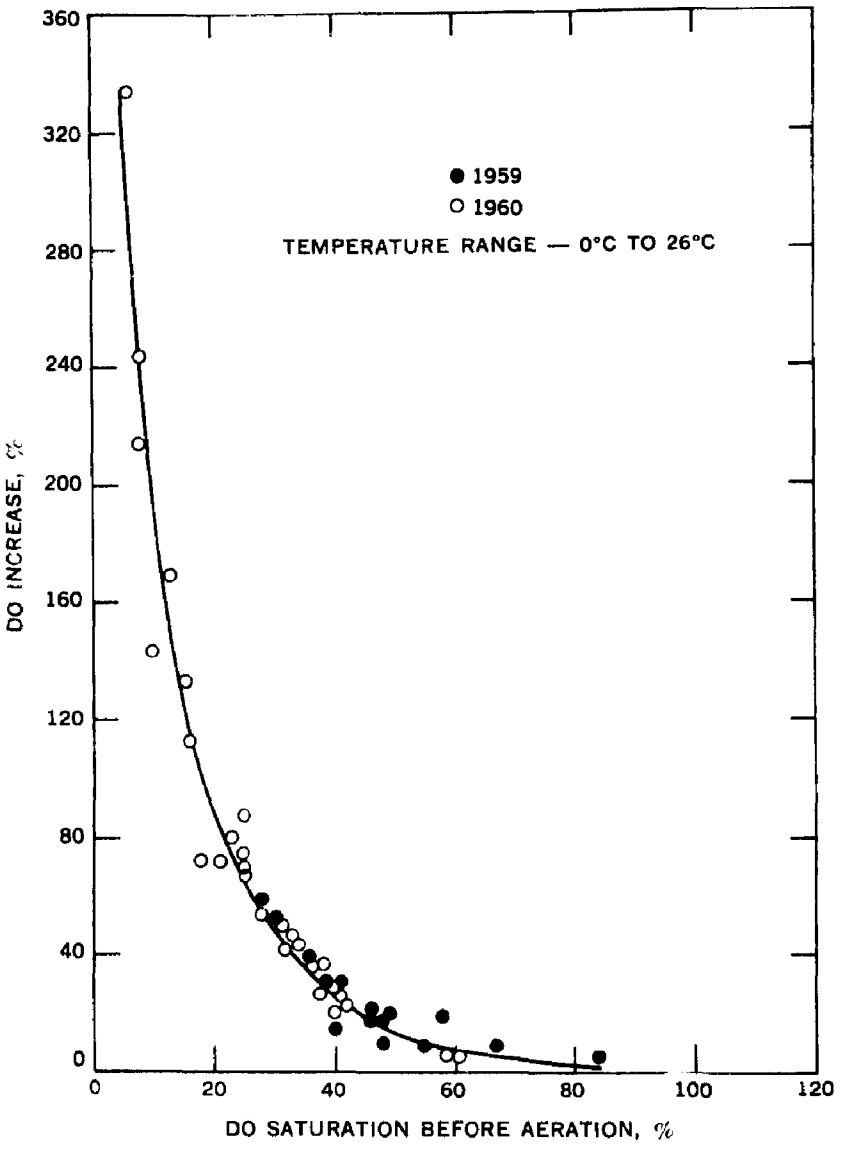

Figure 1 — Relationship of DO saturation to DO absorption by turbine aeration at Pixley Dam.

of the tailrace; later, diffusers were added in the headraces. Appreciable increases in the amount of dissolved oxygen were obtained by this method of aeration, but at a rather low level of aeration efficiency (on the order of 6- to 8-percent oxygen absorption for the air introduced to the water). Many of the original questions about reaerating a river were settled in the preliminary experiments with the diffuser assemblies. Air introduced into the headrace and passing through the turbines did not in any way seem disadvantageous from the standpoints of vibration or corrosion problems.

A brief description of the flow pattern of the river may be helpful in gaining an understanding of the conditions that had to be met to obtain any reasonable advantage from stream aeration.

The Flambeau River receives no known man-made wastes above Park Falls. The river flow is controlled principally by releases from the Flambeau reservoir. The drainage basin at the reservoir outlet is 666 square miles, while at Park Falls the basin measures 720 square miles. The reservoir outlet produces a controlled release of at least 609 cfs 50 percent of the time, and at least 150 cfs 95 percent of the time.

At Park Falls, wastes from a sulfite pulp and paper mill, as well as treated sewage effluent, reach the stream. The strong spent sulfite liquor is either employed as roadbinder or disposed of by hauling for land disposal. Pulp-washing wastes are sprayed on an extensive area of bark fill and leach to the stream. Normal papermill wastes are also discharged to the stream. All wastes, including treated sewage effluent, reach the stream just below Mill Dam at Park Falls, the first dam below the reservoir.

Wastes discharged at this point almost immediately enter the flowage area formed by Lower Dam. Some added holding time is thus provided and the dissolved oxygen decreases. After discharge through Lower Dam turbines, the stream flows more rapidly for about a mile before entering Pixley Dam flowage, an extensive body of water providing considerable holding time. The level of dissolved oxygen in the stream continues to drop through the flowage area and reaches critical levels at Pixley Dam. Discharge from Pixley turbines enters Crowley Dam flowage almost immediately, and this body provides further time for waste decomposition. Below Crowley Dam the river flow is more rapid and the stream is used for recreational purposes, including fishing and canoeing. The objective of earlier consideration of compressed air aeration at Pixley Dam was to improve the section of stream below Crowley Dam down to Oxbow, a resort area located about 25 stream miles below Park Falls. The critical dissolved oxygen conditions developed at the Pixley Dam outlet, 7 stream miles and two flowage areas below Park Falls, and made this accessible point the likely location for aeration facilities.

In 1957 the first experiments with turbine aeration were initiated at Pixley Dam, and when the better efficiency of this method of aeration was proven, the diffuser assemblies were placed in standby. Hydroturbine aeration has been studied each summer since 1957 and during all seasons at that location on the Flambeau River. Two of the three turbines at this dam were equipped for aeration and were operated in excess of 250 days during 1958 and 1959. The aeration facilities were in operation for 144 days in 1960 and for about the same number of days in 1961. Dissolved oxygen levels above the point of aeration at the dam have averaged from 3.1 to 4.3 milligrams per liter for the entire year and from 1.1 to 3.3 milligrams per liter during summer operation. Water temperatures were relatively low, however, on the order of 20°C or less for most of these operating periods. At these temperatures the degree of saturation was usually less than 40 percent, so that aeration efficiency was good in terms of oxygen pickup by the water. Increases in the dissolved oxygen content of the water were on the order of 1 milligram per liter or better.

Lower Fox River

Five dams along the 39-mile stretch of the Lower Fox River between Lake Winnebago and Green Bay are equipped for hydroturbine aeration. Operators at these dams are ready and quickly able to start aeration through the turbines whenever oxygen levels along the river drop below 3 milligrams per liter.

Three water wheels are equipped for aeration at Kimberly. One turbine aeration unit was available and operating in 1958 when conditions of low dissolved oxygen prevailed, but during 1959, 1960, and 1961 water flow conditions on the Fox River were at relatively high levels and dissolved oxygen concentrations remained above 3 milligrams per liter at that location. No aeration was practiced in those years. At Combined Locks, three hydroturbines for power production are now equipped for aeration. One unit was operated for 35 days in 1959 and all three for 19 days in 1961. The dissolved oxygen pickup was substantial in 1959 when the dissolved oxygen level dropped to 0.6 milligram per liter, but oxygen absorption was much less evident in 1961 when the average dissolved oxygen was 2.62 milligrams per liter ahead of the point of aeration. At Rapid Croche Dam farther downstream, hydroturbine aeration was practiced with one turbine for 28 days in 1958 and 85 days in 1959, but not at all in 1960 when stream flows were high and dissolved oxygen levels were above 3 milligrams per liter. A second turbine was equipped for aeration at this dam in 1961, and aeration has been in progress for 72 days with the season of operating continuing. During periods of operation, the dissolved oxygen levels have been shown to be increased substantially by turbine aeration.

At Little Rapids, aeration is conducted through the water wheels operating six grinding wheels in the groundwood mill. Two wheels were equipped for aeration in 1959, four in 1960, and six in 1961. Operating conditions at this aeration facility are unique in that the low head turbines operate at tail-water level, and the water wheels do not create enough suction to draw their own supply of air. Blowers introduce the air to the wheels at this dam.

A fifth power dam at DePere on the Lower Fox was equipped for aeration in 1961, but as yet this unit has not been operated for a sustained period of time and no data are available.

Wisconsin River

Twelve dams along the Wisconsin River have been equipped for hydroturbine aeration. Some of these dams are located in stretches of the river that are below the critical zone of oxygen depletion during warm weather periods of high reaction rates. These dams, however, are located in stretches of the river that become critically low in dissolved oxygen as the critical zones of low oxygen stretch farther downstream to reach the dams. Preliminary trials have been made and it is expected that hydroturbine aeration will be operated at these dams during wintertime conditions. For those dams for which summertime operating data are available, the oxygen pickup by the

water has been on the order of 1 milligram per liter or more in most cases. This amount may at first glance seem insignificant, yet it amounts to 5,400 pounds of oxygen per day per 1,000 cfs of stream flow. The oxidation activity of the stream is considerably increased with tonnage oxygen supplied at these levels.

Table 1 shows the percentage of dissolved oxygen increase and the increase of dissolved oxygen in pounds per 1,000 cfs of daily stream flow for those hydroturbine installations where analytical data are available. A wide variation in the percent of dissolved oxygen increase can be noted, ranging from 2.7 to 1,173 percent. The value of this information lies chiefly in emphasizing the importance of carrying out aeration during periods when the level of dissolved oxygen saturation is less than about 40 percent. It is seldom profitable to attempt aeration when the saturation level is above 40 percent because efficiencies are low. It has been mentioned that most dam operators have agreed to start their aeration facilities when the dissolved oxygen drops below 3 milligrams per liter during warm weather operating periods. The information in Figure 1 and Table 1, therefore, suggests the importance of carrying this operational criterion a step further. This would involve starting an aeration facility when the dissolved oxygen saturation drops below 40 percent.

TABLE 1. DISSOLVED OXYGEN INCREASE BY REAERATION

Location	Year	DO increase, mg/l	DO increase, %	DO increase, pounds/day/ 1,000 cfs
Combined Locks	1959	1.2	200.0	6,480
	1961	0.07	2.7	378
Rapid Croche	1958	1.5	Total	8,100
	1959	1.8	233.0	9,720
Little Rapids	1959	0.35	23.8	1,890
	1960	0.47	21.4	2,538
	1961	0.67	40.4	3,618
Hat Rapids	1959	1.17	260.0	6,318
	1960	0.71	51.0	3,834
	1961	0.77	110.0	4,158
Tomahawk (Exp.)	1961	1.76	1,173.0	9,505
Rothschild	1959	1.80	176.5	9,720
	1960	1.11	40.7	5,994
	1961	1.45	114.2	7,830
Mosinee (Exp.)	1961	1.00	66.7	5,400
Pixley	1958	1.3	37.1	7,020
	1959	1.2	27.9	6,480
	1960	0.9	23.1	4,960
	1961	1.0	32.3	5,400

The value of aeration from the practical standpoint can be shown in the increase in pounds of dissolved oxygen per day per 1,000 cfs of stream flow. Table 1 shows that this varies from 378 pounds of dissolved oxygen pickup per 1,000 cfs in a marginal period of aeration upward to nearly 10,000 pounds of increased oxygen per day per 1,000 cfs. It is apparent that most of the hydroturbine aeration facilities installed in Wisconsin are capable of introducing about 2½ tons of oxygen to 1,000 cfs of daily stream flow; as the methods of introducing oxygen are improved, it is considered likely that most installations can approach the point of introducing 5 tons of oxygen per day per 1,000 cfs of stream flow.

COST OF STREAM REAERATION

A thorough comparative evaluation of capital and operating charges for various methods of introducing oxygen into large streams, rivers, and quiescent water bodies is much needed. Several preliminary evaluations have been undertaken.

Capital Charges

The capital costs for pumping air and laying diffuser beds across a stream or in lakes or bays to achieve direct aeration by diffusion methods may be substantial. On the other hand, hydroturbine aeration may, by use of existing facilities designed for other purposes, be found to contribute substantially large amounts of oxygen with little or no outlay for equipment. Hydroturbine aeration can and is being achieved in several of the 18 installations reported in this paper with little or no alteration of the existing turbine equipment. The simplest turbine aeration system uses draft tube vents, which are often available to introduce air for control of vibration. These are merely opened and used for aeration in some of the cases cited.

Not all hydroturbine installations are equipped for venting of air to the draft tube or wheel. Modern propeller-type turbines usually require special venting, and this can be a considerable undertaking through massive concrete foundations.

Most hydroturbines can apparently benefit from installation of carefully designed venting to fit individual operating conditions and plant design. Opinion varies as to conversion costs under these conditions, but apparently the average cost would be in the range of $5,000 or less for each turbine, not considering down time. This estimate is given merely to provide an order of magnitude.

Operating Charges

The costs of operating aeration facilities vary widely with the method and the conditions that prevail at individual installations (Table 2). The mechanical and diffusion methods of introducing oxygen to the water may have substantial operating charges for power, labor, and supervision.

Turbine aeration at power dams appears to be a low-cost method under most conditions, with charges largely confined to the loss of

power production potential for any given turbine. The exact extent of the loss in power production remains a question not easily answered on a quantitative basis at each of the several power plants where preliminary evaluations have been undertaken. The general picture based on observations made by operators at the hydroturbine installations seems to favor a power loss on the order of 5 percent or less at most low-head dams (15 to 25 ft) and less at high-head installations (exceeding 100 ft).

TABLE 2. COMPARISON OF COSTS FOR AERATION AT PIXLEY DAM

	Diffuser aeration	Turbine aeration
Stream flow, cfs	880	317
O_2 absorbed, lbs/day	2,875	3,330
O_2 absorbed, lbs/1,000 cfs/day	3,270	10,340
Power used, KWH/day	1,320	1,040
Power used, KWH/lb of O_2	0.46	0.31
Cost of Power*/ton O_2 absorbed	$12.85	$8.45
Seasonal operating cost to absorb 5 tons of O_2/day (45 days per year)	$2,900	$1,900
Annual maintenance cost	$1,000	negligible
Installation cost to give 5 tons O_2/day/1,000 cfs	$39,000	$2,000

*@ 1.4¢/KWH.

An example of the problem faced in determining costs for loss in power production may be cited. In this case, panel board readings showed power production from one turbine to be 677.7 kilowatts with the aeration turned off and 599.8 kilowatts with the aerator on. The apparent loss of 77.9 kilowatts amounted to 11.5 percent. The water flowing through the turbine during these tests was determined to be 791.6 cfs with the aerator off and 752 cfs when the aerator was on. Aeration thus reduced the amount of water going through the turbine by 39.6 cfs, which is a 5-percent reduction in throughput.

The power production per unit of water flow is then calculated to be 0.8561 kilowatt per cfs with aerator off and 0.7976 kilowatt per cfs with the aerator on, or a loss of 6.8 percent, which appears as a truer basis for judging the loss of power by the individual turbine during the period of testing.

One must also consider that the restriction of 5 percent of water flow through the individual turbine actually saves this water for later use by that turbine or for use by other turbines if they are available, as is usually the case when summertime operation of hydroturbine aeration facilities is employed during the season of low water flows. With this added consideration, it is readily apparent that the actual loss in power in this example is substantially less than 5 percent of that when operating without aeration.

The overall costs of hydroturbine aeration appear reasonable and economically supportable for the installations surveyed.

CONCLUSIONS

1. Reaeration of oxygen-depleted waters is being successfully developed as a supplementary method of alleviating critically low levels of dissolved oxygen and of increasing the self-purification capacity of streams. As such, stream reaeration is proving to be an important new tool for water pollution control.

2. Mechanical methods of aeration and diffusion of forced air appear promising and probably will find specific applications, but in general appear to be relatively expensive in terms of capital and operating charges.

3. Of the methods of aeration studied and applied to large flows of water, hydroturbine aeration has received widest application, with 18 dams having one or more turbines equipped for aeration in Wisconsin in 1961. Other such installations have also been made and operated on a commercial scale elsewhere.

4. Costs of hydroturbine aeration are considered to be practical and economically feasible in the installations thus far made. Equipment alterations are usually a low-order expense and operational charges appear to be largely a matter of losing a certain percentage of the power production of a turbine, with the loss estimated to be usually 5 percent or less of normal rates for total power production in a multiple turbine installation during seasons of low water flow.

5. The efficiency of introducing air into water has previously been estimated to range to 25 percent with hydroturbine aeration. Data collected for his report indicated that most hydroturbine aeration assemblies now operating can add as much as 2½ tons of oxygen to a stream per day per 1,000 cfs; that several assemblies are now adding as much as 5 tons of oxygen per day per 1,000 cfs; and that well-designed installations for aeration could further increase this efficiency.

6. Each ton of oxygen absorbed by the water from stream aeration facilities greatly increases the capacity of the stream to handle the residual oxygen demand from wastes discharged from the often overloaded treatment plants of cities and industries.

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DISCUSSION

W. S. Lee

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Mr. Wisniewski is to be complimented for the pioneer work in stream reaeration done under his direction in Wisconsin. With the cooperation of many industries and other participating groups, he and his associates have accomplished a formidable task in arranging for reaeration in hydroturbines in about 30 dams on 3 rivers in Wisconsin.

This brief discussion compares his results with the results of similar reaeration experiments conducted by my company at one dam in South Carolina. These experiments are a part of a comprehensive program of water-quality monitoring and research on rivers and lakes within the service area of Duke Power Company in North and South Carolina. This program is directed by Mr. J. Ben Stephenson, Supervisor of Water Research for our company, who is here today.

Our aeration experiments were conducted at the Wylie Station plant located near Rock Hill, South Carolina, on the Catawba River. This station is one of a series of dams operated by Duke Power Company on the Catawba-Wateree River in North and South Carolina. Figure 1 shows a profile of this river on which there are 11 dams with impounded reservoirs and 2 open stretches of free-flowing river in the 221 miles of river shown on the profile.

Significant quantities of BOD load are brought into Lake Wylie by tributary streams. Along the river downstream of Wylie Station are substantial industrial developments involving waste effluents. These developments include a textile finishing plant, a large synthetic textile plant, a large pulp and paper mill, a bleachery, and municipal effluents treated to various degrees. Because of the waste assimilative work-load on this section of the river, Wylie Station was selected as the most appropriate for reaeration experiments.

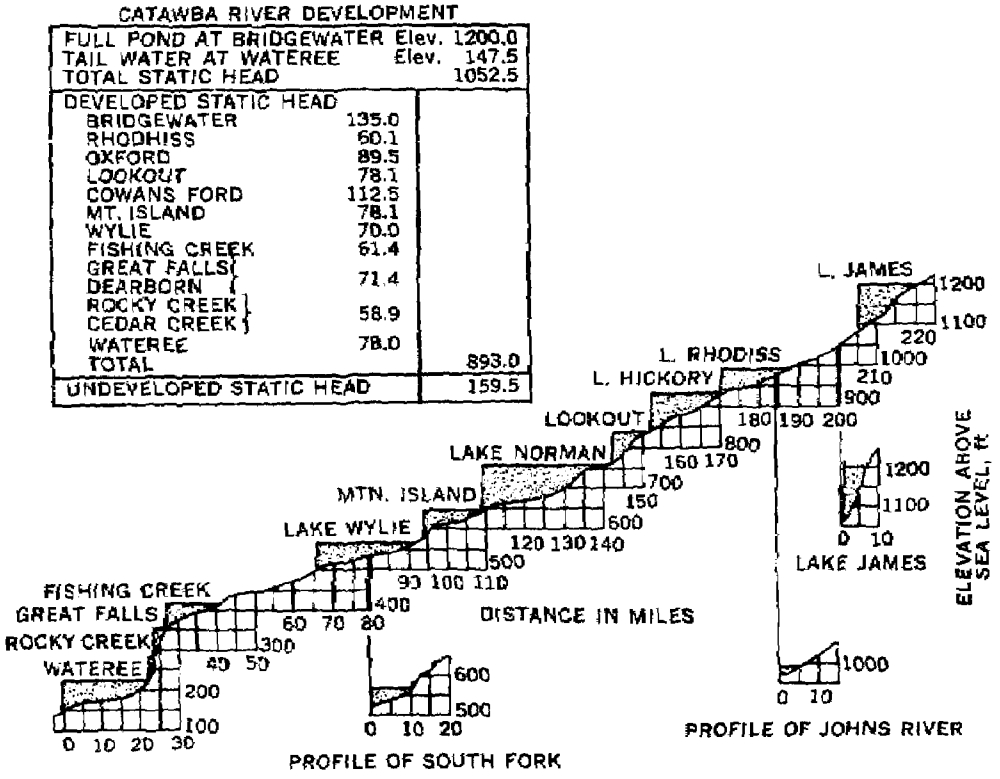


Figure 1 — Profile of Catawba River.

Mr. Wisniewski's work in Wisconsin was done on several types of hydro turbines ranging from about 185 to 1,000 kilowatts in capacity. The dams had heads ranging from a minimum of 7 feet to a maximum of about 22 feet. In contrast, Wylie Station has 4 Francis turbines, each rated at 15,000 kilowatts, and operates under a gross head of about 70 feet. Wylie dam impounds a reservoir with a full-pond storage of about 280,000 acre-feet. During the late summer months when reservoir stratification occurs, there is some degradation of the dissolved oxygen in the bottom waters of this reservoir. This variation in dissolved oxygen content with depth of the lake is shown on Figure 2 which represents data taken on August 28, 1959, a day when the hypolimnion was particularly low in oxygen. Figure 3 shows a cross section of the Wylie Station. By a series of velocity measurements at various depths, we have determined that the plant's turbines draw with about equal velocity from all reservoir depths when operating from half load to full load. As the load is decreased below half load, less of the oxygen-rich surface water contributes to the flow through the turbines. The setting of these units with respect to tail-water elevation is such that the vacuum breakers are not operative unless the units are at very low load. During medium to high loads, no vacuum occurs in the draft tube, but, to the contrary, a positive pressure exists.

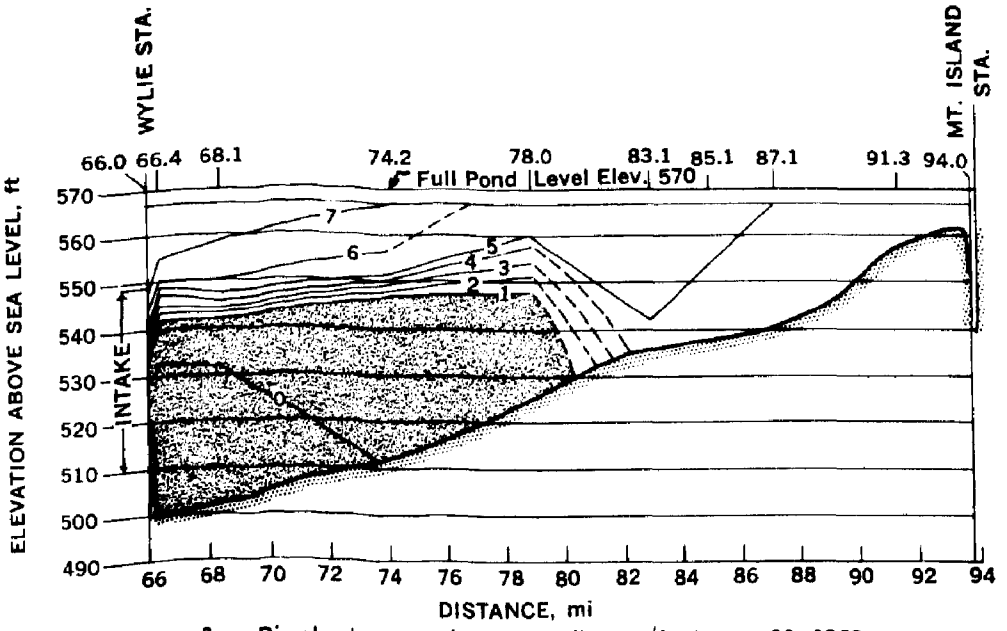
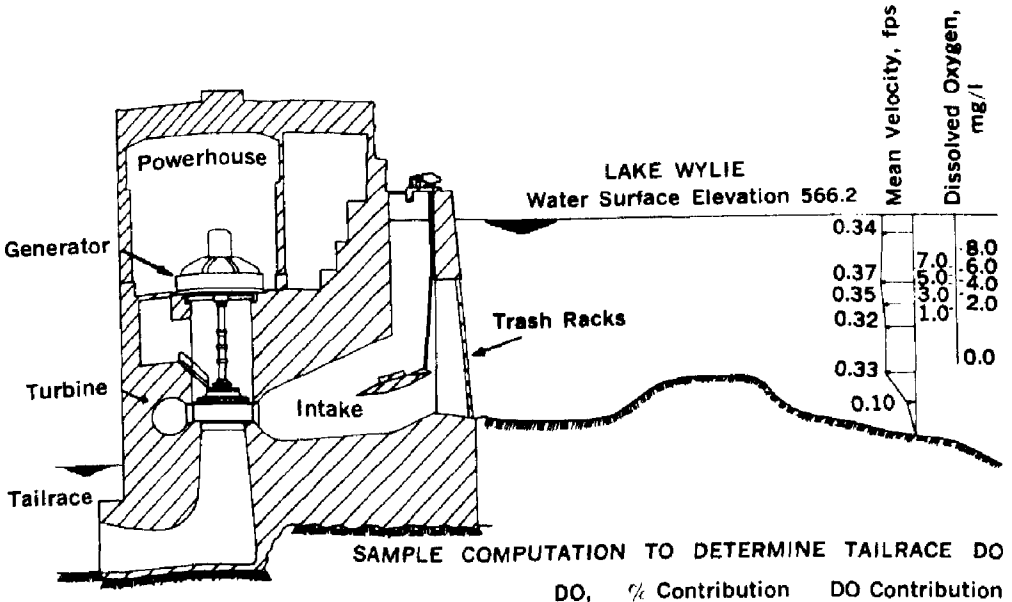


Figure 2 — Dissolved oxygen in Lake Wylie, mg/l. August 28, 1959.



SAMPLE COMPUTATION TO DETERMINE TAILRACE DO

Depth Interval	DO, mg/l	% Contribution 10,200 cfs	DO Contribution 10,200 cfs
0-5	8.4	10.4	0.87
5-10	8.4	11.4	0.96
10-15	7.8	12.0	0.94
15-20	4.8	12.1	0.58
20-25	1.4	11.7	0.16
25-30	0.3	10.8	0.03
30-35	0.2	10.4	0.02
35-40	0.0	9.8	0.00
40-45	0.0	8.1	0.00
45-50	0.0	2.6	0.00
50-55	0.0	0.7	0.00

CALCULATED DO = 3.56 mg/l

OBSERVED DO IN TAILRACE DURING SAME PERIOD VARIED FROM 3.3 mg/l TO 3.7 mg/l

Figure 3 — Velocity patterns at Wylie Station. August 25 and 26, 1959.

Table 1 gives results of the 1959 tests at Wylie Station to determine the effect of vacuum breakers on the discharged dissolved oxygen. Two runs of 2 hours each were made on 3 days with all four units running at a load of 1,000 kilowatts each. This is about 7 percent of their rated load. The unit load was held constant throughout the day. In the first run each day, the vacuum breaker valve was blocked shut so that no air could rush in to satisfy the negative pressure in the draft tube. The second run allowed the vacuum breaker valve to open so that air entered the draft tube for reaeration.

TABLE 1. RESULTS OF TESTS AT WYLIE STATION TO DETERMINE EFFECT OF VACUUM BREAKERS ON DISCHARGED DISSOLVED OXYGEN [a]

Date of sampling, 1959	Discharge, cfs	Loading, kw	No. of units operating	Vacuum breaker operation	DO discharged		DO gain, mg/l
					mg/l	% sat.	
Aug 28	2600	4000	4	No	2.0	37	—
Aug 28	2600	4000	4	Yes	5.7	73	3.7
Sept 12	2600	4000	4	No	4.9	62	—
Sept 12	2600	4000	4	Yes	7.7	98	2.8
Sept 13	2600	4000	4	No	5.5	69	—
Sept 13	2600	4000	4	Yes	8.4	102	2.9
Sept 14	1400	6000	1	No	4.6	54	—
Sept 14	1300	2000	2	Yes	7.4	86	2.8
Sept 16	1400	6000	1	No	5.0	58	—
Sept 16	1300	2000	2	Yes	7.1	83	2.1

[a] The dissolved oxygen values are average values obtained from a series collected at 15-minute intervals for 2 hours. The values in the series showed consistency within plus or minus 0.2 mg/l, verifying a stable flow condition.

The gain in dissolved oxygen varies from 2.1 milligrams per liter to a maximum of 3.7 milligrams per liter. In the August test, the increase of 3.7 milligrams per liter of dissolved oxygen resulting from the vacuum breaker operation is equivalent to a net gain of about 20,000 pounds of oxygen per 1,000 cfs per day. The gain of 2.1 milligrams per liter of dissolved oxygen on September 16th is equivalent to about 11,000 pounds of oxygen per 1,000 cfs per day. These values are about double the increase in dissolved oxygen experienced by Mr. Wisniewski on Wisconsin rivers. In the Wisconsin studies it was found that reaeration was not efficient or productive at temperatures above 20°C when the dissolved oxygen exceeded 3 milligrams per liter before reaeration. In contrast, all of the September tests conducted at Wylie Station started with dissolved oxygen values of more than 40 percent of saturation and showed dissolved oxygen increases as great as 2.9 milligrams per liter. It must be remembered, however, that all of the Wylie tests were conducted at very low turbine loads in com-

parison to the machine ratings, as the vacuum effect is not present at higher loads.

Mr. Wisniewski's work in Wisconsin included several measurements that we did not take during our experiments. The flow through our turbines was estimated from the turbine and generator performance curves and not from flow measurements. We were not able to measure the flow of air through the vacuum breaker pipe, and therefore no computations of absorption efficiency were possible. Mr. Wisniewski's work includes computations of kilowatt hours lost per pound of oxygen added due to decrease in turbine efficiency from adding air below the runner. At Wylie Station, when operating at sufficiently low loads to cause the vacuum breaker to open, the turbines are at their least efficient operating point with or without the vacuum breakers. As a consequence, our kilowatt hour loss due to low load operation exceeds the kilowatt-hour change that might be exclusively effected by admitting air to the draft tube.

When additional work on hydroturbine reaeration is done in Wisconsin, in South Carolina, and elsewhere, it may be possible to better predict the empirical parameters of reaeration at a variety of installations. It is suggested that reaeration effectiveness depends upon the turbine characteristics, the load being carried, the setting of the wheel above tail-water elevation, the vacuum-breaker arrangement, and the shape and dimensions of the draft tube. These physical relationships are in addition to the chemical factors suggested by Mr. Wisniewski.

As we continue our work in this area, we are sure to find more answers and achieve a better understanding of the phenomena involved. It has been a pleasure to discuss the highlights of our work on the Catawba River and to compare it with the notable work in Wisconsin described by Mr. Wisniewski.

DISCUSSION FROM THE FLOOR

Dr. Ingols, Georgia Institute of Technology: In 1957, a paper was submitted to the editor of the Journal of the AWWA, entitled "The Pollution of Downstream Rivers by Hydraulic Power Installations." The editor would not accept the paper with that title on the basis that it merely described a pollution effect. Our meeting here today is at least a partial confirmation of the author's thinking that possibly one could define as pollution the effect of a power dam in degrading downstream water quality.

Mr. Lee, Duke Power Company: There are some of us at this symposium representing power companies, and a number of others representing our sister agencies with the Government who generate power. I do not speak for all of these folks, but I might comment that my company's interest in the subject of pollution and waste assimilation is a strong one. Several fingers have been pointed at us at this symposium, but let me say we are endeavoring in the Carolinas

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to create in these rivers the capacity for doing work that will allow us to go to Michigan where Professor Velz lives, and to Cincinnati, and to Atlanta, and say, "Look, Industry, we have the capacity down here in the Carolinas; come and join us." So our interest is not entirely altruistic.

Mr. Wigglesworth, U. S. Department of Interior: I am concerned with the loss of energy that occurs with turbine aeration. Mr. Lee, in view of the 65 percent loss of energy and the substantially greater oxygen absorption that you cited, do you believe that the greater oxygen absorption was due to the greater loss of energy, or perhaps the reverse, that the greater loss of energy was due to the greater absorption?

Mr. Lee: No, sir, our loss of energy is only very indirectly associated with the aeration phenomenon. Our loss of energy results from not operating at the optimum point on the efficiency curves of the machines that are installed in the dam at minimum discharges, not from admitting air to the turbine. The loads we are talking about are very low with respect to plant capacity. On occasion we operate at this low load on off-peak when water quality downstream indicates it is needed, but this is at some sacrifice of energy. Some emergency might occur in our system that would preclude such operation, but insofar as we are able, we try to be good neighbors and help out when there is trouble downstream.

We are plagued with the characteristics of the machinery and not the effect on efficiency due to the air entering the turbine.

Dr. Falk, E. I. du Pont de Nemours and Company: Mr. Wisniewski, if the loss in efficiency means that the power is produced at a greater cost, who pays this extra cost and who do you think ought to pay it?

Mr. Wisniewski, Wisconsin Committee on Water Pollution: This will vary with the power plant installation. For example, the Flambeau Paper Company owns the Pixley Dam and the downstream dams. They figure that the turbine aeration is their contribution towards helping improve the stream.

We also have installations on the Fox River where a power utility will own a dam and its customer, a pulp and paper mill, will ask the utility to provide reaeration at its dam at a critical time. The pulp and paper mill will then reimburse the power utility for the power loss.

On the Wisconsin River all the power plant operators are members of the Wisconsin Valley Improvement Company and their operation is coordinated by the secretary of this company. During the summer, daily dissolved oxygen determinations are made at every power dam along the river and these are telephoned in to the secretary of the Wisconsin Valley Improvement Company. Depending upon his listing of the dissolved oxygen concentrations on that stream, he then issues instructions indicating which dams should operate to provide reaeration. You all know, as the temperature changes, the

critical zone or the zone of most serious depletion moves up or down the stream and may not necessarily be in the best position for reaeration. The Wisconsin Valley Improvement Company is trying to add oxygen as efficiently as possible, and to provide aeration at the bottom of the oxygen sag curve if possible.

Mr. Grounds, U. S. Army Engineers: Artificial aeration of streams is apparently one method of maintaining higher dissolved oxygen levels in critical reaches. Would you comment, Mr. Wisniewski, on what is being done by your State in the updating of sewage treatment practices?

Mr. Wisniewski: Wisconsin is probably the leading state in updating sewage treatment practices. We have over 400 communities that are connected to about 375 sewage treatment plants. These plants serve 99.9 percent of the sewered population, and provide treatment that reduces the pollutional load from this population by 76 percent. I challenge anybody to match that!

In the field of industrial waste treatment, the pulp and paper industry in Wisconsin has built more waste utilization facilities than there are any place else in the world. The only two yeast fermentation plants in the western hemisphere are located in Wisconsin. We are always proud to say that in Wisconsin we provide employment for 200 people in the production of products from a waste that was formerly thrown away: spent sulfite liquor. We have a number of evaporators; there is more Type 316 stainless steel in the Wisconsin pulp and paper industry than there is in all the rest of the industry in the United States. The United States' average for recovery of pulp mill solids, i.e., sulfite mill solids, is 20 percent; Wisconsin's average is 40 percent. We have the Sulfite Pulp Manufacturers Research League in Wisconsin. This was made up of the first 15 Wisconsin pulp mills. Since their organization in 1939, they have spent several million dollars on research and development of these utilization processes.

We say in Wisconsin that there is no excuse for stream pollution by cannery wastes. We worked for years with the National Canners Association and the Wisconsin Canners Association, and the pollutional load from cannery waste has been reduced by 95 percent. Most of our methods of disposal involve discharge of wastes on land. Our milk waste disposal facilities are providing about 67 percent reduction in the pollutional load.

Mr. Grounds: I did not ask that question to put you on the spot, but rather to bring out that you are doing other things about trying to improve your streams. I happen to enjoy fishing in Wisconsin myself, so I know you do a good job.

Mr. Wisniewski: I wanted to make the point in my talk that we do recognize that even when we get 90 and 95 percent waste removal on some of the small streams in Wisconsin, we still have to go to actual stream treatment in terms of stream reaeration to maintain the quality in those streams.

Let us consider the situation that develops when 1 square mile of what was formerly farmland becomes urbanized. In Wisconsin we base the design of our treatment plants on the 7-day minimum flow in the past 10 years; we can expect that this square mile will discharge 0.1 cfs at its low-flow runoff. A square mile is 640 acres. If we say 140 acres of that will go for roads, that will leave 500 acres to build on. If we build four homes per acre that is 2,000 homes; at an average of three people per home (and that's a low average) that is 6,000 people. The 6,000 people on that 1 square mile will then be producing 1,000 pounds of oxygen demand for a runoff of 0.1 cfs. We must design to meet these conditions. We must depend on water that is coming off from other parts of the watershed to provide dilution even for the effluent from a plant providing a high degree of treatment. So you realize why we must go to high degrees of treatment.

One of the studies we made on self purification of streams established that at 24°C, 11 pounds of 5-day BOD would remove one part per million of dissolved oxygen from a stream. This shows why the loadings must be low.

Mr. Wilroy, Wiedeman and Singleton Engineers: Mr. Lee, in dealing with low flows on the Catawba River at Rock Hill, has any economic study been made on the reaeration that can be obtained in the stream channel below that dam compared with the reaeration obtained in the turbine itself? In other words, is your low-flow operation suppling enough streamflow and additional oxygen to provide the dilution and oxygen needed downstream by the various industries located there? And is it being provided in the most economical manner?

Mr. Lee: No comprehensive economic study of the type that was suggested to us yesterday has been made. This situation is very complex. The low flows we are maintaining are determined by the needs downstream. They happen to be about eight times the minimum 90-day flow that would occur without regulation provided by our upstream storage.

Mr. Wilroy: I just wanted to get across that there are a lot of other factors involved in the provision of minimum flows.

Mr. Lee: We well recognize that.

Mr. Morriss, Atlanta Water Pollution Control: Mr. Lee, if you discharged treated sewage effluent to a small reservoir with the proposed purpose of offsetting some of the expense of treatment by generation of power, would you anticipate that the turbine reaeration itself could play a material part in treating the effluent prior to its return to the stream?

Mr. Lee: It has occurred to us to build one of these waste storage reservoirs and say, "All right, Public, let's have no water skiing, no swimming, and no recreation: this is a lagoon." It is not a very popular thought.

We are putting in very large power installations in terms of capacity today compared to what we did with the Wylie plant in 1925. As a result, we are having to set our wheels lower and lower with respect to tail water elevation to avoid cavitation, not only from a metal loss point of view, but also from a wheel stability and vibration point of view. As a result — and we have studied this in more recent installations — the vacuum breakers will not operate as aspirators so we must use blowers, as Mr. Wisniewski has done at some installations in Wisconsin. At one project, which will have a full load discharge of 42,000 cubic feet per second, we found that in order to increase the tail race dissolved oxygen by one part per million, we needed some 14,000 horsepower in compressors to supply the necessary air. As a result, we have constructed a submerged weir at that plant.

With reference to your original question, the economics of power generation are quite complex, and I cannot answer your theoretical problem directly.

Mr. Wigglesworth: Mr. Wisniewski, can you account for the difference in results that you observed compared with those that Mr. Lee observed?

Mr. Wisniewski: It is difficult to account for the difference. I can go over our own results and show you why they are accurate.

Here are some possibilities. There must be an increased time of residence in the turbines, or what you could consider double passing or something of that sort, which gives a longer exposure of the air to the water. Also, larger amounts of air are introduced than we are introducing. Our turbines are operating under normal operating conditions, not under reduced flow conditions. The intention is to add oxygen at a minimum power loss.

We can get a higher concentration of dissolved oxygen in the tailwater, but only at a terrific sacrifice in power. We make it a practice to add air at a rate only slightly higher than the solubility of air in water, so that we can keep the efficiency of transfer in the proper range. If, for example, we added three times the amount of air that is needed, we would reduce the power output by considerably more than three times the amount of power displaced by the single unit of air. Our operations are carefully controlled, therefore, to conserve power while adding dissolved oxygen.

Mr. Lee: Mr. Wigglesworth, I have a reinforcing surmisal to support Mr. Wisniewski's comment. I think we are getting multiple opportunities for absorption of air. At low load the draft tube below the runner, the elbow, and the exit are enormous structures compared to the flow of water going through them. There is a relatively long detention time there. Also, we are measuring the tail race dissolved oxygen some 300 feet downstream from the power plant. You can observe air bubbles breaking the water surface all around the sample area; I think we are getting additional detention as well as aeration in the tail race.

IMPROVEMENT IN THE QUALITY OF RESERVOIR DISCHARGES THROUGH RESERVOIR MIXING AND AERATION

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INTRODUCTION

The economic utilization of our water resources involves the use of storage basins, both natural and man-made. In nature, a high degree of purification takes place through the filtering action of the ground, photosynthetic mechanisms deriving from sunlight and biological and physical processes depending on oxygen carried in the water and absorbed at the free surface.

In the various types of impoundments, be they for hydro-electric power, drinking water, or waste disposal, the above processes of natural purification are greatly hindered. Thus in deep hydroelectric reservoirs in many months of the year, generally throughout the summer, due to a high ambient air temperature and calm wind conditions, the body of water stratifies thermally(*1*). Then, depending on the size of the impoundment and the throughput, water may be maintained for prolonged periods away from exposure to sunlight and the atmosphere and may become deoxygenated. Discharge of such water through the turbines may lead to unacceptable conditions downstream from the point of view of fish life or purification capacity.

The consequences of such deterioration depend entirely on the purpose of the impoundment and its role in the overall water-resource system(*2*). This concept of a system is beyond the scope of the present paper, but as part of a program to establish a mathematical model of a water-resource system, the author was led initially to examine the economics of various types of reaeration. Enough quantitative data to enable trends to be expressed analytically were needed to carry out a computer optimization of the many design variables. The optimization technique was developed in the nuclear power field where, due to the background of the people involved, there is a keen awareness of the quantitative approach. Details of the technique may be found elsewhere(*3*); only brief mention is made here regarding its application in the design of reservoir installations.

Most of the ideas described in this paper found their birth in an attempt to recreate in a stagnant pool some of the conditions leading to purification in nature. Aero-hydraulic guns, as used in ice-prevention and aerobic sewage treatment(*4*), with their ability to circulate large volumes of a liquid within its own surface level are used to stimulate the conditions found in a fast-flowing river where natural turbulence leads to mixing and aeration.

THE AERO-HYDRAULIC GUN

The aero-hydraulic gun consists of a vertical pipe between 6 inches and 3 feet 6 inches in diameter, into which bubbles having approximately the same cross sectional area as the pipe are introduced intermittently from an air distributor. Figure 1 shows a common arrangement in which the air distributor is located inside the lower end of the stack pipe. The complete unit can be constructed from plastic so that in water treatment applications the equipment is virtually free from corrosion. In reservoir installations, a commonly used method of fixing the guns in position is to anchor them to concrete sinkers via brackets. Because of buoyancy forces, the guns are designed to assume a vertical position when firing.

In operation, air is fed through the hose and into the air distributor and lowers the water level in the middle and outer chambers. This action continues until the water level in the middle and outer chambers reaches the bottom of the inner chamber or central standpipe. At this point, the air is free to travel from the outer and middle chambers to the inner chamber. As soon as the air breaks the water seal at the bottom of the inner chamber, an inverse siphon motion takes place, and the accumulated air in all chambers is suddenly released through the upper opening of the inner chamber into the stack in the form of a large single bubble.

This rising bubble acts as an expendable piston, forcing the water above it up the stack and out at the top. At the same time as the bubble rises in the stack, it draws water behind it, through the ports. This water continues to flow up the stack, drawn by the same bubble. Although the bubbles are released intermittently, the flow is continuous because of the momentum of the water in the stack. The stream, on leaving the top of the gun behaves as a free turbulent jet and entrains further quantities of water in its upward movement towards the surface.

The dimensions of these bubbles are very important. Whenever the bubble fits loosely in the pipe, liquid slips past the bubble more rapidly; on the other hand, friction at the pipe wall seems to increase rapidly as soon as the cross-section of the bubble (if it were unconfined) exceeds that of the pipe. In practice these huge bubbles have the bullet shape shown in Figure 2.

As the bubbles rise, their volumes increase, and in a uniform pipe it is thus not possible to preserve their optimum relation to the pipe cross-section. However, as the linear dimensions of the bubble vary as the cube root of the volume, these changes are relatively small and, in fact, only become important for pipe lengths in excess of 50 feet. Then it becomes desirable to use a tapered or stepped pipe, if pumping efficiency is a critical consideration.

In the determination of the frequency of bubble emission, the inertia of the water column plays a dominant role. In general, at least one bubble should always be in the pipe, otherwise a large portion of the energy required to introduce the air against the hydrostatic pressure, is used in accelerating the water column.

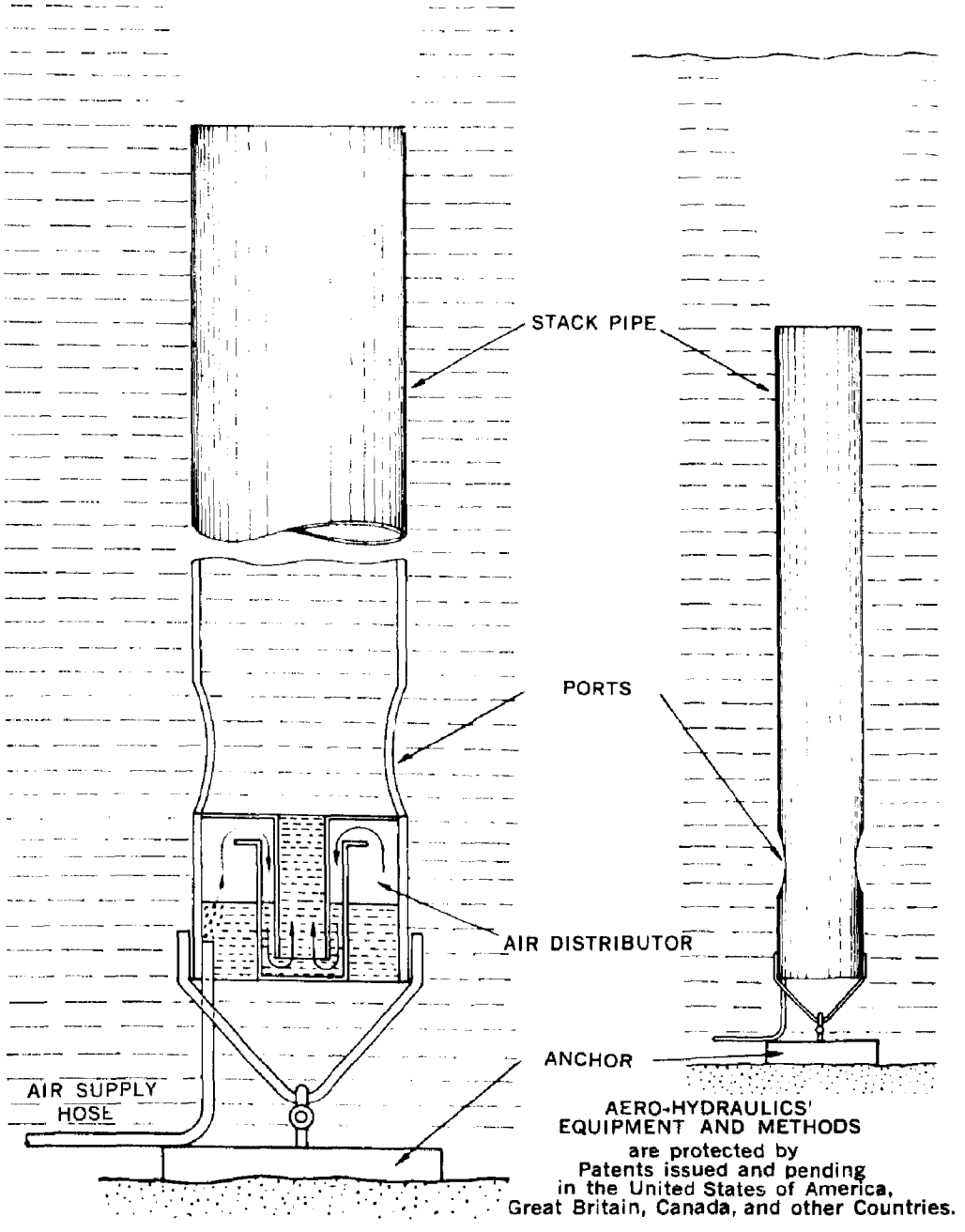

Figure 1 — Aero-hydraulic gun.

The word "optimum" has been used several times, and it should be noted that this must be related to the specific task in view. If an installation is required for aerating a deoxygenated reservoir through the production of high velocity surface currents, the design variables must be combined to achieve this result. A different combination would arise if the purpose were to destroy thermal stratification in the reservoir, for, in such a case, the requirement would be for a high

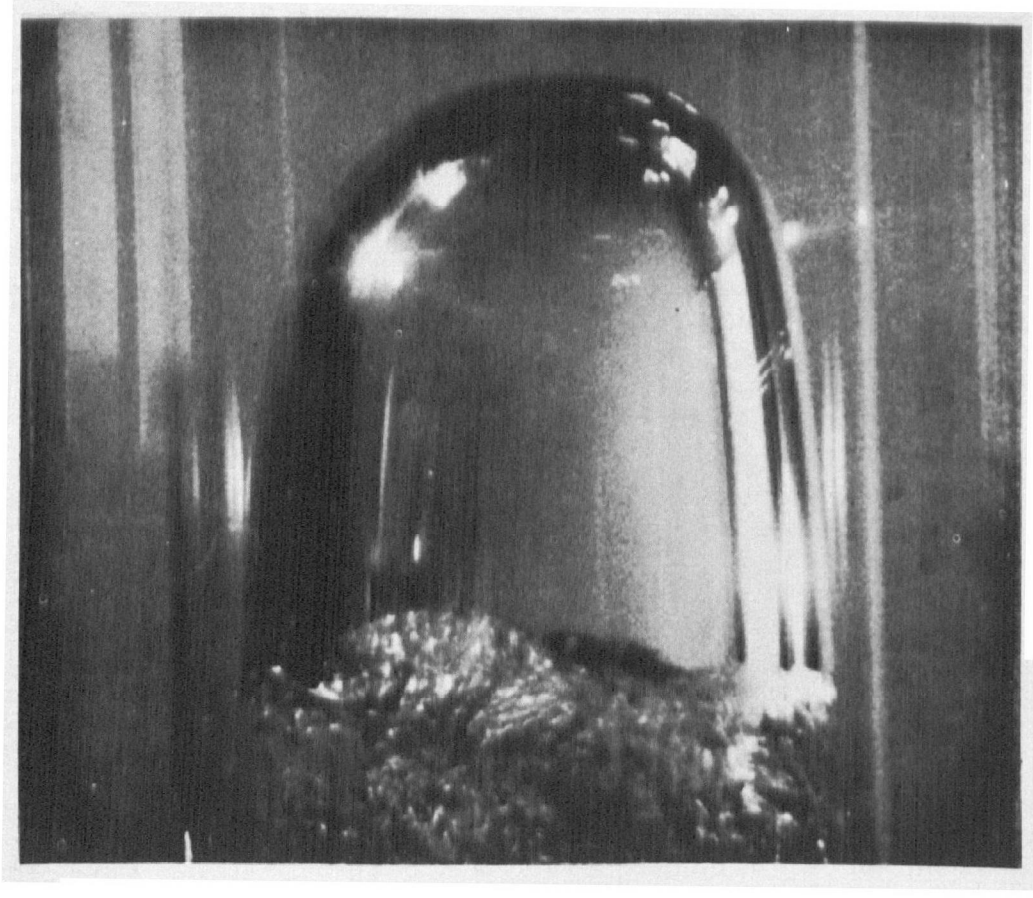

Figure 2 — Bullet shape of a piston bubble.

rate of volume mixing, irrespective of any velocities that might be produced.

To carry out such studies, the interrelations of the design variables have been determined for wide ranges of values. Figure 3 shows a performance chart covering the smaller-sized guns commonly used in reservoir installations. Many variables may be represented on such a chart. If one takes two points that represent conditions with only one independent variable changed, the dependent variable can be determined.

In Figure 3 the compressed air consumption is the volume of air used at the pressure existing at the air distributor. With such a variable, it is unnecessary to include the water depth as a variable. The chart shown relates to the design of the gun shown in Figure 1 in which the siphon is located at the bottom of the vertical stack pipe. In such a case, the hydraulic length is the distance over which the bubble acts as a piston, i.e., approximately the length of the gun. There are applications in which the pipe is extended considerably below the siphon in order to draw water from a greater depth than that to which the air is pumped. In such a case, the chart must be corrected for the additional entrance losses.

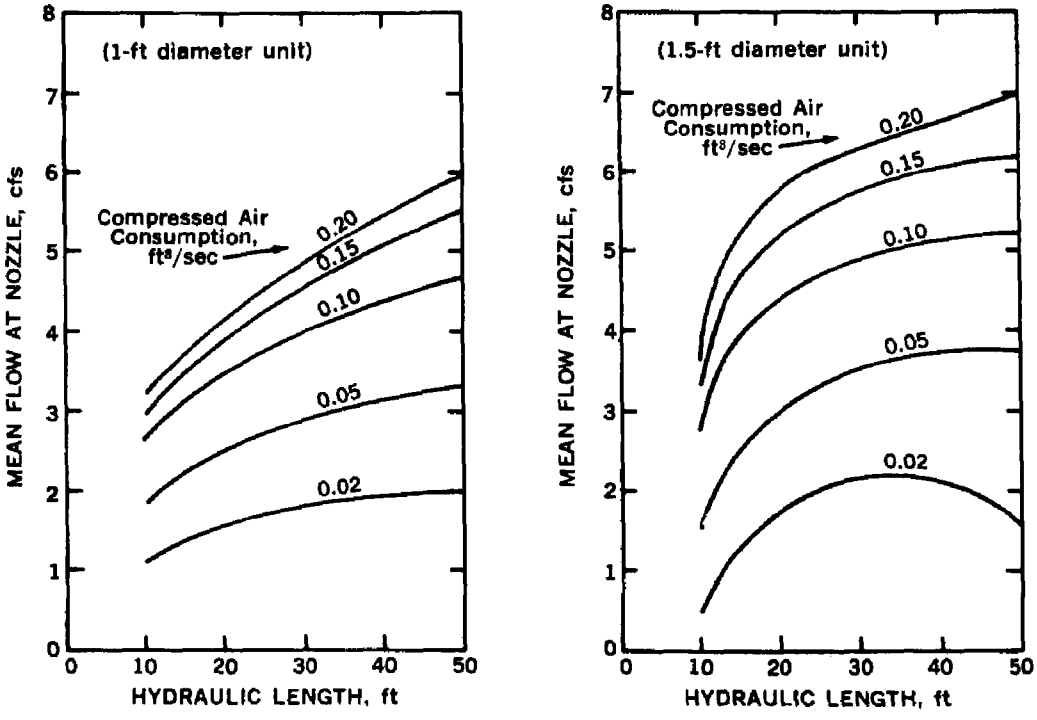

Figure 3 — Performance of aero-hydraulic units in water.

In an optimism study with many variables, the curves of Figure 3 are represented by polynomials, which are programmed for a digital computer. The chart is useful, however, in showing the general features at a glance. Thus in the lower right hand corner, where the air supply rate to a large diameter gun is low, say, 0.02 cubic feet per second, the bubbles are emitted very slowly, for example once every 20 seconds. In these circumstances the large pulsations in the flow absorb energy, causing the output to decrease with hydraulic length.

AERATION CAPACITY AND MIXING

The oxygenation produced by an installation of guns occurs in three distinct regions:

1. In the space between the mouth of the gun and the liquid surface. Here active entrainment of water by the turbulent jet is occurring and oxygen is absorbed from the large interfacial area that is produced when the piston bubbles burst on emerging from the mouth of the gun. The absorption process in this region follows the normal law(5) describing the performance of bubble diffusers, namely,

$$N_r = K_L a V (C_s - C) \qquad (1)$$

where,

N_r = rate of oxygen absorption, mg/hr.

$K_L a$ = overall liquid film coefficient, per hr.

V = liquid volume associated with each aeration unit, l

C_s = saturation concentration of oxygen, mg/l

C = existing oxygen concentration, mg/l

2. Directly above a gun, where the bubbles reach the surface, in a small area in which the turbulence is of an isotropic nature. The extent of this area depends on the depth of submergence of the mouth and may vary from a circle about 5 feet in diameter down to almost nothing. In this zone aeration follows a relation of the form,

$$N_i = K_L A_i (C_s - C) \tag{2}$$

where the liquid film coefficient, K_L, is dependent on the turbulent velocity, v_t. Approximately $K_L = v_t^{1/2}$ and A_i is the surface area over which the isotropic turbulence extends.

3. As the water spreads outward on the free surface, the turbulence becomes non-isotropic and aeration occurs through the shearing of the surface layer. In this region, which is by far the most extensive in reservoir applications, the aeration follows the same form of expression,

$$N_n = K_L A_n (C_s - C) \tag{3}$$

but with K_L depending on the square root of the surface velocity gradient, $\frac{dv}{dz}$, and A_n is the area over which non-isotropic turbulence extends.

Thus, finally, the aeration produced by a system of say, n aero-hydraulic guns, is given by,

$$N = \sum_{r=1}^{n} \left[C_1 K_L a V (C_s - C) + C_2 A_i v_t^{1/2} (C_s - C) + C_3 \left(\frac{dv}{dz} \right)^{1/2} A_n (C_s - C) \right]_r \tag{4}$$

where C_1, C_2, and C_3 are constants involving the diffusivity of oxygen and the temperature dependence of the absorption phenomena.

The values achievable for oxygen absorption depend very much on the operating conditions, particularly the existing level of oxygen concentration, C. With deoxygenated water at 20°C, aeration efficiencies of 1.6 pounds per brake horsepower are obtained at an aeration capacity of approximately 1 pound per hour. Of course these figures are dependent on the values of the design variables, gun dimensions, submergence, etc., which may not be chosen to maximize aeration efficiency.

The flow in the vicinity of the mouth of a gun is extremely difficult to describe mathematically. The zone of flow establishment(*6*) is ill defined, no doubt on account of the periodic bursting of the bubbles. At distances greater than five or six times the diameter of the gun, however, a well defined jet exists. The surface on

which the velocity in the axial direction is half the velocity on the axis, is a cone of semi-angle about 6 degrees.

Over a wide range of flows and depths of submergence of the mouth of the gun, the effect of entrainment can be represented satisfactorily by the expression

$$Q_x = \frac{Q_0 x}{DC_4} \tag{5}$$

where, Q_x = total rate of flow of water passing a section at distance x from the mouth of the gun

Q_0 = rate of flow of water emerging from gun

x = distance from mouth of gun, ft

D = diameter of gun, ft

C_4 = a constant between 1 and 3 that depends slightly on x and Q_0.

The mixing performance of a gun may be described in terms of simple mass and heat balances. Thus if an installation is effected with the guns crossing a thermocline in a reservoir, the homogenizing of the temperature, T, may be predicted by expressions of the form

$$(W_1 + W_2)T = W_1T_1 + W_2T_2 \tag{6}$$

$$H = K_hA\ (T - T_a) \tag{7}$$

where equation (6) represents mass mixing and equation (7) relates to heat exchange with the surroundings.

Such a treatment has proved completely satisfactory in predicting the performance of aero-hydraulic systems for ice prevention where accurate calculation of the resulting temperatures is often required. In these applications the vital feature is the total quantity of bottom water raised to the surface. Pumping rates of about 4 million gallons per day for the expenditure of each brake horsepower are often achieved in a properly optimized system.

DESIGN PROCEDURE

In equations (4), (5), (6), and (7), the terms for aeration and mixing can be related to the design variables, number of guns, their length and diameter, submergence, spacing, and power supply, by use of the performance chart and simple properties of jets. One can then determine the combination of variables required to satisfy some given criteria.

By having the computation programmed for a digital computer and by using a modern technique of optimization(7) one can study the simultaneous interaction of many independent design variables. As a result of this procedure one is often lead to arrangements that most probably would not have been noticed in an examination by conventional methods. The effects of changes in design assumptions can be studied realistically by comparing one optimum with another. The criterion of merit is usually the cost of a particular operation — lowering the temperature in the upper layers of a reservoir, aerating

a lagoon, and so on. Furthermore, the cost itself is a composite variable depending on capital and running costs and it is interesting to study the effect of changes in the relative importance of these factors.

Figure 4 shows the steps in the optimizing sequence. Once a mathematical model of the system has been formulated, the evaluation of the criterion of merit is programmed for a digital computer. This step merely speeds up the process of computation, albeit to a fantastic extent. The optimization proper consists of a further set of calculations in which a search is made for the optimum point. The calculation proceeds automatically, without manual intervention. As the search proceeds, information about the criterion of merit is stored and is used to modify and speed up the process. In geometrical language, one can think of a response surface in many dimensions corresponding to the independent design variables. As points on this surface are determined, a knowledge of its topography is gained and this knowledge is used in further directing the path towards the maximum or minimum, as the case may be.

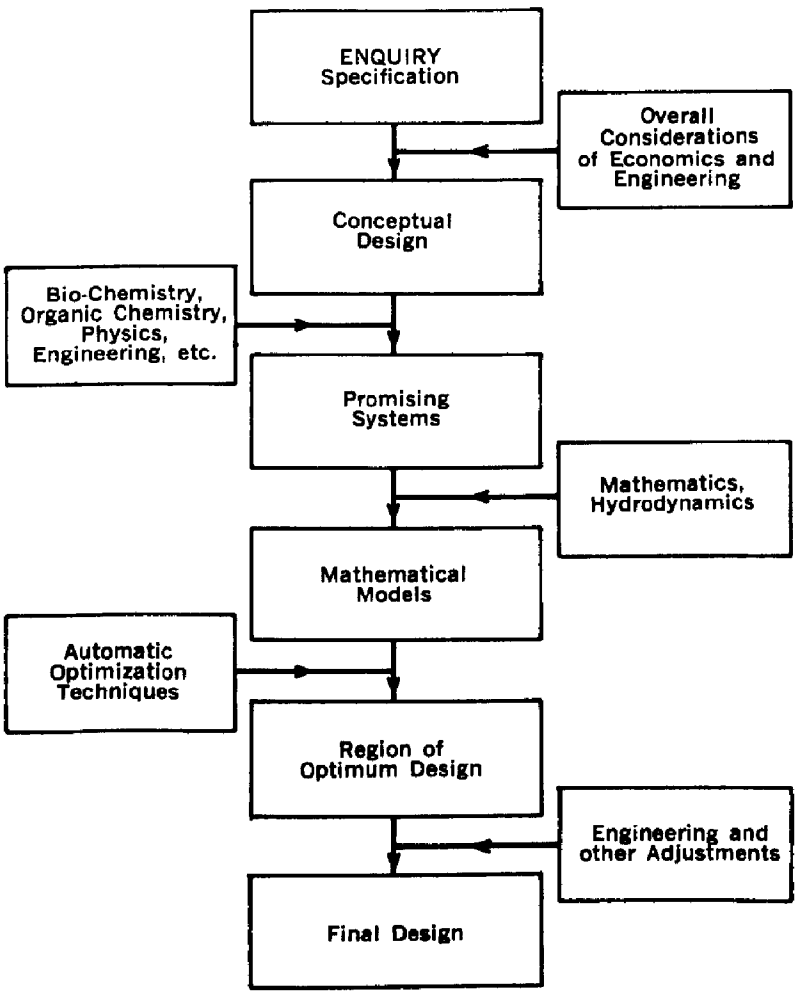

Figure 4 — Optimizing sequence for system design.

Although the hydraulic characteristics of the equipment are relatively straightforward, to determine the effect of completely altering the flow pattern in a reservoir is vastly more difficult. Here, many of the important factors involve biological and biochemical changes that may require many months or even years to evaluate. Moreover, during such prolonged periods, the surface conditions as determined by the weather may change violently and make interpretation of results very difficult. On several occasions after complex instrumentation had been installed for observations on the breaking up of stratification or reaeration, a strong surface wind caused the reservoir to overturn, and the results were completely masked.

A program to evaluate the biological effects of thoroughly mixing bodies of water that had been prone to stratification was begun in 1959 and is still under way. Tests are being carried out in Britain, Ireland, and South Africa and it is hoped that geographical coverage will enable us to assess the influence of a wide range of conditions.

There are many purely chemical or physical aspects of great importance, however, that have been studied sufficiently to provide a basis for the optimized design of installations for specific tasks such as physical mixing, temperature control, and aeration.

PRACTICAL APPLICATIONS

Blelham Tarn

To study the large-scale hydraulic and chemical effects of a system of aero-hydraulic guns under as controlled conditions as one is likely to find in nature, an installation was made in a field-laboratory lake belonging to the Freshwater Biological Association of Great Britain.

The lake, Blelham Tarn, (Figure 5), is at an altitude of 140 feet and is close to the western shore of Lake Windermere in the Lake District. It is 733 yards long, 27 acres in area, and has a maximum depth of 44 feet and a mean depth of 21.3 feet. Over the past 16 years the Freshwater Biological Association has carefully observed temperature, dissolved oxygen, chemical nutrients, and the plankton in the lake.

Between July 31 and August 14, 1961, to provide data for assessment of the physical and biological effects of mixing such a lake artificially at a time of year when it would normally be stratified, five aero-hydraulic guns were used to effect its overturn.

The immediate physical effects of the installation during the 14-day period it was operating are described in Figures 6, 7, and 8 in terms of the temperature, oxygen content and ferrous iron content of the water.

The five guns used were 17 feet long and 12 inches in diameter, and under normal conditions were capable of transferring water from the hypolimnion to the surface at a rate of 10 million gallons per day.

To spread the operation over 10 days so as to make observation easier and to avoid disturbing the bed of the lake, the combined output of the guns was restricted to 3.5 million gallons per day by reducing the frequency of bubble emission from the normal rate of 4 seconds to 9 seconds in three guns, and to 6 seconds in the other two. The guns were located in two pockets deeper than the rest of the lake. Frequent measurements at the 12 stations were consistent, and showed that records for the single station presented in Figures 6, 7, and 8 represent adequately the changes that took place in the lake as a whole.

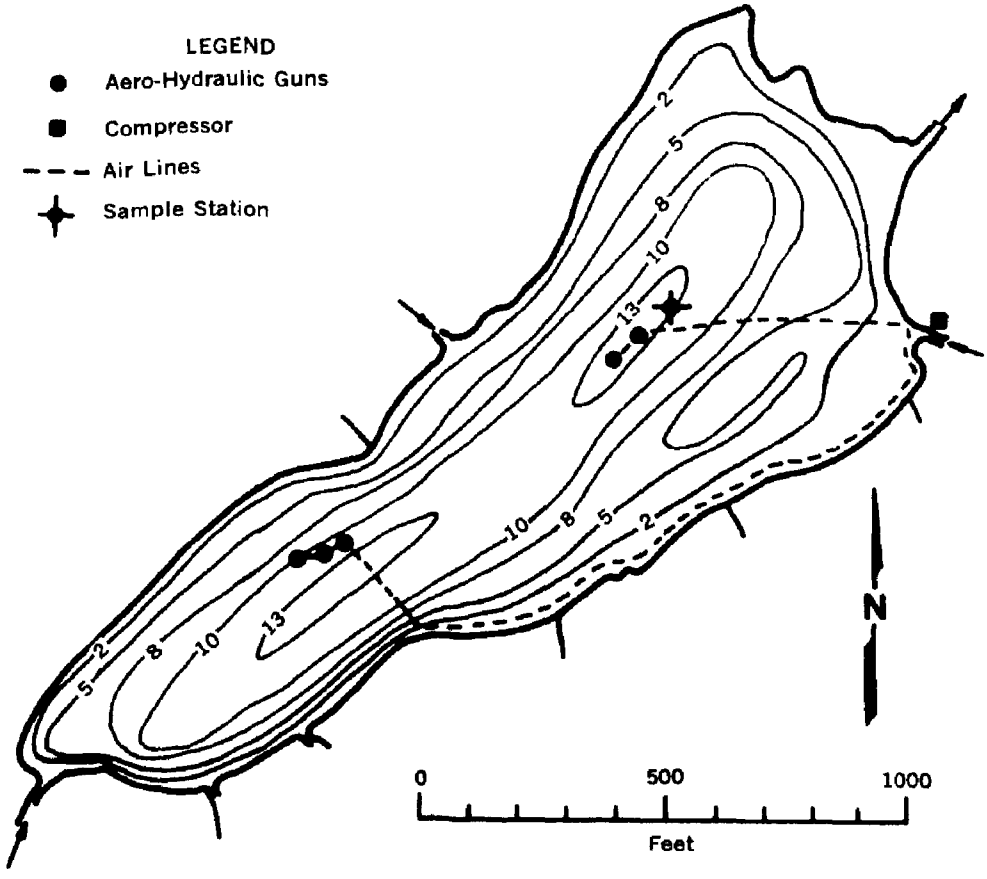

Figure 5 — Blelham Tarn showing positions of the five aero-hydraulic guns and the compressor (depth in meters).

When operations began on July 31, the lake had a marked thermocline between 5 and 9 meters and a subsidiary one at 3 meters. As the hypolimnetic water was pumped up and mixed with the epilimnion, the thermocline moved progressively down, extending from 6 to 10 meters on August 3, and from 7 to 11 meters on August 7. By August 14, all the water below 13°C, except small amounts in the deepest hollows, had been removed, and temperature over almost the whole of the bottom of the lake had risen from 8.7° to about 13°C. This was somewhat influenced, however, by rain and wind during the first week.

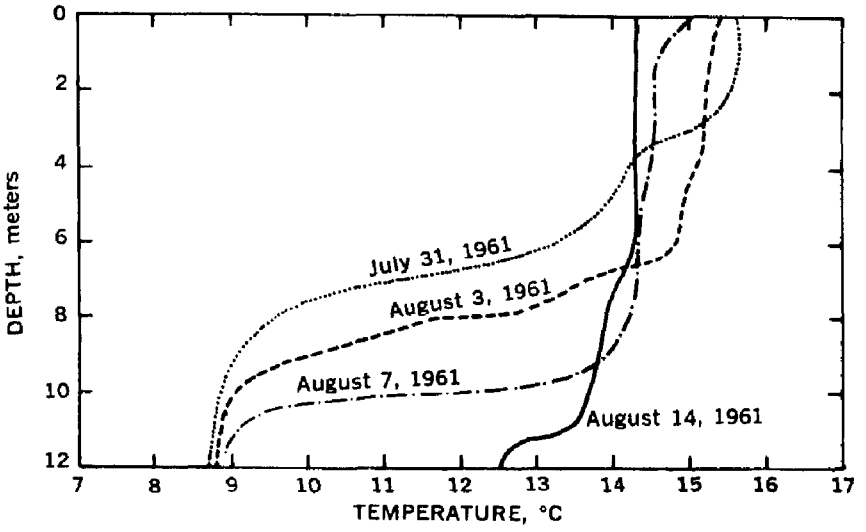

Figure 6 — Effect of mixing by aero-hydraulic guns on temperature in Bleiham Tarn (Freshwater Biological Association).

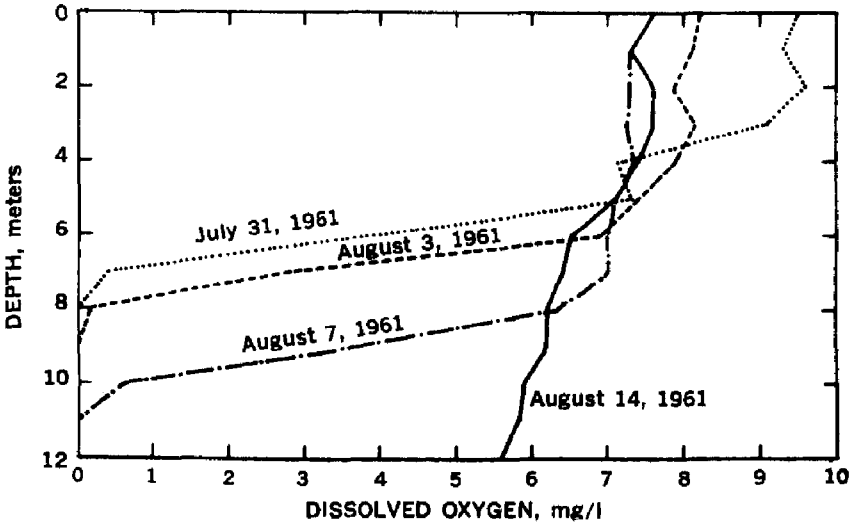

Figure 7 — Effect of mixing by aero-hydraulic guns on dissolved oxygen in Bleiham Tarn (Freshwater Biological Association).

The distributions of dissolved oxygen and of ferrous iron, whose presence in quantity is an extremely sensitive indicator of oxygen-lack, indicate in another way the same sequence of events. On July 31, almost no oxygen was present below 7 meters. By August 7, water rich in oxygen from the epilimnion had penetrated nearly to 10 meters, and on August 14, there was water 60 percent saturated with oxygen at 12 meters.

Inniscarra Reservoir

The Inniscarra Reservoir, in County Cork, Ireland, was completed in 1957 by the Irish Electricity Supply Board. It is situated on the River Lee, above Cork.

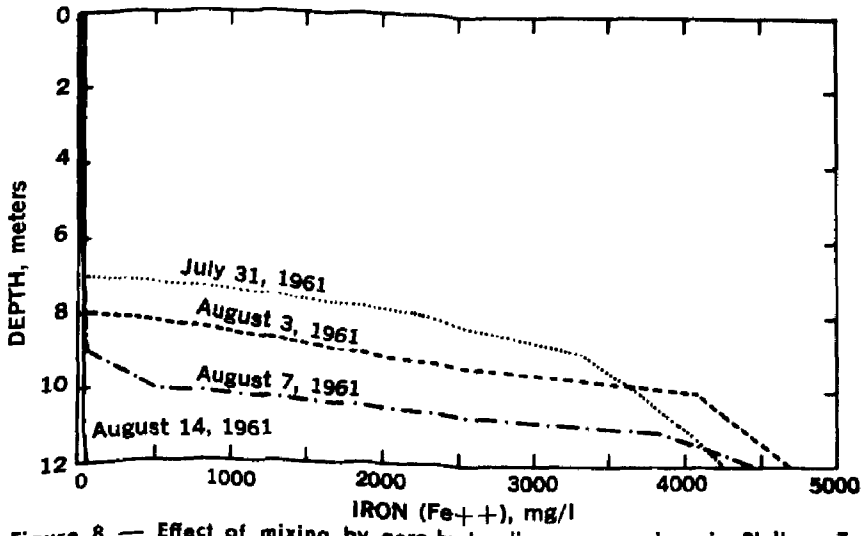

Figure 8 — Effect of mixing by aero-hydraulics guns on iron in Blelham Tarn (Freshwater Biological Association).

The River Lee is an important salmon fishery, and the Board operates a hatchery designed to produce 1.5 million fry each season. A salmon lift is built into the dam.

The catchment area is 540 square miles, the average annual rainfall is 60 inches, and the average annual flow of the river is 970 cubic feet per second. The Reservoir is long and narrow — about 8 miles in length. It has an area of 2,000 acres, and impounds 12,500 million gallons of water. The dam is 800 feet long and 140 feet high, and the power station has one 15,000 KW set and one 4,000 KW set. The depth of water at the dam face is 103 feet and the turbine intakes are between 65 feet and 75 feet. The minimum turbine discharge is 95 million gallons per day. There is a second reservoir of similar area at Carrigadroghid, 11 miles above Inniscarra.

The Reservoir is subject to a normal spring and autumn overturn, and, although it is sensitive to high winds, for an average of some 16 weeks between June and October it suffered from stratification in 1959 and 1960. This, combined with the products of anaerobic decomposition, resulted in toxic water passing through the turbines and poisoning fish downstream. It is estimated that 16 percent of the water was hypolimnetic during these periods of stratification; such conditions are expected to worsen from year to year because of the eutrophic characteristics of the reservoir.

During a period of characteristic stratification in early August 1959, the temperature variations were between 20°C at the surface and 16°C at 24 meters, and the 13° isotherm was above 27 meters. At the same time the oxygen content at the surface was 9.0 milligrams per liter, but only 3.0 milligrams per liter at 18 meters. High winds in mid-August caused a complete overturn, but the reservoir restratified to the same pattern early in September. The fishery authorities of the Supply Board regard 6.0 milligrams of oxygen per liter as the desirable minimum and 5.0 milligrams per liter as the permissible minimum.

In early May 1961, a system consisting of six 12-inch aero-hydraulic guns, each 44 feet in length, was installed, with a combined capacity for transferring hypolimnion water to the surface through their muzzles of 20 million gallons per day. The guns were sited 2,000 feet above the dam, their intake ports being at a depth of 86 feet. Weekly oxygen and temperature readings were taken at the dam and 1 mile above the dam.

Figures 9 and 10 show the oxygen content reading in the vicinity of the dam for 1959 and 1961. The 5.0 milligrams per liter lines in each case have been emphasized, and the depths of the turbine intakes are shown.

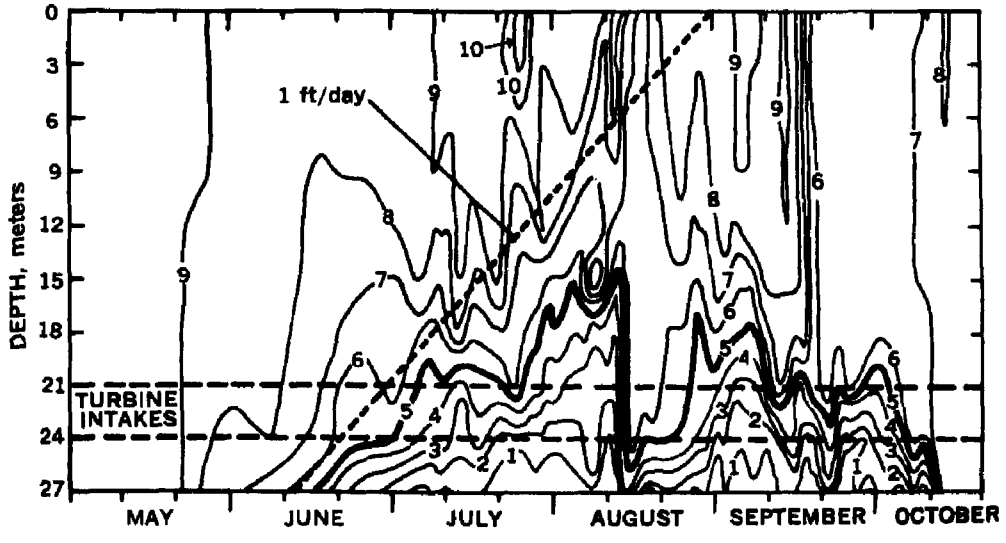

Figure 9 — Dissolved oxygen in Inniscarra Reservoir (in mg/l), in 1959.

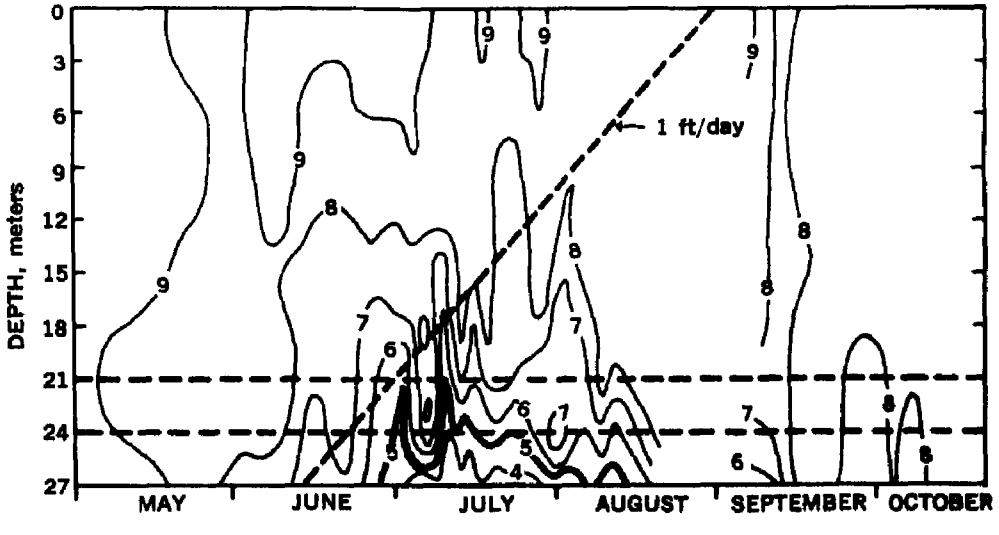

Figure 10 — Dissolved oxygen in Inniscarra Reservoir in 1961, mg/l.
(Electric Supply Board, Ireland.)

May, June, and July 1961 were relatively dry, and the turbines were off load between May 24 and July 15. The only discharge during this period was 70 cubic feet per second compensation spilling. The rainfall recorded at Cork, as a percentage of the 1916-50 average for the corresponding months, was 40 percent in May, 67 percent in June, and 60 percent in July. Under these conditions, the reservoir was relatively static and stratification could have been severe. The readings from June to October 1961 while the aero-hydraulic system was in operation, however, show that the oxygen content of the water delivered down-river from the turbine intakes (located at a depth of 21 to 24 meters) was increased considerably.

Accordingly, the results show how such an aero-hydraulic system can correct a condition of de-oxygenation within a limited area without overturning the whole reservoir.

No fish poisonings were reported during the summer of 1961.

The installation ceased operation on October 27, 1961, when the autumn overturn occurred. The guns were left in position, to be operated annually thereafter during the spring, summer, and autumn.

During 1962 the guns operated satisfactorily and there was no stratification. The installation has required no maintenance and is ready to operate again this year.

Loch Turret Reservoir

Loch Turret (Figure 11) is a natural lake at an elevation of 1100 feet above sea level in the foothills of the Grampian mountains near Perth in Scotland. The lake is used as a reservoir for drinking water and at present has an area of 165 acres. To raise the capacity impounded, a new dam is being constructed about three-quarters of a mile below the present outlet. This will increase the area of the reservoir to about 450 acres and the capacity will be raised to 4 billion gallons.

When the reservoir is extended to the new dam, the top water level will be raised by some 36 feet and the existing reservoir will form a pool (Figure 12a). While stratification has not created problems in the present reservoir, probably because of the natural circulation produced by strong winds from Glen Turret, stratification possibly will occur in the pool once the reservoir is extended.

If freedom from stratification and anaerobic conditions can be assured, the basic purity of the water will permit the use of a filtration plant based on micro-straining and oxidation with ozone. Thus the high cost associated with full filtration involving chemical coagulation can be avoided. In this particular case, a danger arising with anaerobic conditions is the possibility of iron and manganese being brought into solution. The maximum permissible concentration of manganese when treatment is based on the use of ozone is only 0.1 milligram per liter.

The destratification system proposed is designed to counteract such harmful effects by continuously pumping large quantities of bottom water to the surface in the existing reservoir. This is achieved by self-buoyant aero-hydraulic guns sinkered to the bottom and supplied with compressed air through submerged feeder lines as shown in Figure 12. These guns are constructed of low density polyethylene and are approximately 40 feet long and 18 inches in diameter. They can be raised and lowered individually to vary the height of intakes.

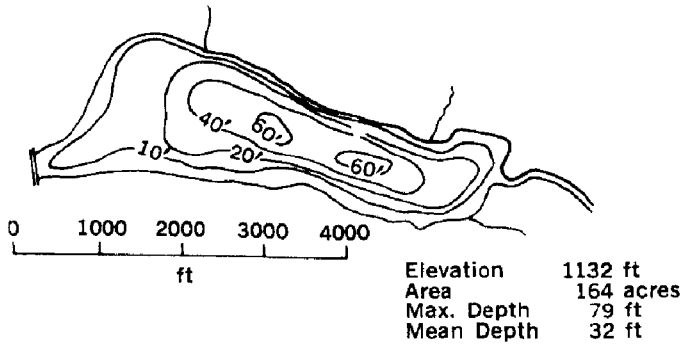

Figure 11 — Lock Turret (from Bathymetrical Survey of June 9, 1903).

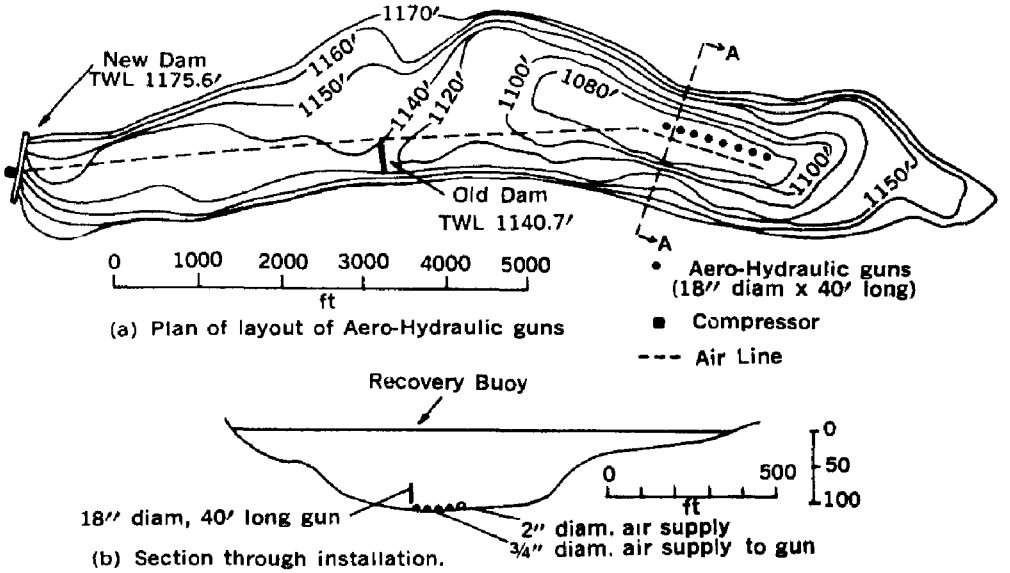

Figure 12 — Proposed layout of destratification equipment in Loch Turret.

The pumping capacity of the installation is based on rate of rise of the thermocline in cases where stratification occurs regularly. Bad climatic conditions similar to those at Loch Turret occurred at Inniscarra. There, as shown in Figure 9, the thermocline rose at a rate of about 1 foot per day until the onset of the autumnal overturn. Greater rates of rise have been noted under hot, still conditions, such as those

at Lake Kariba in Rhodesia. The figure of 1 foot per day has been used as a design criterion for the Loch Turret installation, although it is felt that stratification would not occur at this rate.

The proneness of any particular body of water to stratify must depend mainly on its configuration, the ambient temperature, and wind strength. It is relatively easy to characterize the stability of water arising from thermal gradients alone, but the problem of accounting for the effects of wind is much more difficult. Work being done on the interactions of the atmosphere and the oceans(*8*), however, is throwing much light on this question and there is distinct hope that an analytical treatment may be useful.

When the reservoir is extended, the water level will be raised by about 36 feet. Although stagnant conditions are not found at present in Loch Turret, when the level is raised an extreme upper limit for stagnant water would be a layer 36 feet above the bottom; i.e., at about 1090 average ordinance datum (AOD).

Figure 13 shows the approximate volume impounded as a function of water level above OAD. If we assume that the thermocline, or the upper level of hypolimnetic water, rises at a rate of 1 foot per day, the rate of increase of the hypolimnion is about 12.9 million gallons per day. The aero-hydraulic installation is designed to have this pumping capacity. The compressed air requirement is then about 90 cfm free at about 80 psia.

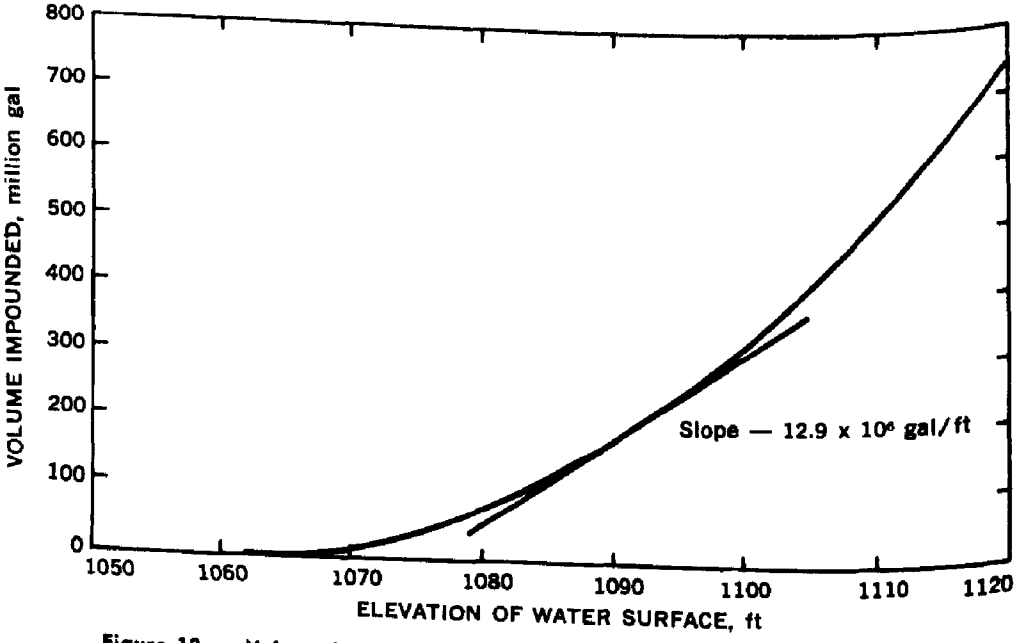

Figure 13 — Volume impounded in Loch Turret vs water surface elevation.

The total quantity of water brought to the surface by the action of the system will be many times greater than the above 13 mgd because of the entrainment in the jets issuing from the guns. In the system proposed here, about 150 mgd will be brought to the surface. Although in Loch Turret most of this water will be from the epilim-

nion lying above the tops of the guns, such a continuous rate of turnover will make the occurrence of stagnant conditions extremely unlikely.

Figure 12a shows the layout of the aero-hydraulic guns. The compressor is located at the new dam, and a 2-inch-diameter polyethylene pipe extends along the bed of the reservoir for about 1½ miles until the deep pools are reached. The guns are connected to this header by ¾-inch-diameter feeder lines (Figure 12b). The whole installation will be floated into position and then sunk by filling certain air chambers with water.

CONCLUSION

In many cases, it is economical to improve the quality of reservoir discharges by promoting mass mixing by the use of compressed air and aero-hydraulic guns.

By a proper consideration of the effects of interacting design variables that is made possible by modern digital computing techniques, a system can be optimized for a specific function. With this approach to design, many more factors can be taken into account than would otherwise be possible. One may be led to study quite unconventional arrangements, and some of the pitfalls of oversimplification may be avoided. This may be particularly important in the design of a multipurpose impoundment where there are many interacting variables relating to biological, chemical, and physical phenomena.

The systems discussed here have proven extremely reliable in operation. If carefully installed — for example, no excessive strains are imposed on the pipework during laying — a trouble-free life of 5 to 10 years can be expected.

Much data is still to be collected and analyzed before any definite pronouncements can be made regarding many of the biological results of turning-over reservoirs artificially. The large scale hydraulic effects have been sufficiently established, however, to make useful applications possible.

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DISCUSSION

Dr. L. L. Falk

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We can predict reasonably well the grossly obvious effects of stratification on impounded waters. Dr. Bryan points out some of these effects in his paper: in the deeper layers oxygen may become depleted, temperatures do not reach high levels, iron and CO_2 concentrations rise, etc. And it is true that some of these effects are not always desirable for subsequent use of the impounded water.

I would like to touch brefly on certain aspects of overturning this natural stratification. There are, perhaps, some advantages not touched on by Dr. Bryan, and there are some disadvantages, too. I shall talk about the significance of overturning in regard to waste assimilative capacity, heat load dissipation (sometimes called "thermal pollution"), and biological productivity. These and other factors you may think of can be particularly significant in multi-purpose impoundments.

WASTE ASSIMILATIVE CAPACITY

Mixing of impounded waters can increase waste assimilative capacity in several ways. The most obvious is to increase the rate of oxidation of organic pollution loads. This occurs because:

1. Turnover increases reaeration. More water is exposed to reaeration from the atmosphere as well as to the bubbles of aeration devices or Dr. Bryan's Aero-Hydraulic Gun.

2. Turnover raises the average water temperature. This raises the overall reaeration rate coefficient, commonly called K_2, for the entire body even though the temperature at the surface is somewhat lower than in the stratified condition. Of course, higher temperatures also raise the overall deoxygenation rate constant, K_1, so that oxy-

gen is used up at a faster rate. However, I think that the overall effect will be to raise the organic load assimilative capacity of the impounded water, given a specific minimum dissolved oxygen criterion.

Another way that turnover increases waste assimilative capacity is by reducing the effects of density currents. Fry, Churchill and Elder(*1*) found density currents in Cherokee Reservoir on the TVA system. Water entering the reservoir in the fall was heavier because of lower temperatures and higher chloride concentrations. A density current traveled along the bottom for the entire 47-mile length of the reservoir. One can visualize that mixing of the reservoir contents in its upper reaches would destroy this density current.

HEAT LOSS

The atmosphere is the heat sink for the processes of human civilization. Excess heat from industrial processes is dissipated either directly to the air (e.g., air coolers, exposed equipment, etc.) or indirectly with water as the heat transfer medium. When water is used, its release to a stream may result in thermal pollution. This happens when heat release to the receiving water is higher than the heat transfer capacity of the stream to the atmosphere; the temperature rises to a higher equilibrium level and may affect water quality for a subsequent use. Many people do not recognize that this would be a more serious problem if it were not for the fact that the heated cooling water is lighter than the receiving stream. It floats on the top where contact with the atmosphere allows rapid heat dissiptation by evaporative cooling, convection, and radiation. This loss of heat may be even faster in impounded waters because of less turbulence and mixing to deeper depths. If the need to maintain the warm water on the surface is not recognized and the impoundment is artificially mixed for other reasons, the rate of heat release from the water will be less, and undesirably high temperatures throughout the entire impoundment may occur.

There is another aspect to the heat problem. Power plants on large impoundments often take advantage of the cooler hypolimnion. A curtain wall prevents warmer, upper waters from reaching plant intakes; cooler, deeper waters are preferentially used with considerable economic advantage. Mixing such a reservoir would result in an economic penalty for any cooling process.

PRIMARY PRODUCTION

Multi-purpose impoundments serve many uses: flood control, pollution control, power production, recreation, wildlife development, etc. I wonder what effect complete mixing would have on biological productivity. The production of desired fish life depends ultimately on the primary production of algae — the starting point of the biodynamic chain or cycle. A mixed reservoir will have a lower temperature in the upper layers where most algae grow (solar energy availability). Will this lower temperature reduce algae productivity?

Algae convert carbon dioxide to cell material. In an unmixed stratified impoundment the carbon dioxide concentration in the deeper waters is several fold higher than in the upper layers. Some surely diffuses upward for use by the algae. If the waters are completely mixed, will the loss of carbon dioxide by diffusion to the atmosphere reduce the algae productivity?

On the other side of the coin, the mixing of reservoirs can expose more water to the solar energy zone. More nutrients become available to algae. This factor would increase algae productivity. One also wonders whether this would favor algae known to create taste and odor problems in reservoirs.

The literature is not clear on the effect of mixing on algae production. Riddick(2) studied the effects of forced circulation of a 103 million-gallon reservoir by aerators at Ossining, New York. He found that this seemed to inhibit the algae.

CONCLUSION

Mixing of impounded waters on a large scale has several advantages, as Dr. Bryan's paper points out. Where the impoundment is used for many purposes, however, the effects of the mixing must be looked at from many points of view. What may be an advantage from one standpoint may turn out to be a disadvantage from another. The total credits and liabilities must be balanced in determining the benefits of reservoir mixing.

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DISCUSSION FROM THE FLOOR

Dr. Ingols, Georgia Institute of Technology: I could not help but notice the temperature of the water at the surface of the lakes Dr. Bryan showed in his figures, and wonder whether one would ever have a recreational lake if 14° and 15°C water temperature were common to the Atlanta area. It chilled me just to look at those figures.

Dr. L. Williams, U. S. Public Health Service: I have been in charge of the plankton program of the National Water Quality Network for nearly 5 years, and in that capacity have been examining waters from the major waterways throughout the nation. I am therefore familiar with the plankton counts at various locations and have some idea as to what algae, plankton, and microorganisms can do to

water. I have been very much impressed with the fact that water coming from the bottom of impoundments contains very few microorganisms; on the other hand, samples from many of our impounded stations contain total counts of from 80,000 to 120,000 per milliliter. If these organisms contribute oxygen in large amounts, much of it must be dissipated back to the air so that it is not available for maximum self-purification of streams. It would seem that nature can provide the best way to handle organic material, both that contributed by productivity of the algae themselves and that contributed by wastes from domestic, industrial, and other sources. The discharge of some of the surface waters from an impoundment not only provides dissolved oxygen, but also provides seeds that make it possible for the stream below the impoundment to recover more rapidly by making its own oxygen while producing organic material needed in the food chain for fish.

For example, in the St. Paul area, at Red Wing, Minnesota, there is a large impoundment. The algal counts there are enormous, yet the fish productivity is also very great; as long as the blue-green algae do not come in, the dissolved oxygen never reaches low concentrations and taste and odor problems do not occur. We need to make better use of the aquatic organisms available in the stream. When an organism provides oxygen, essentially all of it can be absorbed, while much of the oxygen injected into water as a jet of air cannot be absorbed.

To provide for further photosynthesis downstream, therefore, it seems desirable to use sufficient of the surface water to mix with the water discharged from the lower levels of the reservoir.

As a further consideration, in an impounded situation algae themselves become BOD. They eventually settle out as detritis and then contribute to the depletion of the available oxygen in the bottom of the impoundment. This is highly undesirable, and should be considered mismanagement. By the discharge of some of the surface waters we can reduce the deoxygenation of the hypolimnion and use the organisms to provide oxygen and food; thus we can perhaps use nature to help solve the problem of pollution and still have fish and wildlife.

Dr. Symons, U. S. Public Health Service: Dr. Bryan, since you can mix and reaerate an impoundment through simple pumping with a large-volume low-head pump, I wonder if you would express an opinion as to the relative importance of your device as a high-capacity pump, or as a diffusion device.

Dr. Bryan, Aero-Hydraulics Corporation: I think the merit of the device is almost entirely due to its high pumping capacity.

In relation to what Dr. Williams said, the basic idea in the development of this equipment was to try and recreate some of the purification processes that take place in nature. The idea was, in fact, to lift water from the hypolimnion to the surface, so as to expose that water to natural processes of aeration. Most of the aeration takes

place on the surface; very little takes place in the zone between the mouth of the pipe and the surface.

Dr. Symons: If that is true, I wonder how your device compares economically with an ordinary pump.

Dr. Bryan: I think it compares favorably, especially in view of the tremendous simplicity of the equipment. There are no moving parts submerged, which is, of course, a great advantage in many sites that are very remote. If the dimensions of these large piston bubbles are properly proportioned to the pipe, the slip is very low, indeed, and most of the work that is done in getting the air down to the bottom is, in fact, recovered. This, of course, is not so with the ordinary airlift pump that works with a continuous supply of air and largely viscous drag.

Mr. Wilroy, Wiedeman and Singleton Engineers: I would like to point out that there are definite economic considerations in reservoir aeration. In Georgia we are concerned with a small water supply reservoir where we have a manganese problem that persists for about 3 or 4 months during the fall. Removal of the manganese from the two mgd used each day costs between $1,500 and $1,800 a month. Therefore, if we could turn over this reservoir for something less than the $4,500 to $7,500 expended each year for treatment we would consider it economical. This is definitely a possibility for preventing the formation of the manganese. We are considering the cost of using either an airlift pump or a mechanical mixer.

Dr. Ingols has been working fairly closely with this problem. We have been concerned with just the removal of manganese alone. Other benefits may accrue, but we can definitely tie down the economics of the manganese removal.

Mr. Summers, Missouri Water Resources Board: Dr. Ingols, I have been slow in putting all this together, but it has occurred to me that no mention has been made of turbidity in any of the papers presented. I am wondering if perhaps the turbidity, especially the colloidal turbidity, might be of value in getting the oxygen into the water. Here we would have the benefit of adhesion, which would allow a longer time for the oxygen to dissolve in the water. This has come to our attention in Missouri, particularly in the Missouri River where the recovery rate is more rapid than we had anticipated. The only reason for this we can think of is that it contains a lot of colloidal turbidity. Is it possible, therefore, that the difference in results between Wisconsin and the Carolinas might be related to turbidity?

Dr. Ingols: I am not qualified to answer that question. I will be glad to entertain an answer from someone in the audience.

Mr. Wilroy: I would like to comment on the effect of turbidity. On the Chattahoochee River below Buford Dam, we have had tremendous reductions in turbidity as a result of the construction of the dam. Prior to the dam, the turbidity ranged from a low of 600

units to several thousand. At the present time it drops to the range of 30 to 40 units and persists for months at a time. Simultaneously with this reduction in turbidity, we have experienced a tremendous algae bloom in the river each spring. This creates problems for the waterworks along the river, occasionally from a taste and odor standpoint, but more importantly, from a pump-clogging standpoint. The algal blooms have been severe enough to result in clogging, which required that the pumps be pulled down and several hours spent in getting the algae growths out. In 1961, we estimated that, with an average flow of around 2,000 cfs, between 200 and 300 tons of algal material was passing down the river each day.

Dr. Bryan: I would like to say a few words about the problem of manganese. In the Loch Turret Reservoir, shown in my paper, the water is of a fairly good quality, but there is a slight color problem. We thought this could be oxidized out, using ozone. The presence of even minute quantities of manganese (perhaps 0.1 to 0.2 milligram per liter), however, rendered treatment by ozone relatively ineffective. One of the main incentives for mixing in this particular installation is to keep aerobic conditions at the bottom of the deep pool that will be formed by the existing reservoir to prevent manganese from coming into solution.

Dr. Falk's comments raised some most useful points that add to my already very long list of unsolved problems.

Mr. Swiggart, U. S. Army Engineers: Yesterday Mr. Moore of the Tulsa District mentioned that we are building reregulating structures below some of our hydroelectric multiple-purpose projects. One example is the Keystone Reservoir about 17 miles up the Arkansas River from the City of Tulsa, Oklahoma. The purposes of the project include hydropower, flood control, and flow regulation to improve water quality conditions at Tulsa or at least to maintain the conditions existing prior to construction of the dam. Since we are talking about a 5 to 10 percent load-factor plant, both daily and weekend fluctuations will occur. We have designed and are building a reregulating structure to take care of the flow sag due to hydroelectric power generation.

Now that we are taking care of the flow sag, the problem that concerns us is, "What quality of water is going to be coming out of the reservoir?" So far during this conference I have not heard how we can forecast whether or not we will have a problem with the water discharged? In the White River Basin in Arkansas we have the Bull Shoals Project, which has a head of from 170 to 200 feet for hydroelectric power generation (a 34-foot drawdown) and the Norfolk Project, which has a head of 170 feet. Our main problem below these reservoirs is keeping the trout fishermen out of the tail race.

Trout have been introduced below Tenkiller Ferry Reservoir on the Illinois River in Oklahoma, but we have no fish life in the first 8 miles below the reservoir.

Can't we forecast whether we are going to have a problem with the water discharged? It will not do us much good to build reregulating structures if we are still going to have water that will not support the desired uses. Since most of our hydroelectric projects are marginal, financially, anyway, we cannot spend a lot of money building some kind of a skimmer when we do not need it. Further, I do not know what kind of a skimmer we could build where we are going to have 30 to 40 feet of drawdown.

Mr. McLean, U. S. Public Health Service: I think the design of the Smith Mountain pumped storage project being built by Appalachian Power Company in Virginia provides a logical method for the correction of low dissolved oxygen. There, one of the intakes extends to a higher level providing an opportunity for mixing surface water with the hypolimnetic water when needed.

Mr. Swiggart: My primary question is, how can you forecast in advance whether you will have a problem of stratification and discharge of bad water? All of the projects in our Division are good except one. If we had known we would have the problem of providing dissolved oxygen maybe we would not have built the project to begin with, because it would not be justified economically considering the money that would have to be spent in providing these features.

Mr. McLean: We have not been able to forecast this in the past. I hope, from our experience with the dams that have been built, we will be able to forecast the quality of water that will be discharged. The Public Health Service has initiated research in this area under Dr. Woodward, Mr. Weibel, Dr. Symons, and Dr. Irwin in the Basic and Applied Sciences Branch. Several Corps of Engineers offices have done a considerable amount of work in observing water quality changes in and below their reservoirs, and we are discussing ways of working with them on it. At this time, however, we can not say exactly what will happen in a specific proposed reservoir.

Dr. L. Williams: I believe that whether or not the organisms will develop can be predicted from a survey in advance of the construction of an impoundment. If the enrichment of the water is such that it is very highly productive, one can predict that large crops of algae will be produced, and that when they settle to the bottom they will decompose, using up the oxygen in the lower levels of the reservoir.

Dr. Ingols: I have noticed that during the spring turnover in Bufford Reservoir the water is completely uniform and the Chattahoochee River below the dam is extremely green. Once stratification sets in, all the algae trapped below the thermocline are going to contribute to the organic matter in this layer; we have to consider this, as well as how much organic matter is going into the reservoir, in order to evaluate the productivity.

Mr. Whitehouse, Central Electricity Research Labs, England: I would like to comment on this problem of forecasting the possibility

of biochemical stratification developing, even if thermal stratification does not. In the planning of the Chew Valley Lake Reservoir for water supply storage the biologist carried out a survey of the river prior to impoundment. Based on the mineral composition of the water and the biota present, he predicted with almost absolute certainty that biochemical stratification would set in, given certain physical conditions. These conditions were that there be high insulation rates in summer and low wind velocities. When these conditions occurred, sure enough, biochemical stratification developed along with all its obnoxious effects. But the biologist had had the foresight, as a result of investigating the river in advance of impounding the water, to suggest to the engineers involved in the project that they build a multiple-level intake. On the basis of his advice, they built an intake tower so that they could draw from the surface, the middle, or the bottom of the reservoir. Depending on the depth to which biochemical stratification had risen from the bottom, they were able to determine which level intake to use. Except in one instance where blue-greens developed because the nutrient level was sufficiently high to allow them to grow, they have not had a problem of taste and odor in the drinking water delivered to the residents of the city supplied by this reservoir.

Dr. Ingols: This is one of the parts of the program that I think is tremendously significant. I would like to inject two points, if I may.

At a luncheon recently I talked with somebody who said, "We do not have any problem with the hypolimnion, we simply inject chlorine into it." Ray Derby, from Los Angeles, reported they are introducing chlorine into the hypolimnion to control the quality of water so that it will not require taste and odor treatment before it goes into the distribution system. This is a direct reservoir supply with no flocculation or filtration.

The other point is that I know of several reservoirs that are receiving wastes without interference with recreation because of the presence of a thermocline and the discharge of the waste into the hypolimnion. The surface waters are being used for recreation even above the point of waste discharge. It has always been interesting that one can watch fish being taken from the lake above the outlet because this is where the fish accumulate. This is apparently the most productive point in the lake. The waste is discharged after treatment on a trickling filter. I hardly need say that a trickling filter effluent contains sensible numbers of worms, larvae, and so forth, and that this, of course, makes excellent fish food, particularly for the scavenger fish.

Session 6

OPERATION AND ADMINISTRATION OF FLOW REGULATION PROJECTS

Moderator: **W. E. Bell**
U. S. Public Health Service

GPO 821-740-12

WATER QUALITY MONITORING FOR WATER QUALITY CONTROL

Stanley Ragone and B. J. Peters

Virginia Electric and Power Company, Richmond, Virginia

Peaking hydroelectric power is a great asset to the modern electric utility that generates the major portion of its system electric load with steam. The fact that hydroelectric generators can be started and brought up to full load in a relatively few minutes provides excellent protection to the power system in the event a large steam unit suddenly fails in service. Its main purpose is, however, to provide generation for the peak demand periods, thereby reducing the daily starting, loading, and shutting down of older steam-generating units with the lowest efficiencies in the power system.

On the Roanoke River in North Carolina, the Virginia Electric and Power Company now has two peaking hydroelectric stations that are operated in conjunction with the U. S. Corps of Engineers' John H. Kerr and Philpott hydroelectric projects, which are also peaking stations.

Prior to any discussion of our experience in flow regulation and monitoring for water quality control at our Roanoke River projects, it is necessary to briefly explain the operation of these peaking hydroelectric stations in conjunction with our steam stations. Figure 1 shows a typical winter daily load pattern for the Virginia Electric and Power Company, with our steam energy carrying the major portion of the system load and with the available hydroelectric energy taking care of the peak portion of the load cycles. The Roanoke River does not have sufficient flows to provide energy around the clock throughout the year, and it is necessary to schedule the water flows for maximum utilization of the energy available. The figure also shows that some energy is used each hour (small rectangles at top of steam energy generation) to maintain minimum streamflow requirements from the station farthest downstream. This variation in river flows, from a minimum that will satisfy the Federal, State, and local agencies to the flows necessary to provide the most economical electrical energy production and at the same time provide maximum dissolved oxygen content, was the prime reason that the Virginia Electric and Power Company undertook elaborate studies of reservoir and river flow conditions, oxygen monitoring, and hydroelectric station design and operation. The following discussion includes the more important phases of these studies pertaining to water quality monitoring and flow control of the Roanoke River.

The Roanoke River is an interstate stream rising in the mountains of Virginia, entering North Carolina in the Piedmont Plateau, and terminating in the Albemarle Sound. Figure 2 shows the Roanoke River Basin and the following hydroelectric stations, (1) Philpott — 14 MW (U. S. Corps of Engineers), (2) John H. Kerr — 204 MW (U. S. Corps of Engineers), (3) Gaston — 200 MW (Virginia Electric and Power Company), (4) Roanoke Rapids — 100 MW (Virginia

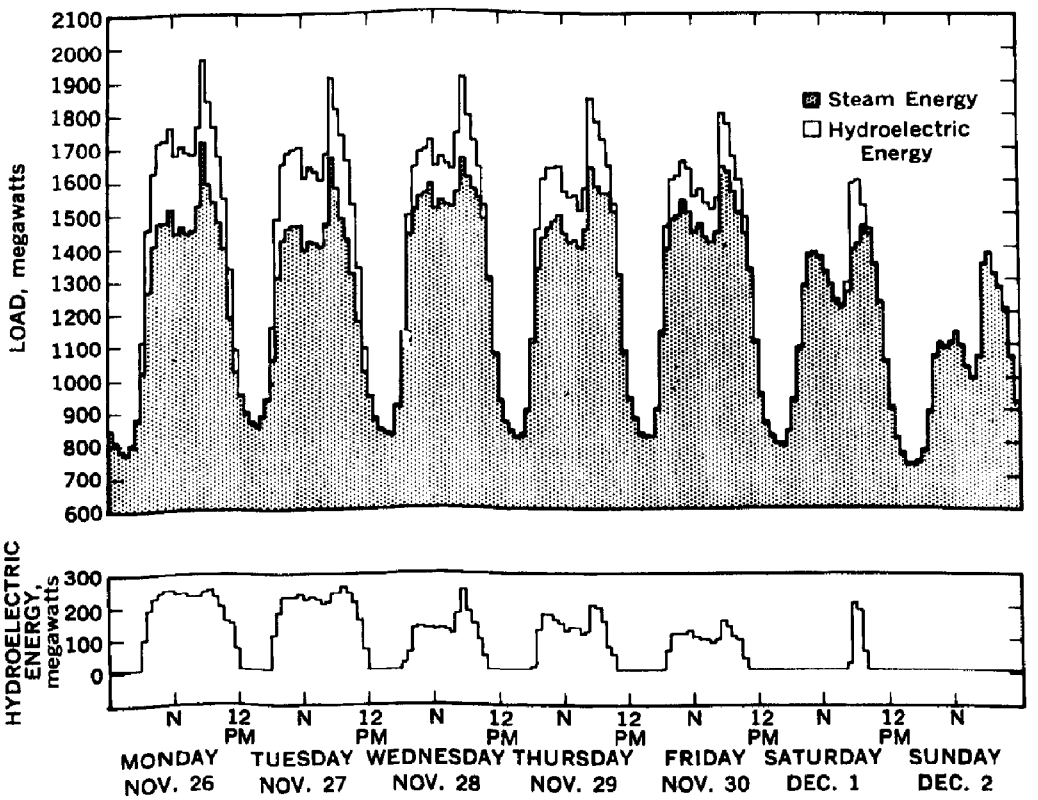


Figure 1 — Typical daily load pattern of Virginia Electric and Power Company for week ending December 2, 1962.

Electric and Power Company), and (5) Smith Mountain Pumped Storage Project — 480 MW (Appalachian Power Company — now in the final stages of construction). The drainage area of the Roanoke River above the USGS gage at Roanoke Rapids is approximately 8,400 square miles. The average river flow at this gage prior to regulation was 8,364 cfs, with a maximum discharge of 261,000 cfs and a minimum of 458 cfs. The 7-day once in 10-year minimum flow was 925 cfs.

In August 1950, the U. S. Corps of Engineers' multipurpose John H. Kerr Dam began regulation of flows in the lower Roanoke River. Figure 3 shows the section of the Roanoke River from Kerr Dam to Roanoke Rapids. The minimum flows provided by Kerr Dam were never clearly defined in the Definite Project Report; however, they closely approached the minimum flows later provided by the Virginia Electric and Power Company's Roanoke Rapids project under its license from the Federal Power Commission.

The Virginia Electric and Power Company had planned for development of their Gaston and Roanoke Rapids hydroelectric sites on the Roanoke River for a number of years and in 1948 applied for a license to construct the Roanoke Rapids Dam and hydroelectric station. Litigation ensued for 4½ years and finally, in 1953 the Supreme Court confirmed the license for the project and construction was started immediately. The Roanoke Rapids Dam assumed the regulation of the lower Roanoke River upon its completion in July

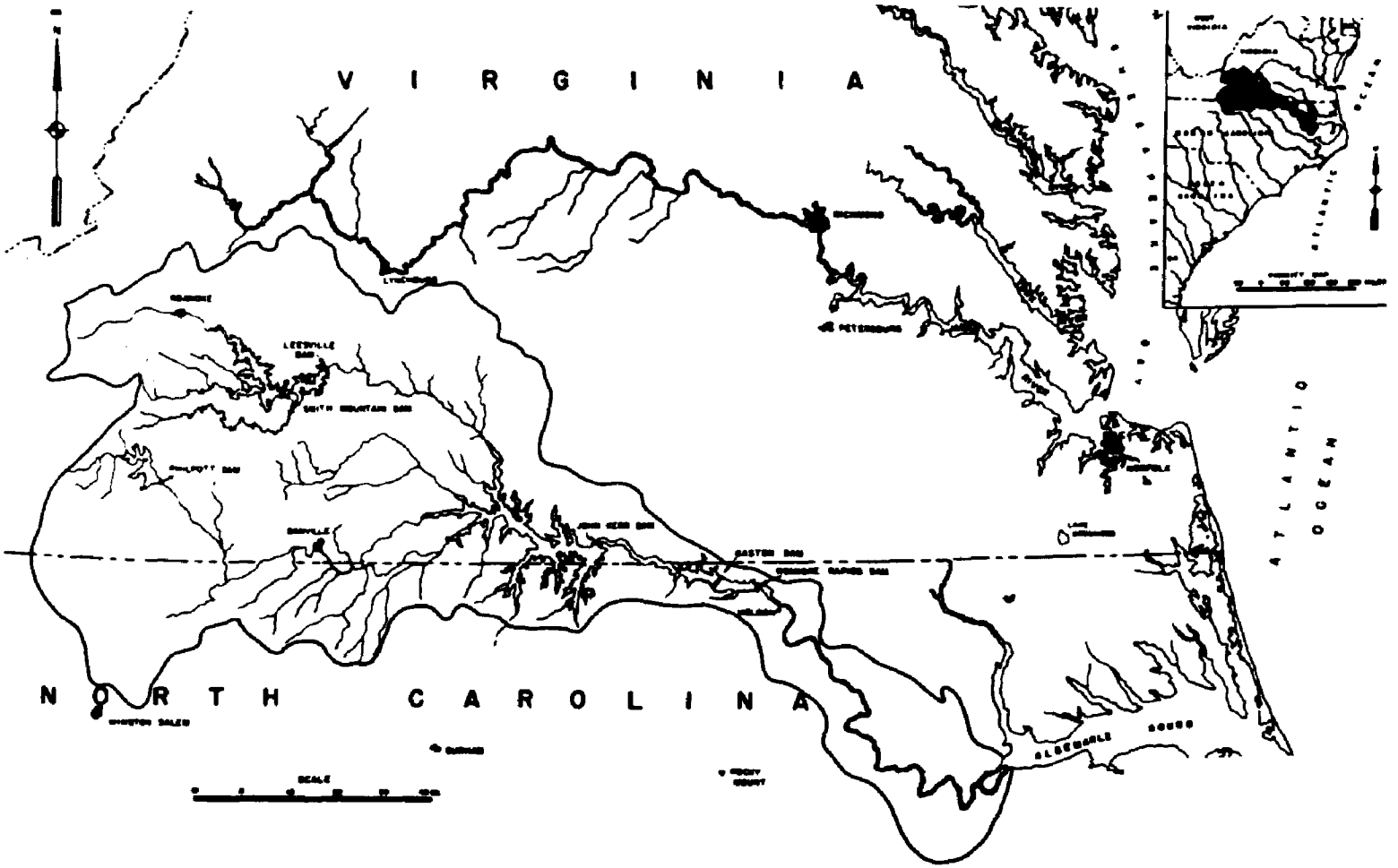


Figure 2 — Location map of Roanoke River Basin hydroelectric projects.

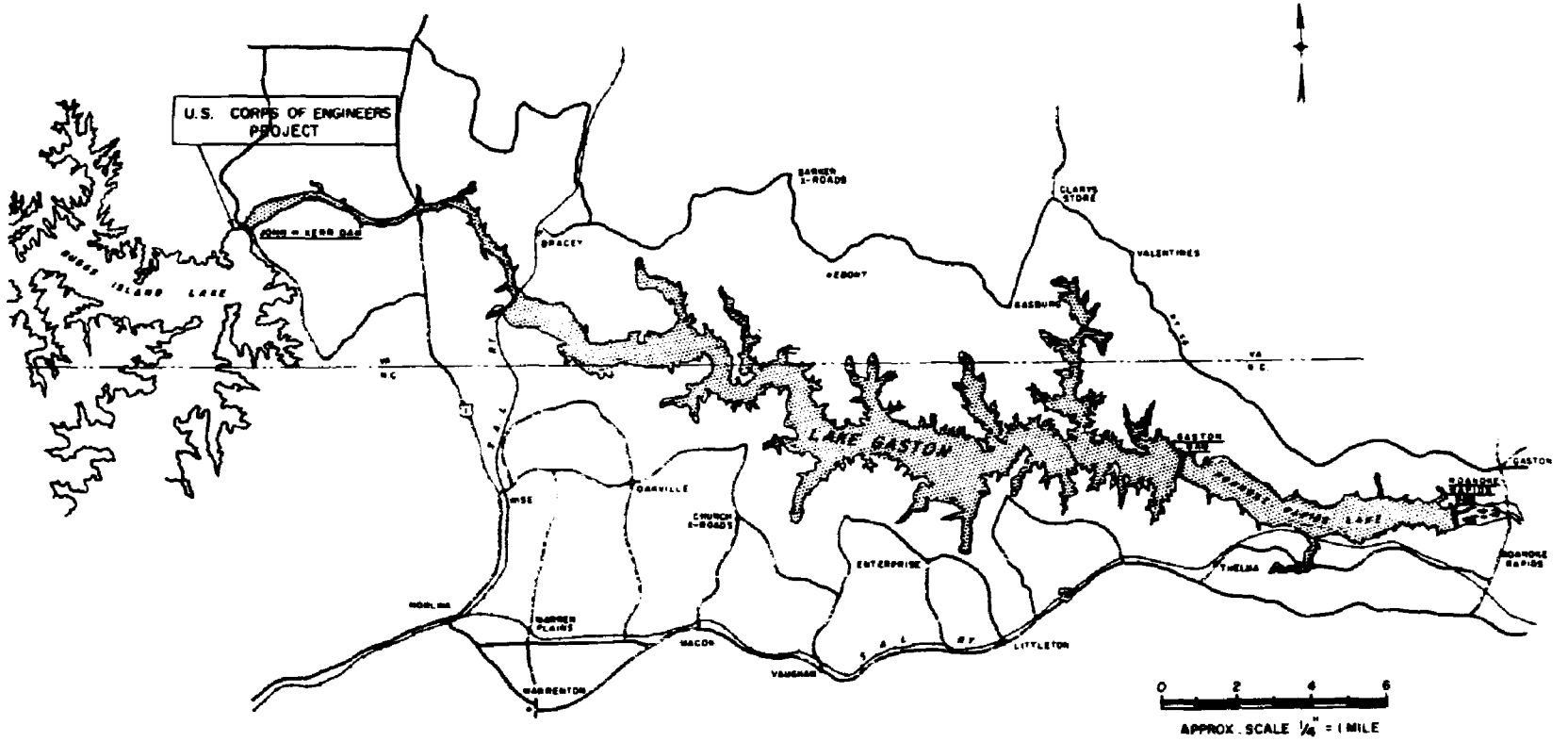


Figure 3 — Virginia Electric and Power Company Roanoke River developments.

of 1955. The instantaneous minimum flow requirements initially established by the Federal Power Commission license are shown in Table 1.

TABLE 1. INSTANTANEOUS MINIMUM FLOW REQUIREMENTS ESTABLISHED BY FEDERAL POWER COMMISSION FOR ROANOKE RAPIDS DAM

Month	Instantaneous minimum flow, cfs	
	Weekday	Weekend
January	500	500
February	500	500
March	500[a]	500[a]
April	500[a]	500[a]
May	1250[a]	600[a]
June	2000[a]	1000[a]
July	2000	1000
August	2000	1000
September	1600	800
October	1250	600
November	500	500
December	500	500

[a]Striped bass spawning flows: minimum of 2,000 cfs for 75 days to begin no earlier than March 15 and to end no later than June 15, at the request of the North Carolina Wildlife Commission.

In the 3-mile stretch immediately below the Roanoke Rapids Dam, an untreated industrial and domestic waste load, with a population equivalent of 590,000(*1*), is discharged into the river. The reduced weekend flow was based on the premise that a reduction in this waste load would occur over the weekend. This was not the case, however, and at the request of the Division of Water Pollution Control, North Carolina State Board of Health, the Virginia Electric and Power Company agreed to modify these flows, with the consent of the Federal Power Commission, to discharge more water on weekends for stream protection and to lower weekday minimums. The following revised schedule of minimum flows for the critical hot weather months has been observed since June 1956.

In 1951, prior to issuance of the Roanoke Rapids license, the Virginia Electric and Power Company petitioned the Federal Power Commission for a license for the Gaston project to be located 8 miles upstream from the Roanoke Rapids project.

In 1953, the Virginia Electric and Power Company applied for a license change in the design and electrical capacity of the Roanoke Rapids Project. During the hearings concerning these modifications, interveners brought up the new problems of stratification in reser-

voirs, low dissolved oxygen, density currents, iron, and manganese. The interveners claimed that the low-level intakes in the Roanoke Rapids and Gaston Projects would allow the cold oxygen-deficient discharge of Kerr Reservoir to move as a density current through the lower reservoirs and emerge from the Roanoke Rapids Reservoir with such a low dissolved oxygen content that waste being dumped in the river could not be assimilated and the lower Roanoke River would become a dead stream. This brought severe protests from the sport and commercial fishing interests, because the Roanoke Rapids — Weldon area is the major breeding ground of the Albemarle Sound species of the striped bass.

TABLE 2. REVISED INSTANTANEOUS MINIMUM FLOW REQUIREMENTS FOR ROANOKE RIVER DAM (June 1956)

Month	Instantaneous minimum flow, cfs	
	Weekday	Weekend
June	1500[a]	2000
July	1500	2000
August	1500	2000
September	1200	1600
October	900	1500

[a]Spawning flows are the same as in Table 1.

Faced with this new problem, the Company immediately hired consultants and started studies of the Kerr Reservoir and the Roanoke River. This testing was put on a regular schedule and involved determination of dissolved oxygen, temperature, pH, iron, and manganese at 10-foot intervals of depth in Kerr Reservoir and at five stations over a 77-mile stretch of the river below the Kerr Dam.

Based on the data obtained by Virginia Electric and Power Company on the Roanoke River and information obtained on other reservoir systems, our consultants in 1955 recommended the construction of a submerged weir or curtain wall around the turbine intakes as part of the proposed Gaston Project. This weir was to function as a high-level intake that would discharge the upper-level high-dissolved-oxygen waters from the project and prevent density current flow-through in the reservoir system.

Severe doubts and objections were raised to this plan by interveners to the Gaston license application, and finally, the Company agreed to construct a weir to within 25 feet of the surface in front of the Roanoke Rapids turbine intakes to allow testing of such an installation. Figure 4 illustrates the weir construction and configuration. Since the Roanoke Rapids reservoir had been filled 2 years before and the station was in operation, the construction of this weir was a difficult engineering feat. Figure 5 shows how the rock fill was handled.

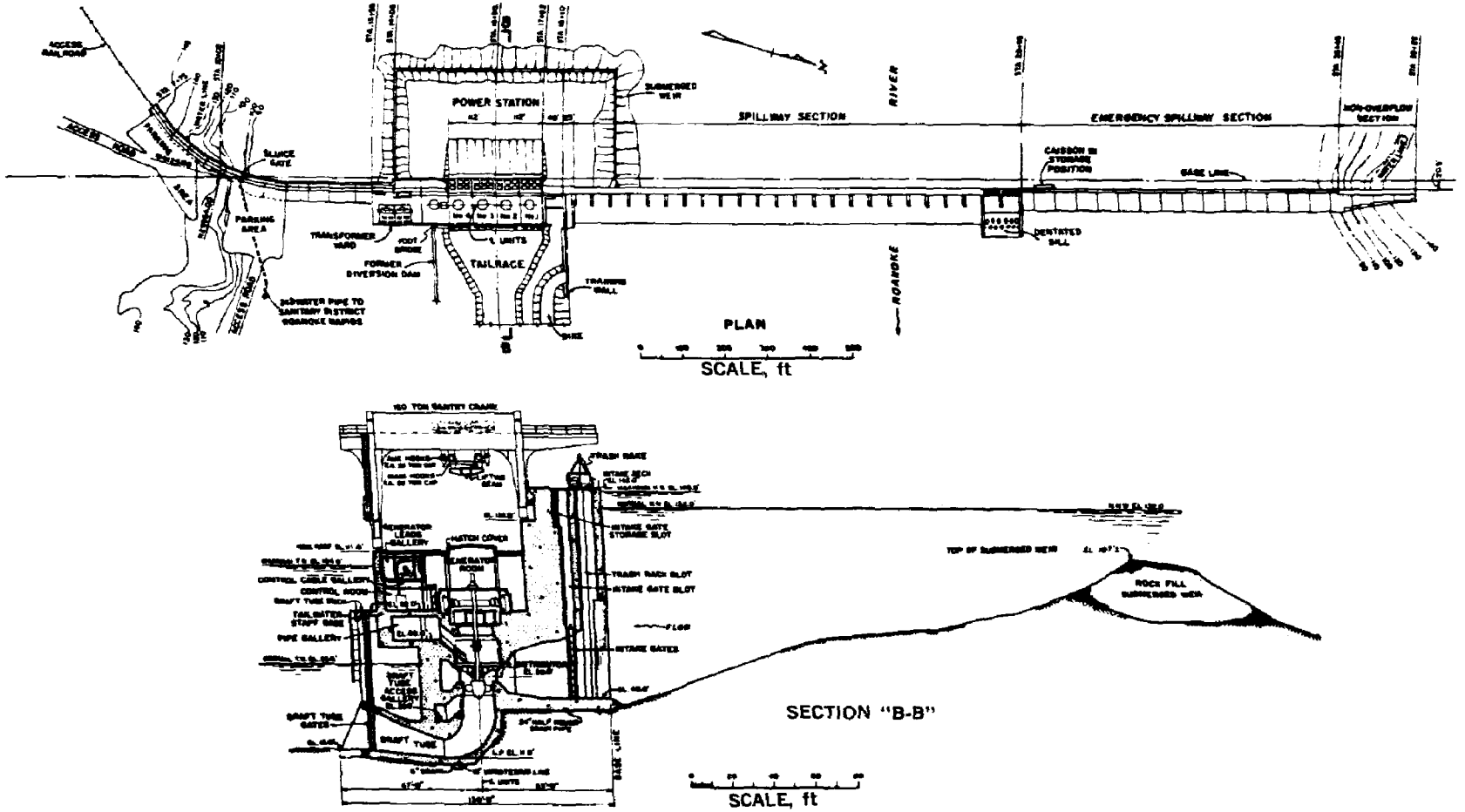


Figure 4 — Plan and elevation of Roanoke River Rapids hydroelectric station.

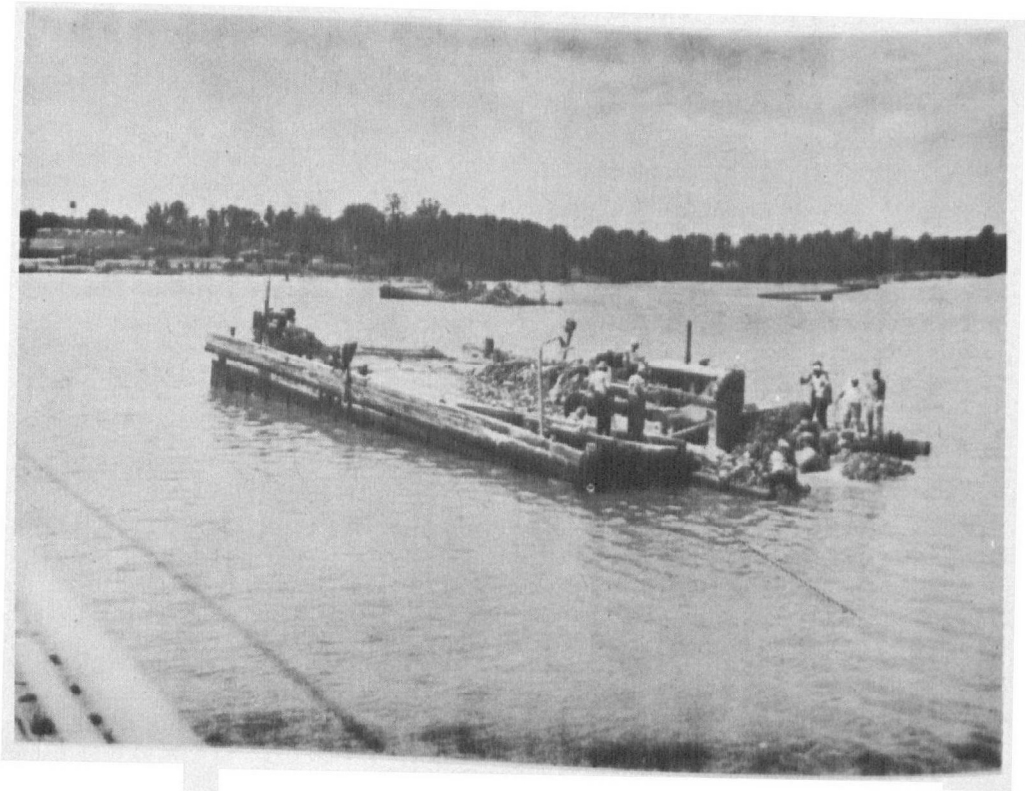


Figure 5 — Placement of rock fill for Roanoke Rapids weir.

This work was completed in July of 1957 at a cost of approximately $210,000 and an intensive survey of the performance of the weir was conducted. This survey, cooperated in by personnel of the Division of Water Pollution Control, North Carolina State Board of Health, North Carolina Wildlife Commission, U. S. Public Health Service, the U. S. Fish and Wildlife Service, and Virginia Electric and Power Company and its consultants, extended from July 15 through September 15, 1957, and had up to 24 men working in the field at times. Dissolved oxygen and temperature profiles were conducted throughout the Roanoke Rapids Reservoir, and dissolved oxygen and temperature analyses were made in the Kerr and Roanoke Rapids tailraces. In addition, water current studies were conducted around the weir to determine its effect on flow patterns and hydroelectric generation.

Based upon the data obtained during the 1957 survey, the efficacy of a weir was proven. The Gaston Project weir was designed to rise to within 15 feet of the surface in order to draw the uppermost layers of reservoir water into the turbines. The installation of a weir can create an appreciable hydraulic head loss, with a corresponding reduction in generation. Because of this a thorough study was made to determine the proper length of weir for full utilization of the available hydraulic head. This study indicated that the length should be approximately 1000 feet, and the weir was designed accordingly. Figure 6 shows the design of the weir and its configuration. The Virginia Electric and Power Company was able to bring the top of

this weir to within 15 feet of the normal water level of the Gaston lake because variations in level for this project during normal power operations will be less than 1 foot. This was not true of the Roanoke Rapids lake, and with wider variations in lake level, the weir could only be brought to within 25 feet of the surface. Figure 7 illustrates the overall construction of the Gaston weir upon completion, and Figure 8 is a closeup view showing the rock-filled concrete cribbing that was a more economcal installation than the construction of a completely rock-filled weir of the same height. The Gaston weir cost approximately $650,000, which was considerably more than the Roanoke Rapids weir. This was primarily due to the greater height and length of the Gaston weir.

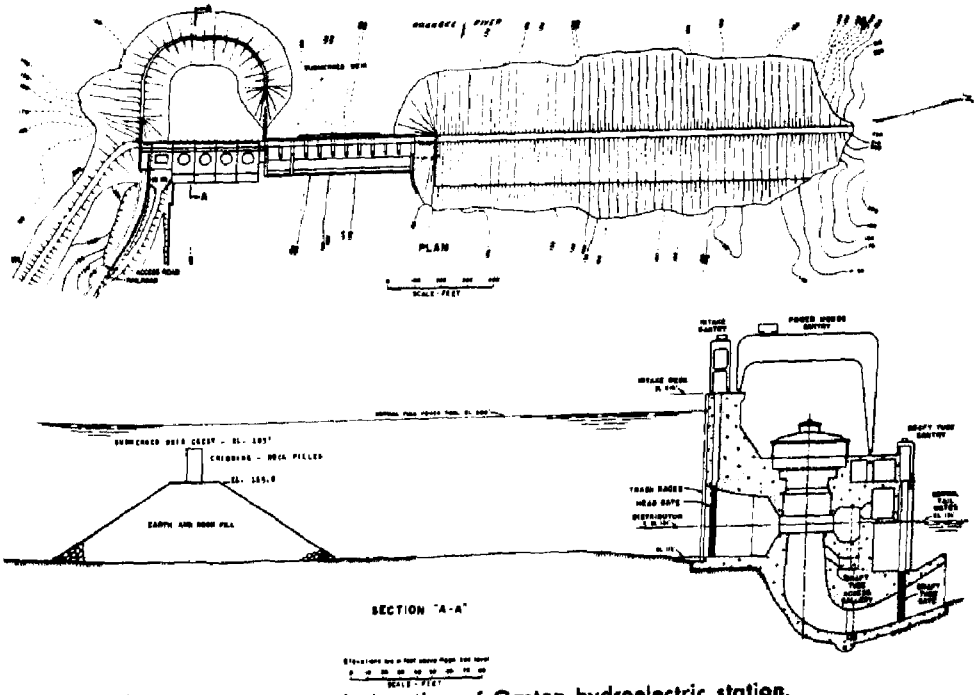


Figure 6 — Plan and elevation of Gaston hydroelectric station.

Virginia Electric and Power Company continued its bi-monthly surveys of the Kerr and Roanoke Rapds reservoirs and the river below these reservoirs by graduate chemists and engineers. Figure 9 illustrates a typical survey report. In 1958 it was decided to add routine around-the-clock testing of the Roanoke Rapids tailrace for dissolved oxygen. To accomplish this, it was necessary to provide facilities and train the power station operators at Roanoke Rapids in the necessary techniques of Winkler tests for oxygen. In addition to this, arrangements had to be made for the operator to obtain a representative sample of the tailrace discharge at any time. This required the installation of a submersible pump suspended from a raft located in the tailrace of the Roanoke Rapids project from which a continuous sample was piped into the Roanoke Rapids station. Figure 10 is a close up of the raft showing its construction. This installation cost approximately $500, but it assured the availability

of a continuous sample of the discharge of Roanoke Rapids for the operators conducting the tests. Oxygen tests were run and recorded every 4 hours by the operator unless conditions indicated analyses were required more often. During minimum flow conditions and/or during the critical summer season, tests were run hourly. Two years of testing indicated that reliable determinations of oxygen in the discharge from Roanoke Rapids could be made by station operators, and we concurred with the issuance of a license in 1960 for the Gaston project. This license included requirements for minimum instantaneous and minimum poundage per day of dissolved oxygen in the Roanoke Rapids discharge, in addition to minimum flow requirements. To our knowledge, this is the first license to contain such a provision. Article 25 of the Federal Power Commission license for Gaston, which pertains to these minimum flows and dissolved oxygen, is shown in its entirety in Appendix I. Construction was started almost immediately on the Gaston project, with completion planned in 1963.

Figure 7 — View of completed Gaston weir looking upstream.

With the dissolved oxygen provisions of the license, the Virginia Electric and Power Company wanted to provide an even more reliable and continuous means of monitoring the oxygen content of the Roanoke Rapids discharge. Considerable experience had been obtained in the Virginia Electric and Power Company steam stations with dissolved oxygen analyzers and recorders on condensate in the steam cycle and with flue-gas oxygen analyzers and recorders of

various manufacture. The problem of continuous recording of dissolved oxygen in river water was discussed with several instrument manufacturers. It was decided to install a newly designed Hays dissolved oxygen analyzer and recorder on the same Roanoke Rapids discharge sample being piped into the station for the operator analysis. The installation of the Hays equipment was completed in 1960 at a cost of approximately $4200. Figure 11 shows the completed installation and the small test bench used by the operators at Roanoke Rapids. It was necessary to increase the size of the submersible pump suspended from the raft to supply the water flow requirements for the analyzer and for operator analysis. The cost of this larger pump is included in the total cost of $4200.

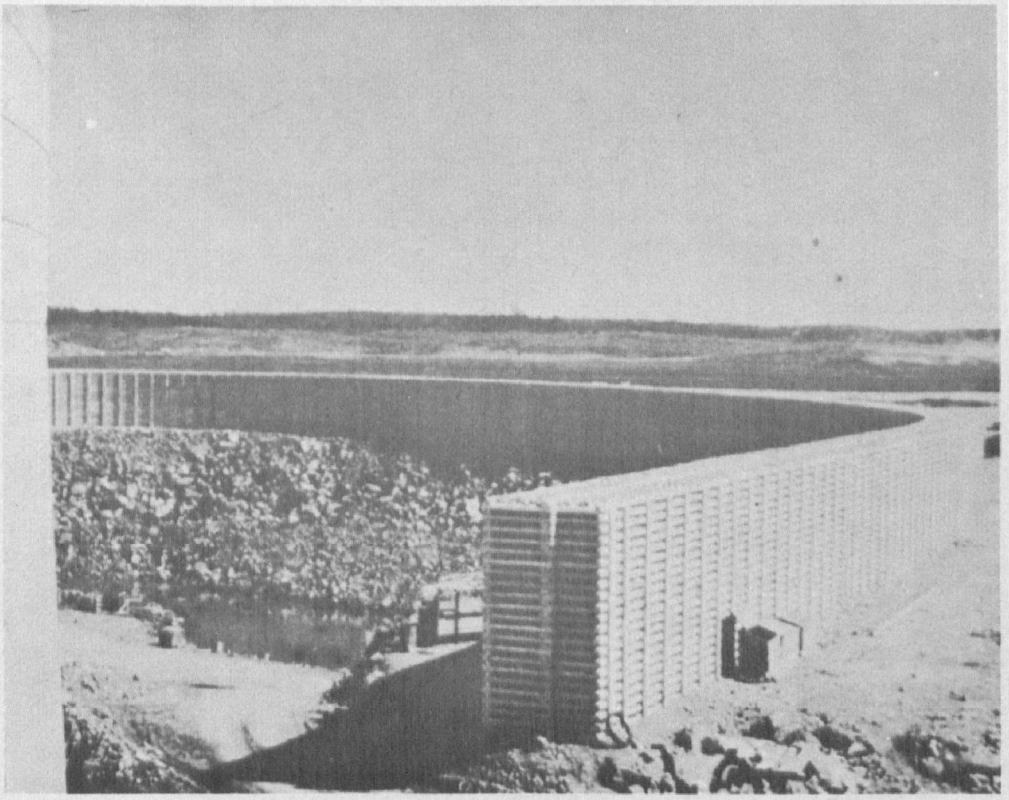


Figure 8 — Rock-filled concrete cribbing in the submerged weir in Gaston Reservoir.

Winkler tests have been run by the operator every 4 hours from March through October and every 8 hours the remainder of the year since the installation of the analyzer and recorder to check the dependability and accuracy of the recorder. During the 3½ months following the installation of the continuous analyzer in July 1960, 630 analyses were run by the operator and compared to the dissolved oxygen determinations by the continuous analyzer. These tests indicate that 85 percent of the recorder readings were within 0.2 milligram per liter oxygen and over 95 percent were within 0.3 milligram per liter of the corresponding operator's oxygen determination. Because of the difficulty with analyzing for oxygen by relatively unskilled personnel, it is believed that analyzer-recorder determination

of dissolved oxygen is more reliable and accurate than operator's analyses.

VIRGINIA ELECTRIC AND POWER COMPANY

ROANOKE RIVER DATA

DATE	July 16, 1962					
SAMPLE POINT	HOURS	°F	D.O.	PH	Fe	Mn
Kerr Reservoir 1'	0930	82.0	8.5	7.8		
5		82.0	8.5			
10	0940	81.0	8.6	7.8		
15		81.0	8.4			
20	0950	81.0	8.1	7.8	0.25	0.06
25		78.0	6.1			
30	0955	76.0	5.1	7.7		
35		76.0	4.1			
40	1000	76.0	2.2	7.2	1.37	0.06
45		75.0	1.2			
50	1010	74.0	0.4	6.8		
55		74.0	0.4			
60	1020	74.0	0.3	6.4	2.74	0.12
65		73.0	0.3			
70	1025	72.0	0.3	6.4		
75		71.0	0.2			
80	1030	71.0	0.2	6.5	2.70	0.24
85		69.0	0.1			
90	1040	68.0	0.1	6.2		
Scroll Case	1115	69.0	0.4	6.4		
Tail Race	1130	70.0	1.7	6.4	2.20	0.53
U.S. 1 Bridge	1220	75.0	5.9	6.4		

DATE	July 17, 1962					
SAMPLE POINT	HOURS	°F	D.O.	PH	Fe	Mn
Gaston Dam	1440	80.0	7.4	6.8	0.72	1.49
Ro. R. Reservoir 1'	1040	81.0	8.0	7.4		
5		80.0	8.0			
10	1050	78.0	7.6	7.4		
15		76.0	7.1			
20	1100	76.0	5.9	6.8	1.18	0.06
25		75.0	5.4			
30	1110	74.0	4.7	6.9		
35		74.0	4.7			
40	1115	73.0	4.3	6.9	1.20	0.06
45		73.0	4.4			
50	1125	70.0	4.1	6.9	1.00	0.06
55-58		68.0	0.8			
Scroll Case	1200	75.0	6.4	7.5		
Tail Race	1205	75.0	6.7	7.5	1.20	0.06
N.C. 48 Bridge (2nd Span)	0850	74.0	6.8	7.7		
U.S. 301 (Weldon) South	0740	73.0	4.9	7.4		
U.S. 301 (Weldon) Middle	0730	73.0	5.8	7.8		
U.S. 301 (Weldon) North	0720	73.0	6.2	8.5		
U.S. 258 (Scot. Neck)	1430	77.0	4.8	7.6		
Pump Inlet (Filter Plant)	0900	77.0	6.2	7.6	1.32	0.09
Plant Effluent (Filter Plant)	0910	77.0	7.5	7.3	0.00	0.00

July 16, 1962 Kerr Reservoir: Water clear, surface calm - very hot, sunny sky, air temperature 95°F at 3:00 p.m. No wind.

July 17, 1962 Roanoke Rapids Reservoir: Water slightly turbid, choppy - North breeze - air temp. at 12:00 Noon was 75°F.

Figure 9 — Typical Roanoke River data report.

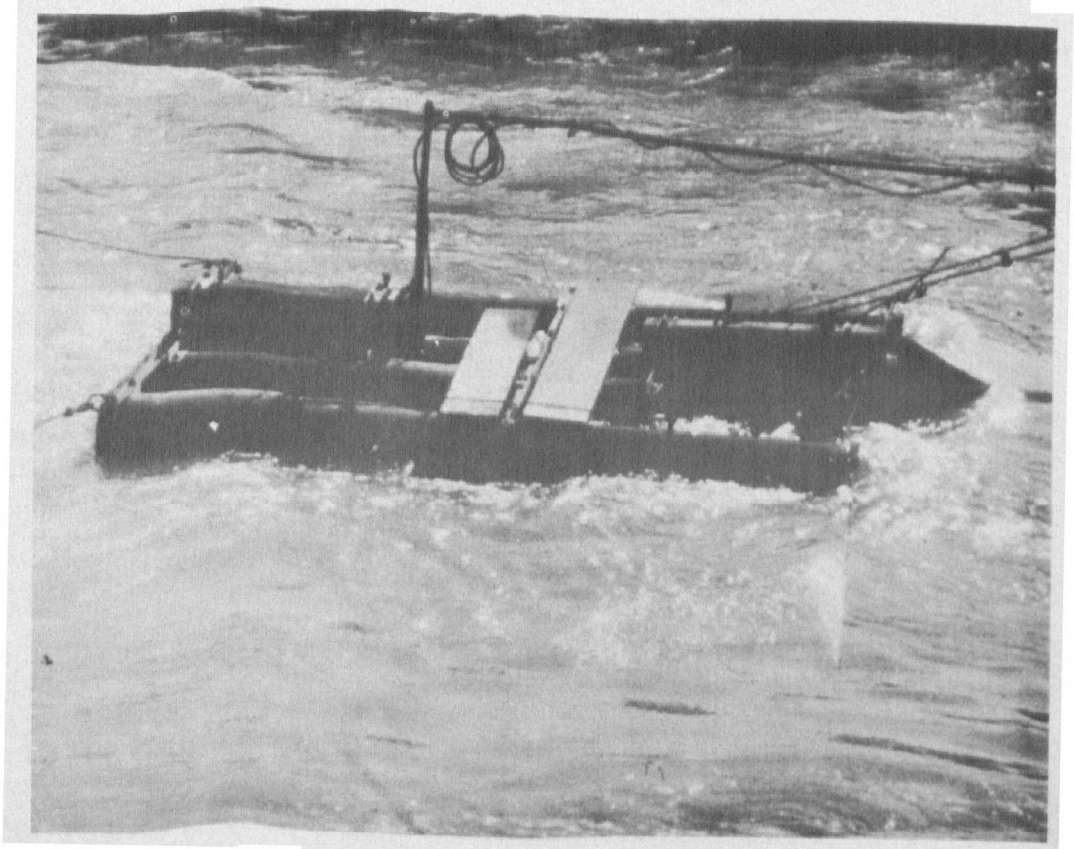


Figure 10. Raft in Roanoke River tailrace.

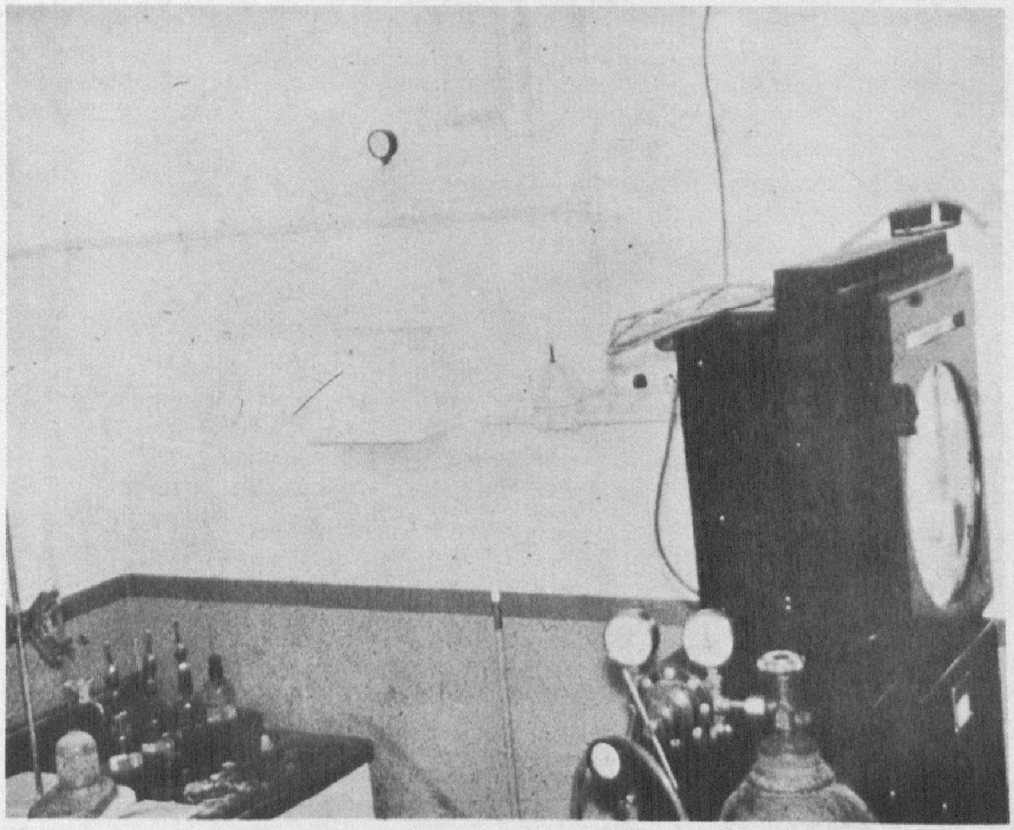
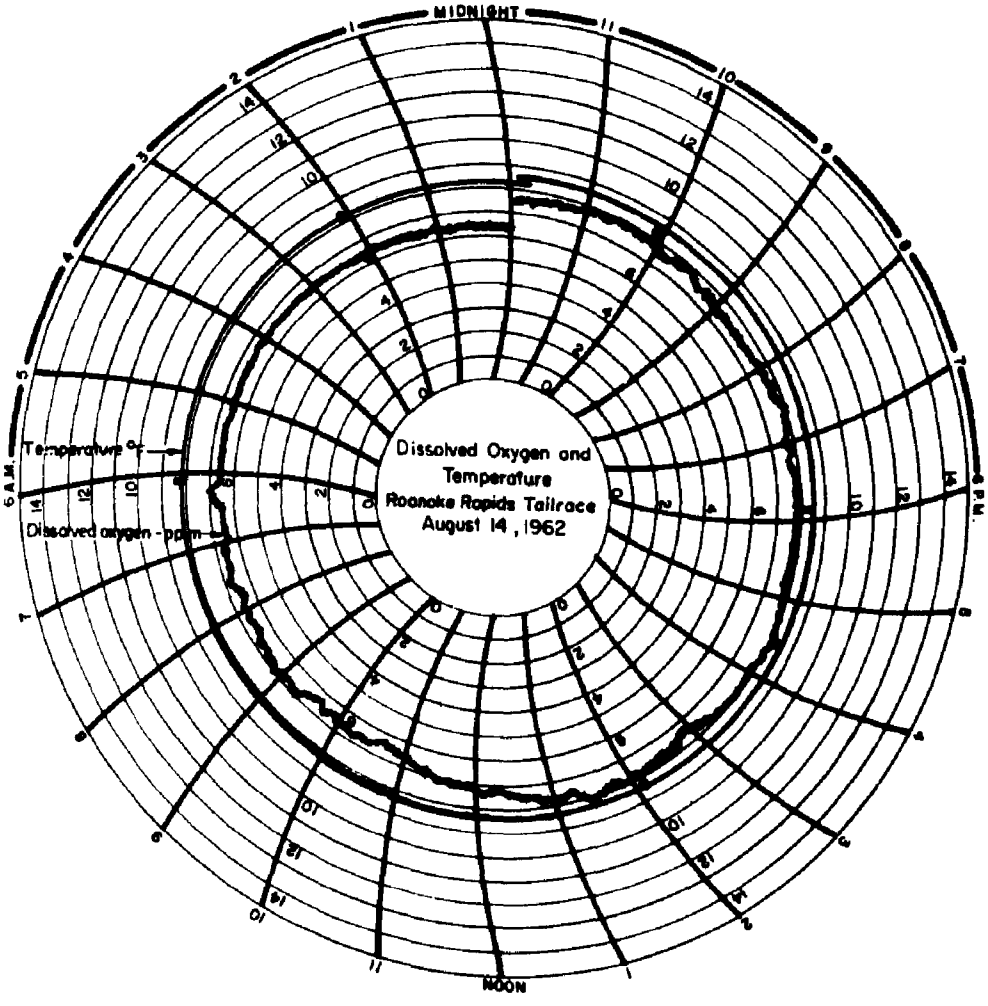


Figure 11 — Hays dissolved oxygen analyzer at Roanoke Rapids power house.

Except for a few maintenance problems soon after installation, primarily due to shipping and wiring damage, the analyzer and the recorder have required very little maintenance. In fact, no technical personnel are available any closer to Roanoke Rapids than Richmond, Virginia, and the maintenance problems associated with this equipment have been such that only a few trips for servicing the instrument have been required in the past 2 years. Maintenance costs have been less than $200 per year. The station operators have been instructed in the proper procedures for regularly zeroing and calibrating the analyzer and recorder. After calibration, if their analysis deviates by more than 0.3 ppm from the analyzer, they are instructed to call the chief chemist and start running oxygen analyses hourly until the instrument can be checked and repaired if necessary.

The chart from this analyzer and the daily dissolved oxygen log sheet for August 9, 1962, are shown in Figure 12. A marked increase in dissolved oxygen can be noted at 6:15 a.m. This increase is due to the placing of a second water turbine in service while remaining at a low total flow and thereby bringing vacuum breaker operation into play for aeration of the discharge. (This operation will be discussed more fully later.) It can also be noted that as the discharge increased to 12,000 cfs, the dissolved oxygen increased considerably. This increase was caused by the drawing of upper level waters over the weir into the water turbines.



VIRGINIA ELECTRIC AND POWER COMPANY
ROANOKE RAPIDS POWER STATION
DISCHARGE AND DISSOLVED OXYGEN LOG

Hour	Hourly Average and Accumulated Rate Discharge - cfs: Avg. For Hour	Avg. For Hour Accum.	Avg. For Hr. Accum. ÷ No. of Hrs.	Dissolved Oxygen: Avg. For Hour ppm	Hourly Discharge lb.	Accum. Discharge lb.
1A	1600	1600	1600	6.2	2200	2200
2	1600	3200	1600	6.2	2200	4400
3	1600	4800	1600	6.4	2300	6700
4	1500	6300	1575	6.4	2200	8900
5	1500	7800	1560	6.4	2200	11100
6	1500	9300	1550	6.4	2200	13300
7	5600	14900	2128	6.4	8100	21400
8	9800	24700	3087	6.5	14300	35700
9	12600	37300	4144	6.8	19300	55000
10	12500	49800	4980	6.8	19100	74100
11	13000	62800	5709	6.8	19900	94000
12N	12500	75300	6275	7.0	19700	113700
1P	12800	88100	6777	7.8	22500	136200
2	12000	100100	7150	7.8	21100	157300
3	12500	112600	7506	7.7	21700	179000
4	12100	124700	7793	7.7	21000	200000
5	11000	135700	7983	7.8	19300	219300
6	9500	145200	8066	7.7	16600	235900
7	8500	153700	8089	7.7	14700	250500
8	11300	165000	8250	7.6	19300	269800
9	10700	175700	8366	7.4	17800	287600
10	5500	181200	8235	7.5	9300	296900
11	1500	182700	7963	7.7	2600	299500
12M	1500	184200	7675	7.5	2500	302000

No. of Units Oper.	Instantaneous Rate: Discharge Rate cfs	Analyzer: Temp. °F	Analyzer: D.O. ppm	Titration D.O. ppm
1	1400	82°	6.2	
1	1600	82°	6.2	
1	1600	82°	6.4	
1	1500	82°	6.4	6.4
1	1500	82°	6.5	
1	1500	82°	6.4	
2	5600	82°	6.4	
3	9800	82°	6.5	6.5
3	12600	83°	6.9	
3	12500	84°	6.8	
4	13000	85°	6.8	
4	13500	85°	7.4	6.8
4	12800	85°	7.8	
3	12000	86°	7.8	
3	12500	86°	7.6	
3	12100	86°	7.9	7.8
3	11000	86°	7.8	
3	9500	86°	7.7	
3	8500	86°	7.7	
3	9500	86°	7.6	7.5
3	10700	83°	7.6	
1	5500	83°	7.5	
1	1500	86°	7.7	
1	1500	83°	7.5	7.6

Tuesday August 14, 1962

Figure 12 — Typical dissolved oxygen-temperature recorder chart and log.

The Virginia Electric and Power Company has been thoroughly satisfied with the performance of the dissolved oxygen analyzer and recorder. The 2½-year test period that the analyzer-recorder has undergone has convinced us that such an instrument is sufficiently reliable to monitor the discharge of the Roanoke Rapids project for compliance with our Federal Power Commission license provisions. Several times during the period that we have been continuously monitoring the project discharge we have been able to absolve the project discharge from blame in downstream fish kills.

Because of the very dependable performance of the analyzer and recorder in the Roanoke Rapids discharge, it was decided to install a similar instrument in the Gaston project discharge. This was a more difficult task because the Gaston flows were almost double that of Roanoke Rapids and the tailrace was not as narrow as that at Roanoke Rapids. The raft and pump installation required large heavy piers to position the raft so that a representative continuous sample could be obtained. Figure 13 shows the outer pier above the water line in the tailrace. The other pier is near the shoreline and cannot be seen in the figure. Gaston's four units went in service in January and February 1963, but the raft and pump installation will not be completed until April. Figure 14 shows the raft with pump and strainer prior to its being placed in the discharge. Figure 15 shows the Gaston analyzer and recorder installation. The analyzer and recorder were placed in a small enclosure on the bank of the tailrace. This was the most economical installation, since there was no need to take the sample into the Gaston Station because it is remotely controlled from the Roanoke Rapids Station and the oxygen record is transmitted by microwave to the Roanoke Rapids operators. This analyzer and recorder was in service during the filling of the Gaston Reservoir in November 1962; however, it has been taken out of service until the raft and pump can be installed in the tailrace. It is planned that this equipment will be in service by April 1963.

The cost of the Gaston installation was considerably more than the Roanoke Rapids installation because of the necessity of transmitting the signal by microwave to Roanoke Rapids and because of the more complex pier arrangement to position the raft properly. The analyzer, recorder, and weatherproof cabinet installed cost $7,500; the microwave facilities and miscellaneous wiring $6,500; and the raft, piers, pump, and cable $23,000.

There are many benefits to operation of a hydroelectric project from such analyzer installations. Of course, the main benefit of the installation is that it permits the maximum utilization of available water for generation while complying with the license provisions for the project. An additional benefit of continuous monitoring and recording oxygen in the discharge is the permanent record provided in case fish kills occur downstream.

There are other hydroelectric operations that are benefited by the continuous analysis for dissolved oxygen. These operations involve the most economical methods of increasing the oxygen content

of the discharge from a hydroelectric project when indications are that the oxygen content is low. A brief description of these procedures illustrates the complexity of peaking hydroelectric operations.

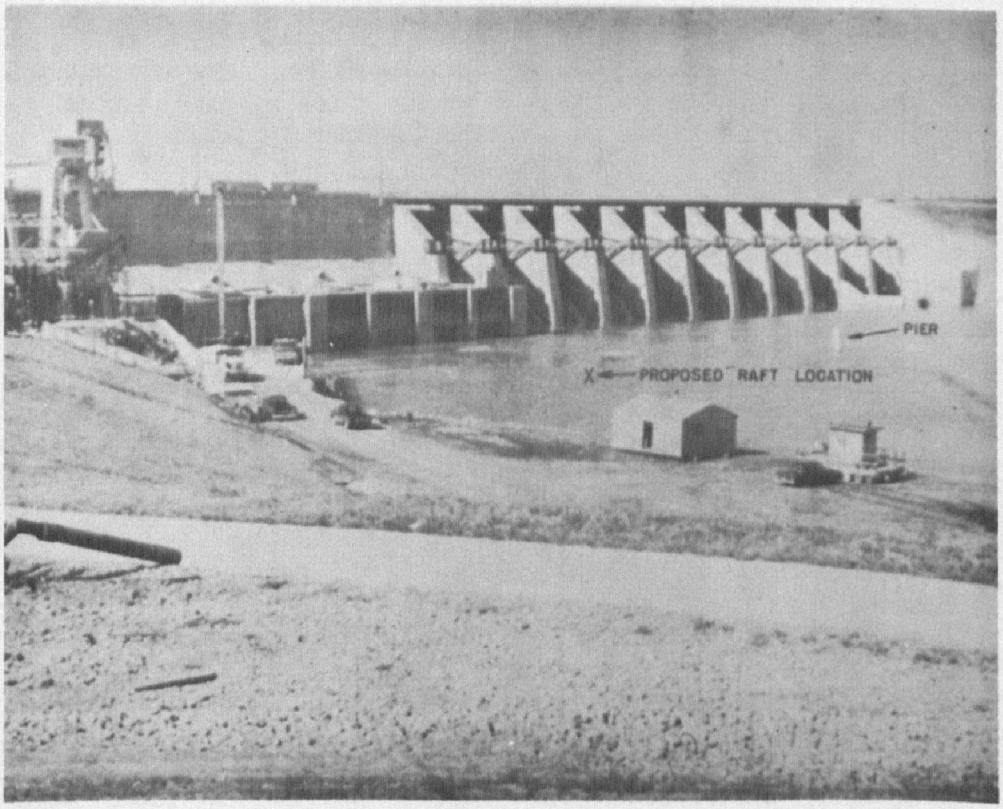


Figure 13 — Heavy pier for anchoring pump raft in Gaston tailrace.

VACUUM BREAKER OPERATION

Hydraulic turbines are equipped with spring-loaded vacuum breakers in the head cover. These breakers draw in air when the turbines are operating at low load. The air thus introduced into the turbine is intimately mixed with the water flowing through the turbine and a considerable quantity of oxygen is absorbed.

By this procedure, the Virginia Electric and Power Company has been able to increase the dissolved oxygen in the project discharge during periods of minimum flow by splitting the minimum flow between two turbines to bring this vacuum breaker operation into play. In this manner, the same minimum flow is made to contain appreciably more pounds of dissolved oxygen. It must be realized, however, that this method of dissolved oxygen improvement is not without cost to the Virginia Electric and Power Company, since a loss in generation occurs when waterwheels operate near their minimum capability and cavitation can occur, causing increased maintenance.

Figure 14 — Raft with pump and strainer for Gaston tailrace.

SPILLING OF WATER OVER PROPERLY DESIGNED SPILLWAYS

During the winter months when minimum flows are 500 cfs, the Virginia Electric and Power Company found it best to spill this flow through the skimmer gate rather than put it through a turbine. This 500-cfs flow is barely sufficient to maintain turbine speed, and no generation is realized. The spilling of this water ensures its complete saturation with dissolved oxygen and provides the best stream conditions at this flow. Figure 16 illustrates spill from the Roanoke Rapids project and the white water produced.

By the use of a continuous monitor in installations such as the Roanoke Rapids and Gaston Hydroelectric projects, which have both minimum flow and minimum dissolved oxygen rate requirements from the lower project, it is possible to use various methods to reach an optimum operating condition. If the quantity of available water is low and dissolved oxygen is also low, it is possible to employ vacuum breaker operation that splits minimum flow between two wheels rather than to increase flow. It may be advisable to spill minimum flows to ensure the highest degree of saturation. If water supplies are plentiful but oxygen is low, it may be better to increase

flows sufficiently to ensure meeting total oxygen requirements. It is impractical to expect a station operator to balance such factors by repeated Winkler oxygen analyses; however, by referring to continuous flow and oxygen recorders, he can quickly establish the optimum operating condition that will satisfy the requirements.

Although the Virginia Electric and Power Company provides the oxygen content prescribed in the license for Roanoke Rapids and Gaston, cooperation by all downstream users is essential if fish kills from excessive river contamination are to be avoided.

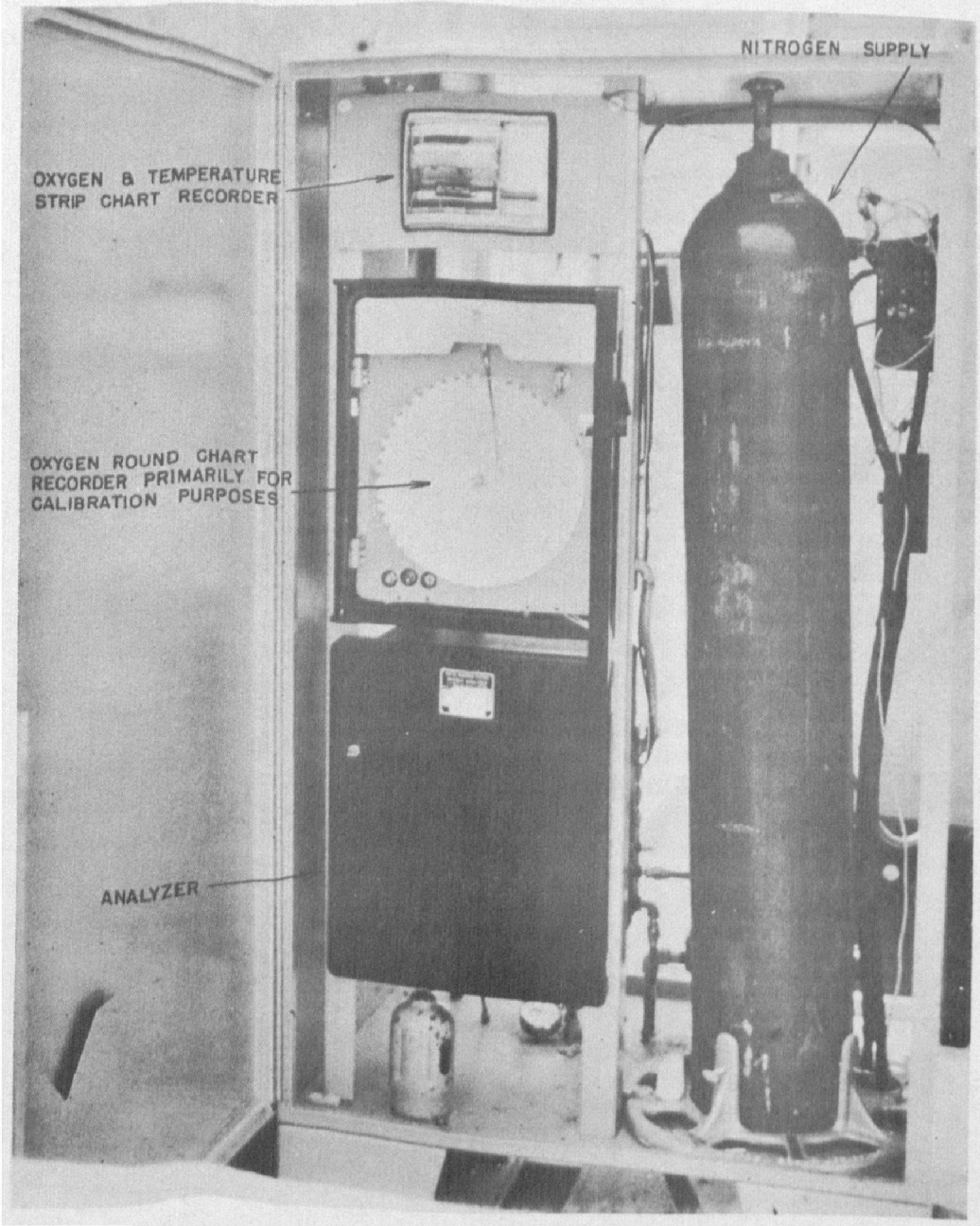


Figure 15 — Gaston dissolved oxygen analyzer-recorder installation.

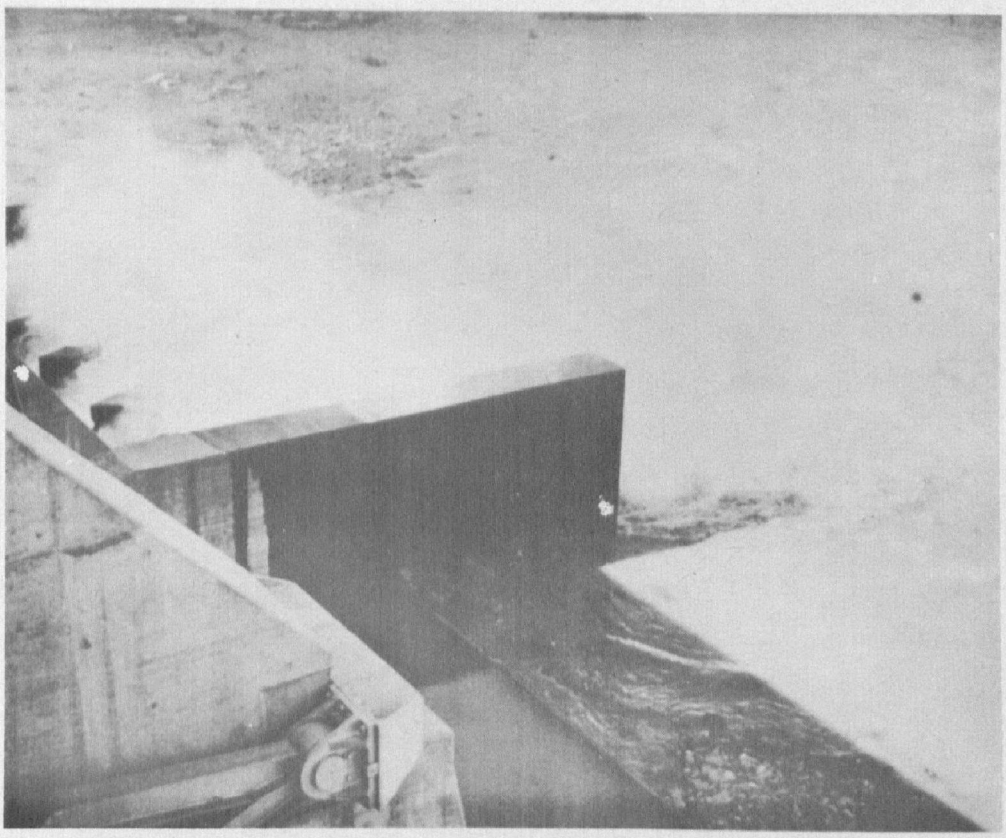


Figure 16 — Discharge from Roanoke Rapids spillway for minimum flows.

If other users monitored the river continuously, the information on streamflow and dissolved oxygen content would allow polluters, by simple lagooning, to discharge their wastes in relation to the assimilative capacity of the stream at any time and ensure against lowering the river below predetermined limits at the downstream sag point. The dissolved oxygen continuous analyzer-recorder installations are relatively expensive; however, the maintenance costs are low and the dependability and availability are excellent, and it is our opinion such analyzers could be of inestimable value for the proper control of stream conditions.

REFERENCES

1. Report on studies below the John H. Kerr Reservoir — August-September 1953 and April-May 1954. USPHS, Southeast Drainage Basin Office, Atlanta, Ga. Mar. 1955.

APPENDIX I.

FEDERAL POWER COMMISSION LICENSE PROVISION ARTICLE 25 — PROJECTS 2093 (GASTON) AND PROJECTS 2009 (ROANOKE RAPIDS)

Effective with commencement of operation of the Gaston Development, the Licensee shall release sufficient water from the Roanoke

Rapids reservoir to maintain minimum flows and pounds of oxygen in the Roanoke River as measured at the point of project discharge to meet the following requirements:

Requirement A: Minimum Instantaneous Flows

Month	Cubic feet per second
January, February, March	1,000
April	1,500
May, June, July, August, September	2,000
October	1,500
November, December	1,000

The above flows are subject to the following special provisions:

(1) These flows may be reduced on weekdays, Monday through Friday, during off-peak hours by not more than 20 percent, but such reduction shall not dispense with compliance with Requirement B.

(2) The average flow for any day shall equal or exceed the minimum instantaneous flow specified for that month.

(3) A minimum instantaneous flow of 2,000 cubic feet per second will be furnished by the Licensee for the period requested by the North Carolina Wildlife Resources Commission, to begin as early as April 1, but not later than April 15, and to continue for at least 60 days but not longer than 75 days in any one year, in accommodation to annual variations in the time and duration of spawning activities of the striped bass.

(4) The reduction in instantaneous flows permitted above shall not apply when special spawning flows are being passed for the benefit of striped bass.

Requirement B: Minimum Oxygen

Discharge from the Roanoke Rapids Development shall be maintained to provide dissolved oxygen at an instantaneous rate of not less than 78,000 pounds per calendar day during the months May through October, except as is permitted under the following conditions:

(1) A reduction not in excess of 34 percent of the instantaneous rate of 78,000 pounds per day will be permitted for periods not exceeding 14 consecutive hours.

(2) Any oxygen deficit so created shall be offset by greater discharges so that a cumulative average rate of discharge of 78,000 pounds per day will be attained within a period up to but not exceeding 16 hours from the beginning of the oxygen deficient flows, and this condition (2) shall again begin to operate as soon as the instantaneous rate again falls below 78,000 pounds per day.

The Licensee shall not be required to compensate through increased flows or other changes in operations for any lessening in the quality of water entering the Gaston Development which may after the effective date of this article be created by Acts of God, or through acts of others than the Licensee, and beyond its reasonable control.

Requirement C:

In the event of temporary emergency conditions arising in performance of Requirements A and B the Licensee will cooperate in good faith with the North Carolina State Department of Conservation and Development, North Carolina State Stream Sanitation Committee and/or North Carolina Wildlife Resources Commission to take such reasonable steps in regard to the reductions permitted by item (1) under Requirement B as may be proper to meet the emergency conditions and in the interest of maintaining during such emergency conditions water quality in keeping with the standards required of class "C" waters by order of the North Carolina State Stream Sanitation Committee effective September 1, 1957. But nothing herein is intended to compel the Licensee to correct conditions which it has not created and no permanent change of operations shall be made without the approval of the Federal Power Commission.

DISCUSSION

Robert K. Horton

Ohio River Valley Water Sanitation Commission, Cincinnati, Ohio

May I, first, compliment Mr. Ragone and Mr. Peters on their paper. It is stimulating to read of the ingenuity used in solving a difficult problem. And the straightforward manner in which the story is told — with simplicity and clarity — is refreshing.

The paper illustrates several principles in the water-quality-management field that are worthy of comment and elaboration.

First of all, the paper demonstrates that "obvious" problems must be solved promptly and on the basis of "today's" needs.

The Virginia Electric and Power Company had a real and immediate problem. It wanted to develop a natural resource in order to expand the company's hydro-generating facilities. The problem was that the proposed development might destroy another valuable resource, the breeding ground of the Albermarle-Sound species of striped bass.

Giving immediacy to this conflict was the fact that the power company wanted the additional generating capacity "today."

We do not know what mental reservations those concerned might have had at the time, or still might have, about the manner in which the problem was resolved. Certainly, the solution is acceptable to the

power company and, obviously, requirements of State and Federal authorities regarding the breeding grounds have been met.

But what would have happened if at the time the Federal Power Commission was on the verge of issuing its precedent-making license, someone had come forward and said, "This solution is fine for the time being, but what assurance can be given that the solution as now formulated will maintain adequate quality conditions in the Roanoke River 50 years from now?" And the questions might have continued: If additional reservoirs are built, will the patterns of stratification and density currents be so changed as to render invalid the tests on which the license for the Gaston project is based? Has enough research really been done on breeding requirements of striped bass? What changes will occur in waste loads downstream from the Roanoke Rapids dam? How many people and new industries will move into the area by the year 2010?

We can only guess at the amount of time the Gaston project might have been delayed if all such questions had to be answered with some degree of finality. The point is that so much effort may be devoted to side issues that the immediate job becomes subordinate. In the words of Dr. Edward J. Cleary, Executive Director of the Ohio River Valley Water Sanitation Commission (ORSANCO), "There is failure to do the obvious."

Nothing is implied here that in any way minimizes the importance of planning for the future. The fact is fully appreciated that if water resources are to be managed properly there must be adequate planning, both short-term and long-range. Planning involves forecasting, studies, surveys, and research. All of these are essential.

The problem is to see that administrators do not become so interested in forecasting, surveys, and research that knowledge already acquired is not applied simply because answers to all aspects of a problem have not been developed. Delays and failures have resulted from such misdirected interest. Let me cite an example, based on an experience of ORSANCO, having to do with the establishment of control measures for acid mine drainage.

For years there was an attitude of defeatism throughout the coal industry regarding mine drainage. Operators believed that control work could not be started until a complete understanding of the complex reactions and inter-relationships involved in the formation of mine acid had been established through research. The idea of waiting for research to solve the whole problem had become so entrenched that as late as 1955, when ORSANCO adopted basic requirements for control of industrial wastes, mine drainage was specifically exempted from control "until such time as practical means are available for control." The irony of it is that even at that time practical methods were available for ameliorating the effects of mine drainage. These methods were simple in principle and had been proved to be effective, although they were by no means a complete solution to the mine-drainage problem. Fortunately, a change in attitude was gradually

brought about, and in 1960, the exemption was removed and control measures based on existing knowledge and experience were adopted. Adoption of the control measures represented the establishment of a new attitude regarding the mine-drainage pollution problem in the Ohio Valley. This change did not result in a stoppage of research activities. It merely opened the door for taking control action "now."

Another example of how delays may be created can be found in the emphasis that is given to long-term surveys (6 to 8 years, for example). This is not to say that surveys and comprehensive plans are not essential; they are.

But unfortunately, someone is always ready to seize on a survey-and-planning program as an excuse to delay action. The plea is made: "Why should I do anything now. Let us wait until the survey-and-plan are completed. Then we'll know what has to be done." This is reasonable up to a point; it ignores the fact that in many cases some of the things that will have to be done, sooner or later, are already known.

In recognition of just such a problem, ORSANCO recently saw fit to take a stand regarding Federal survey-and-planning activities in the Ohio Valley. These activities are mandated by law, and — I repeat — there is no question regarding their necessity or desirability. The Commission deemed it prudent, however, to issue a policy statement to the effect that development of a Federal comprehensive plan will not be tolerated as an excuse for municipalities and industries to delay construction of pollution-control works.

RIVER MONITORING AND INSTRUMENTATION

Another principle brought into focus by the paper by Mr. Ragone and Mr. Peters is that river monitoring is an essential part of water-quality management and that instrumentation can be of great value in this endeavor.

In view of the great popularity of monitoring programs and data-collection networks today, the paper serves as a reminder that the objectives of these programs should be as specifically understood and as clearly enunciated as those of the Roanoke Rapids project.

The paper illustrates with clarity the advantages of instrumentation. The great advantage in this instance, of course, is that "it permits the maximum utilization of available water for generation." As pointed out by the authors, various methods are available to the power company for achieving its objectives: vacuum-breaker operation, discharge over spillway, increasing flow through the power plant, etc. Because of the complexities involved in water-quality management projects, the following conclusion, therefore, has particular pertinence: "It is impractical to expect a station operator to balance such factors by repeated Winkler oxygen analyses; however, by referring to continuous flow and oxygen recorders, he can quickly establish the optimum operating condition that will satisfy the requirements."

The experience of the Virginia Electric and Power Company is in harmony with that of ORSANCO regarding the use of automatic equipment. Since 1960, ORSANCO has installed automatic analyzers — known as robot monitors — at strategic locations in the Ohio Valley for continuous reporting of water quality. Today the system comprises 11 monitor stations and a central receiving and data-logging station.

Important as the development of hardware is, however, there are other aspects of river monitoring that are just as important to the proper management of water quality. In the Ohio Valley, air and boat surveillance have become vital factors in furthering compliance with pollution-control regulations. This type of surveillance involves the ferreting out of unsightly conditions (scum, oil, unusual color, etc.) that are in obvious violation of clean-stream standards.

In connection with river monitoring, mention should be made of a new tool that has recently been placed in the hands of water-quality-control administrators. This tool is the development of techniques by the U. S. Weather Bureau by which streamflow and velocity can be forecast several days in advance.

An important application of this tool is its use in connection with "hazard-alert" operations — those operations by which downstream water users are notified of potential hazards caused by some unusual happening upstream. The value of advance flow-information is illustrated by the following incident: A truck carrying cyanide overturned above 20 miles above the Louisville, Kentucky, waterworks intake. Radio and television stations were broadcasting bulletins saying the river was poisoned.

Thanks to advance flow-information, it was possible to advise the city promptly that no hazard existed. About a thousand pounds of cyanide had been spilled. Flow in the Ohio River, however, was sufficient to accommodate 1,750,000 pounds of cyanide before creating a hazard. Furthermore, velocity of flow was such that it would take 48 hours for water at the scene of the spill to reach the city's intake. The fact that no hazard existed was confirmed subsequently by on-the-spot analyses.

PROPORTIONATE DISCHARGE

Still another principle highlighted by the paper is that the concept of proportionate discharge can be incorporated as an effective part of water-quality-management operations. How clearly the authors of the paper state the principle: "If other users monitored the river continuously, the information on streamflow and dissolved oxygen content would allow polluters, by simple lagooning, to discharge their wastes in relation to the assimilative capacity of the stream at any time . . . ."

An example of how the principle of proportionate discharge can be applied is the program for the control of chloride-waste discharges now in effect in the Ohio Valley. Study of the chloride problem indi-

cated that the most practical way by which concentrations could be kept within satisfactory limits was to take advantage of the diluting effects afforded by river flow. The control regulation promulgated calls for the construction of impoundment basins and the development of discharge schedules for producers of chloride waste. The discharge schedules show the amount of waste that can be discharged directly to the river for any river flow. Additional chloride must be impounded for later release at higher flows. As the authors indicate, it seems reasonable to anticipate that the principle of proportionate discharge will be applied with increasing frequency.

CONCLUSIONS

In conclusion, then, the paper by Mr. Ragone and Mr. Peters illuminates several important principles for better administration and operation of water-quality-management projects.

Among these principles are the following:

1. Research, surveys, and long-range planning cannot be tolerated as an excuse for delaying obvious jobs and for failing to apply knowledge already at hand.

2. Surveillance programs must include on-the-site observations as well as collection of laboratory data.

3. Instrumentation offers greatly expanded opportunities for understanding river characteristics and for improving water-quality control.

4. Streamflow forecasting is a new tool that has application in hazard-alert operations and in the management of waste-control facilities.

5. The principle of proportionate discharge can be an effective part of water-quality-management projects.

REFERENCES

1. Cleary, E. J. Safeguarding water resources through pollution control. Presented at ASCE Water Resources Eng. Conf., Omaha, Nebr., May 14, 1962.

DISCUSSION FROM THE FLOOR

Mr. Bell, U. S. Public Health Service: I think it is quite significant that the Virginia Electric and Power Company, a private power company, has gone to such lengths and expense to install dissolved oxygen and temperature recording equipment and to maintain it in this fashion.

Mr. Ragone, Virginia Electric and Power Company: Thank you, Mr. Bell. When Mr. Peters and I were first invited to present a paper at this symposium, we felt a little like Daniel must have felt when

he was informed he was to be placed in the lions' den. We thought we might be the only representatives of a private power project on the program. Mr. Lee, of course, strengthened our ranks. After reviewing the objectives of the symposium, we welcomed the opportunity to tell what can be and has been done on water quality control and monitoring of the Roanoke River through the cooperative efforts of Federal, State, and local agencies, and private enterprise.

Mr. McDermott, U. S. Public Health Service: In October 1953, prior to construction of Roanoke Rapids Dam, the Public Health Service surveyed the Roanoke River in cooperation with Mr. Hubbard's office. At that time we found a diurnal fluctuation in the dissolved oxygen downstream from Roanoke Rapids and the Halifax Paper Company that corresponded to the diurnal change in discharge from Kerr Dam. This diurnal fluctuation in flow, together with wastes discharged in the area, caused dissolved oxygen concentrations as low as 1.9 milligrams per liter at the critical point of the dissolved oxygen sag about 17 miles below Roanoke Rapids.

I note that the control for the regulation of dissolved oxygen has been placed at Roanoke Rapids Dam. It seems more logical that the control should be at the point of minimum dissolved oxygen, and that a considerable reduction in the loss of power could be attained by making use of the aeration in the rapids between Roanoke Rapids and Weldon and oxygenating only the water corresponding to low-flow discharges so as to increase the dissolved oxygen downstream at the minimum point rather than continuously meeting some dissolved oxygen requirement at the dam. Mr. Ragone, could you comment on whether consideration was given by VEPCO to placing the control at the oxygen sag critical point rather than at the dam?

Mr. Peters, Virginia Electric and Power Company: That is a very difficult problem. The possibility of establishing some criteria downstream was considered during the studies. From our own standpoint, however, we would rather control what we have on our own property and let the downstream users do the same.

Mr. Ragone: You know that a large waste load is discharged to the river about 8 miles downstream from the dam. Dissolved oxygen observations at or below that point would depend on the operation of that plant as well as ours. We surely would not want to be involved with another company's operation. We are in the power business, hope to stay in the power business, and do not want to get involved in any other business.

Dr. Ingols, Georgia Institute of Technology: Wouldn't the time lag between the dam and the sag point be significant in trying to control the dissolved oxygen concentration at a point downstream rather than at your tail race.

Mr. Peters: Yes, you might have a boat down there, moving all the time, because the location of the sag point varies up and down the stream depending upon the flow and, of course, upon the pollutional load discharged to the river.

Dr. Yevdjevich, Colorado State University: I have a question on the engineering features of those submerged weirs. When we have a submerged structure the difference in pressure on two sides should be very small. Why does this require such a tremendous investment? I question the necessity of building such an expensive dam just to separate two different types of water.

Mr. Ragone: The cost of the first submerged weir in Roanoke Rapids Reservoir was high because the reservoir was filled, and the only way we could build the project was to dump rock from a barge. The cost of caissons was prohibitive. There is a tremendous velocity effect, especially as you get into high flows, so the strength has to be there.

On the Gaston Project, we considered a thin concrete wall, but it would not work. It was more expensive to reinforce a thin concrete wall than to use the rock fill for the major portion of the structure and put the cribbing on top. I was not personally involved with the engineering studies on the different dams, but our consultants assured us that these were the most economical structures that would provide the strength needed for the velocity over the top. Since the Gaston weir was within 15 feet of the surface the length had to be 1,000 feet. We had originally started out to make it 600 feet long, but had to increase it just because of velocity.

Dr. Yevdjevich: Did you conduct hydraulic model studies on the impact of the crest velocities?

Mr. Ragone: No, but very elaborate studies were made on the Roanoke Rapids weir by our consultants. We also consulted people that were well versed in the problems of flow over this type of configuration, and their data were used in the design of the Gaston project to determine the necessary strength and length.

Mr. Lee, Duke Power Company: Duke Power Company has just finished a submerged weir that is a little higher than the VEPCO weir (80 feet) and almost the same length (about 900 feet). We had the opportunity to build it in the dry before the reservoir was filled. It is made of low-grade earth, secondary material that is not highly compactible and could not be used in the main earth dam. Our weir was very much less expensive than the Gaston weir.

One section of the weir has precast concrete stop logs running the full height of the weir to equalize the pressure on the inside of the weir so that there would not be a full head against the outside of the weir as the reservoir was filled. The weir was designed to resist the velocity head with 10 feet of water flowing across the crest of the weir under our maximum discharge conditions.

I did not notice in your slides, Mr. Ragone, whether you provided a way to fill the pool inside of your weir?

Mr. Ragone: They do not show, but two small doors, about 8 feet tall by 6 feet wide, were used in the filling so that the pressures

were balanced on both sides. We used precast concrete stop logs on top, as you can see.

Concerning the use of rock fill for the Roanoke Rapids weir, we had to blast an 8,000 foot tailrace through the rock of the river bed so there was rock available; in fact, we stored it on the side for a while.

Mr. McLean, U. S. Public Health Service: The establishment of the minimum flows for Roanoke Rapids is very interesting. I am under the impression they were established in about 1946 or 1948, before the expansion of the paper company and its waste loads. The importance of considering the future growth of industry in an area and the changes that may come about is very apparent in this situation.

COOPERATION IN THE SOLUTION OF WATER QUALITY PROBLEMS ASSOCIATED WITH FLOW REGULATION

Willis King and Edward C. Kinney
Bureau of Sport Fisheries and Wildlife
U. S. Fish and Wildlife Service, Washington, D. C.

WHY COOPERATION IS NEEDED

The years ahead will be characterized by a sharp rise in human population, a concentration of people in metropolitan areas, and increased demands for water to supply man's daily requirements, to meet industrial needs, to remove waste products, and to provide recreational opportunities (Tables 1 and 2). At present, supply and demand for water of good quality are about equal in the United States. The demand is increasing faster than the supply, and by 1980 will probably be double the 1960 standards. Statistics are available showing that more water is being used every year in the home, in industry, in agriculture, in waste removal, and for recreation. By the year 2000, which is within the lifetime of many of us, our population will have doubled and the demand for water will be several times that of 1960. Man's ingenuity, as well as nature's supply, will be taxed to adequately meet the Nation's requirements. These needs can be met only if all agencies concerned with the development and management of water resources are willing to cooperate in seeking equitable solutions to the many problems that must be solved. Cooperation in this undertaking will be necessary to maintain our American standard of living and our prominent world position.

The job ahead requires that administrators, planners, engineers, and biologists work together more closely than in the past. The skills of those in research, as well as those in management, must be properly directed and applied to the problems that are even now with us. Competition for water and conflicts in its use must be resolved on a basis of public need and willingness to accept the principle that compatible and essential uses of water must be allowed, even encouraged. Water quality must be maintained at acceptable levels, even though this means less financial income to some.

COOPERATION IN PLANNING FOR FLOW REGULATION

All water development projects start with an existing need, an anticipated requirement, or an idea. As soon as this stage arises, it is time to determine what the effects of such a project would be on the volume of stream flows, on the quality of water that results from the anticipated use, and the steps that may be necessary to restore water quality should it be damaged. The effect on uses already existing cannot be overlooked.

The legal support for cooperation in water resource planning is reasonably well established. Administrative machinery in the form

of Federal departments and the various State water boards and agencies is already in existence. Federal and State laws usually say what must be done before water can be impounded, diverted, polluted, consumed, or treated with chemicals. Sometimes the laws are inadequate or poorly enforced, but we will not attempt to analyze their weaknesses in this paper.

TABLE 1. PROJECTED WATER REQUIREMENTS IN THE UNITED STATES[a] — BILLIONS OF GALLONS PER DAY

Type of use	1954	1980	2000	Change, %
Waste dilution	512	332	447	—13
Waterpower	374	616	637	70
Steam generation	74	259	429	478
Navigation	281	238	221	—15
Irrigation	176	167	184	4
Sport fish habitat	78	171	241	210
Manufacturing	32	102	229	613
Municipal	17	29	42	147
Mining	2	3	4	100

[a]From Senate Report No. 29, 87th Congress, Report of the Select Committee on National Water Resources. 1961.

TABLE 2. CHANGE IN WATER WITHDRAWALS IN THE UNITED STATES[a] — BILLIONS OF GALLONS PER DAY

Type of use	1950	1955	1960	Increase, %
Waterpower	1,100	1,500	2,000	82
Industrial[b]	77	110	140	82
Irrigation	108	110	110	2
Public supplies	14	17	21	50
Rural	3.6	3.6	3.6	0

[a]From Geological Survey Circular 456, "Estimated Use of Water in the United States," 1960. Washington, D. C. 1961.

[b]Includes steam generation.

NOTE: Table 1 figures were projected from the 1954 base. At the time the study was undertaken, the 1954 use figures were the most recently available data common to all of the uses listed. The requirements for waste dilution are based on anticipated 70 percent treatment by 1980 and 80 percent treatment by the year 2000.

The data in the two tables differ considerably in the withdrawals for water power. The figures in Table 2 are higher as they include the amounts used at each hydroelectric installation. In Table 1, only the amount used once at the largest plant on any one stream was counted. That is, if there were several plants on one stream, only the amount used by one plant was included.

LEGAL BASIS FOR COOPERATION

Fish and Wildlife Coordination Act

One of the major purposes of Public Law 85-624, the Fish and Wildlife Coordination Act, is to assure that wildlife conservation receives equal consideration and is coordinated with other features of water-resource development programs (Appendix I contains excerpts from the Act). The term "wildlife," as used in the Act, includes fishes and aquatic life. Coordination is accomplished through effectual and harmonious planning.

The Act requires that the Fish and Wildlife Service and the head of the State wildlife agency be notified by any Federal agency or any public or private agency under Federal permit or license whenever a water development project is proposed or authorized. This specifically applies to impoundments, diversions, channel improvements, and other modifications including drainage and navigation improvements.

The Secretary of the Interior is authorized to provide assistance and to cooperate with Federal, State, public, and private agencies in the development of all species of wildlife and their habitat. This includes quality of water as well as flow regulation.

After project notification has been received, the Fish and Wildlife Service arranges for a joint meeting of Federal and State wildlife biologists and personnel of the agency in charge of the development. Following this briefing session, Federal and State biologists arrange for whatever joint surveys and investigations are required to determine:

1. Possible damage to wildlife resources.
2. Proposed means and methods of preventing losses or mitigating damages.
3. Possible developments for the improvement of wildlife resources (enhancement).

After the investigations, a report is prepared describing any damages to wildlife attributable to the project and measures proposed for mitigation. Specific recommendations are made for wildlife conservation and development, lands to be utilized or acquired, and the type of management required to achieve anticipated results. Other interested agencies and groups are consulted during the preparation of the fish and wildlife report.

For Federal projects, the Secretary of the Interior submits a copy of the report to the agency responsible for construction. The constructing agency includes the wildlife report in any project report submitted to Congress or authorizing agency. The State fish and game department may also submit a report to the constructing agency. Usually, however, the State report is included in the coordinated report of the Secretary of the Interior.

The Federal agency responsible for the construction is required to give full consideration to the report and recommendations of the Secretary of the Interior and to any report of the States. The constructing agency may modify or add to the structures and may acquire land for the conservation, maintenance, and management of wildlife resources, as directed by Congress in appropriating funds for the project.

The use of such waters, land, or interests for wildlife conservation purposes shall be in accordance with general plans approved jointly by the head of the department or government agency exercising primary administration, by the Secretary of the Interior, and by the head of the State wildlife agency.

Impoundments of less than 10 surface acres are exempted from provisions of the Act, as are developments carried out by Federal agencies on lands under their jurisdiction. This Act forms the backbone of cooperative effort in planning, developing, and operating water storage projects, where fish and wildlife resources are involved, throughout the United States.

Projects for hydroelectric developments, proposed by private interests, must be submitted to the Federal Power Commission, where all applicable information is reviewed, weighed, and considered before a license is granted for the construction and operation of the desired facility. These reviews are especially thorough when important public interests are involved. The Commission has, in recent years, shown itself to be receptive to recommendations from other private and public interests having legitimate concern over what the proposed development may do to an existing water supply. Needless to say, it is better to have taken these related effects into account before filing the license application. Likewise, objectors or representatives of conflicting interests should also have their case well justified and documented if they are to influence the terms of the license granted by the Federal Power Commission.

The Watershed Protection and Flood Prevention Act

The Watershed Protection and Flood Prevention Act (Public Law 83-566 as amended by Public Law 87-703) authorizes the Secretary of Agriculture to cooperate with other Federal agencies, with the States, and with local units of government in planning and carrying out works for soil conservation and other purposes. The Secretary is authorized to cooperate in making investigations and surveys of watersheds and proposed waterways as a basis for the development of coordinated programs.

After the Secretary of Agriculture approves the request from a local agency for planning assistance, the Secretary of the Interior is notified. The latter may then make surveys and investigations and prepare a report with recommendations concerning the development of wildlife resources. Full consideration is given to the wildlife recommendations during the final drafting of the local plan. The wildlife section of the plan is a cooperative effort developed by the Bureau

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of Sport Fisheries and Wildlife, the State fish and game agency, the Soil Conservation Service, and local fish and game interests.

Many of the potential fish and wildlife developments are described in Bureau of Sport Fisheries and Wildlife Circular 100 titled, "Better Hunting and Fishing on Small Watershed Projects."

Federal Water Pollution Control Act

The Federal Water Pollution Control Act (Public Law 84-660, as amended by Public Law 87-88) provides for water pollution control activities in the Public Health Service of the U. S. Department of Health, Education, and Welfare and for other purposes.

The Secretary of Health, Education, and Welfare, after investigation and in cooperation with other Federal agencies, State and interstate agencies, and with municipalities and industries involved, prepares and develops comprehensive programs for eliminating or reducing the pollution of interstate waters and their tributaries, or navigable waters, including coastal waters. In this development, due regard is given to the improvements that are necessary to conserve such waters for public water supplies, propagation of fish and aquatic life and wildlife, recreational purposes, agricultural, industrial, and other legitimate uses.

In recognition of the common interests in the field of water pollution and to provide an effective program of inter-agency cooperation, a Memorandum of Understanding, July 1958, was developed between the Departments of Interior and Health, Education, and Welfare. The Memorandum resulted in the establishment of close liaison at various levels between the two Departments. It also provided for cooperative water quality studies involving the well-being of fish and fisheries and joint investigations of major fish kills.

The Act provides that in the surveys or planning of any reservoir by any Federal agency consideration be given to provision for storage of water so that streamflow may be regulated for the purpose of water quality control.

State Laws

Most States have laws designed to maintain the quality of their water resources in a condition so as to protect public health and permit industrial growth. Sometimes recreational uses are neglected or ignored, but public sentiment is growing rapidly, calling for full understanding and cooperation in the development and use of water. More will be said in this connection in the discussion of water quality standards.

BASIC CONCEPTS IN COOPERATION

Cooperation in water quality control is largely dependent on the free exchange of information. Recognition of the primary objectives of a project must come early in its history. Likewise, secondary purposes or what is generally considered a better concept, "compatible

uses," should also be defined. Rarely does any project confine itself to a single purpose. The point here is that all necessary and potential uses must be recognized and considered when planning is started.

Field surveys must be made to determine the level of use that can be provided, the capacity for future growth, and the effects one type of use may have on the quality and quantity of water passed downstream or made available for other uses. This information and often more must be in the hands of the designers of the project before their work has gone very far.

Frequently, operating plans for dams or other water control structures control the type of uses that a given body of water may serve. The extent of drawdown, seasonal and daily variations in flow pattern, and the effects of these on water quality, as well as quantity, must be understood in the light of available knowledge. The biologist must be able to think in terms of generating capacity, kilowatt hours, density currents, operation of the rule curve, and waste assimilative capacity. Engineers must not be content with understanding their own jargon, but must know what is meant by photosynthetic production, such terms as ecosystem, and the basic physiological requirements of fishes and other aquatic organisms. For the sake of brevity, I will not even attempt to mention the terminologies of the economist and the biometrician, which nowadays are frequently encountered. For those engaged in the development and management of the Nation's water resources, it is no longer enough to understand only the terminology and requirements of a single field of interest.

WATER QUALITY STANDARDS

Water quality standards have been established by many of the States and interest compacts formed for the various uses of water. California adopted water quality criteria instead of standards. It was believed that standards were too specific to apply to natural waters. It is often difficult to set minima to many pollutants because other chemicals in the water may nullify or intensify their effects. Most of these standards are established by State pollution control agencies. Some are established by public health agencies. Most agencies have consulted with their fish and game organizations in setting the standards.

Our purpose in reviewing the generally understood water quality levels described below is to emphasize that different uses require different standards and any use that would tend to downgrade the quality of water so that other uses cannot exist must be closely scrutinized and evaluated.

REQUIREMENTS FOR VARIOUS WATER USES

Drinking Water

The standards for drinking water are usually taken from the current Public Health Service Drinking Water Standards.* Most

*Latest revision — 1962.

natural waters that meet these standards will support aquatic life. Although sufficient dissolved oxygen to support aquatic life is not required for drinking purposes, the established minima are usually above 5.0 milligrams per liter. Most specifications require that no materials toxic to fish life be present.

Industrial Water Supply

There is considerable variation in the water qualities required by various industries. Water used in the food and beverage industries are in the higher drinking water class. Water used for cooling purposes should be cool, soft, but not too acid. Water used in the manufacture of steel should be soft, almost neutral, low in organic matter, and cool. Pulp and paper mills require soft, almost neutral water. Soft water with a higher pH can be used in rayon manufacture.

Irrigation

Because of the differences in soil types, precipitation pattern, and vegetation tolerances, it is difficult to establish critical limits for irrigation water quality. Highly acid waters (below pH 3.0 to 4.0) and highly mineralized waters are not suitable for irrigation because of their harm to the soil and to agricultural crops.

Fish and Other Aquatic Life

A tremendous amount of research has been done on the effects of pollutants on aquatic organisms. Much of this work has been summarized by Ellis, Westfall, and Ellis(*1*), by the California Water Pollution Control Board, and by various reports from the Department of Health, Education, and Welfare's Robert A. Taft Sanitary Engineering Center. Fish production is favored in near-neutral to slightly alkaline, moderately hard waters that are nearly saturated with oxygen; contain sufficient nutrients for good phytoplankton production; are free of injurious amounts of chemicals; have low turbidities; and are subject to not more than moderate fluctuations in water levels and flow velocities.

Navigation and Water Power

It is desirable that water used for these purposes be low in corrosive substances; debris and silt; objectional odors; and algae, fungi, and other substances that clog passageways or cling to vessels.

Swimming, Water Skiing, Boating, and Esthetic Enjoyment

Waters used for these activities should have a low coliform count, be clear, and be free from objectionable odors, pathogenic organisms, and irritants.

Water Dilution

Even after waste products are treated, some water is usually required for dilution. For organic wastes, the water should have a

high oxygen content and have temperature and pH characteristics that favor decomposition bacteria. It should be free of bactericides. Sufficient volume is required so that bacterial action will not result in low oxygen conditions. Inorganic wastes should be sufficiently neutralized or diluted so as not to be harmful to aquatic life.

EXAMPLES OF THE COOPERATIVE APPROACH TO SOLVING PROBLEMS OF WATER QUALITY CONTROL

Discussions of this broad subject of water quality control through flow regulation can easily be lost in generalities and platitudes unless we get down to actual cases. We will, therefore, cite situations where water quality control has been sought through flow regulation and where both success and failure have resulted.

The Roanoke River, North Carolina

It is worthwhile to describe the approach taken in dealing with problems on the Roanoke River in North Carolina and the solutions that were reached. Many attending this symposium are familiar with this story and participated in its development. For those who are not acquainted with it, I hope the resumé given here will be of interest. Like many similar situations, the problems were not all of sudden origin, nor were the answers quick to come, immediate in their application, or favorable to all interests.

The headwaters of the Roanoke River arise in the Blue Ridge Mountains of Virginia. The mainstem of the river is formed by the confluence of the Dan and Staunton Rivers, and some 200 miles downstream, it empties into the western end of Albemarle Sound (Figure 1). Two-thirds of the watershed is in Virginia, and the river is very important to the health, industry, and recreation of residents of the two States. The river carries more water by far than any other stream in North Carolina — the average flow through the State is about 8500 cfs.

The river is historic as an avenue of transportation and commerce, since the days of the early settlers of the region. Its waters are the home of the largest spawning population of striped bass south of Chesapeake Bay. It offers many opportunities for recreational developments that are largely unrealized at this time. The first two major developments that affected the life of the river were the establishment of kraft pulp and paper mills at Roanoke Rapids and at Plymouth in the 1930's and the construction of the Buggs Island Dam (now called the John H. Kerr Dam) by the U. S. Army Corps of Engineers, starting in 1946.

The North Carolina Department of Conservation and Development became aware that the river was changing in the early 1940's. Fishkills were reported; sportsmen and commercial fishermen complained that the striped bass and other fisheries were being destroyed by the pollution from the pulp mills. New industries were coming into the valley and old ones were expanding. Several cities became

concerned about the quality of their water supplies. At that time, the State did not have the funds or personnel to study the situation intensively.

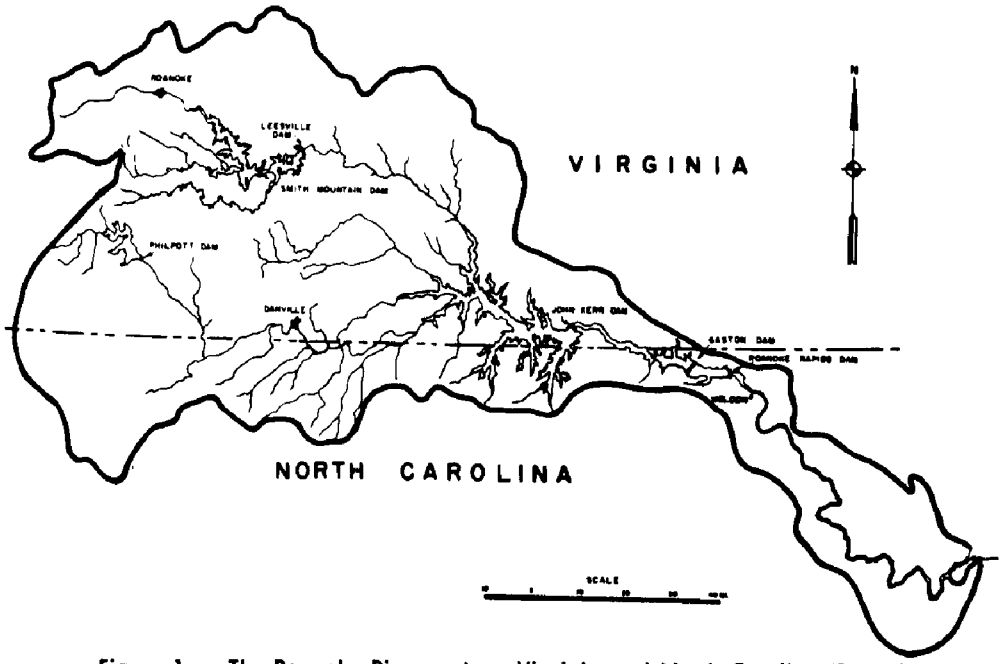

Figure 1 — The Roanoke River system, Virginia and North Carolina (Ref. 2).

The Federal government was brought into the picture when hydroelectric developments on the river were under consideration by the Corps of Engineers. The U. S. Public Health Service and the Fish and Wildlife Service supplied recommendations in 1942 and 1943 in which minimum flows, thought to be needed to make the river habitable for fish and to dilute the already evident pollution load, were proposed. When the Buggs Island Dam at river mile 179 was authorized by Congress, the Fish and Wildlife Service was asked to recommend minimum flows for the protection of the striped bass fishery. The study and report that followed were the first to point out that the striped bass spawning populations might be adversely affected by proposed hydroelectric developments on the river. A minimum of 5 milligrams of oxygen per liter was considered necessary to protect the striped bass, and a minimum average daily flow of 2000 cfs was proposed for the fish spawning season. There were other recommendations incorporated into the operating procedure for the Kerr Dam (then called the Buggs Island Dam). The first electrical power was generated in 1952, and flood control provisions of the project were also effected that year. It soon became apparent that the water discharge pattern greatly affected the migrations and spawning of the striped bass.

Private power entered the picture when the Federal Power Commission granted a license to the Virginia Electric and Power Company in February 1951 to construct and operate a hydroelectric plant at Roanoke Rapids (river mile 137). The Company was ordered to maintain the same minimum flows specified for the Federal project,

with certain additional features and with the stipulation that its Roanoke Rapids Dam should serve to reregulate water discharged so that the water requirements designated for pollution abatement and fish conservation could be met. The Commission left the way open for further protective steps by inserting the following clause in Opinon and Order No. 204, Project 2009:

> "The Licensee shall construct, maintain, and operate such fish protective devices and shall comply with such special conditions in the interests of fish life as may be prescribed hereafter by the Commission upon recommendation of the Secretary of the Interior."

Observations made by State fishery biologists and by State Stream Sanitation Committee workers in 1952 and in 1953 indicated that the minimum flows designated in the Roanoke Rapids license and in the operating plans for the Kerr Dam were not enough to protect the striped bass and to reduce the pollution entering the river to safe levels. Some field studies were conducted by the State in the spring of 1953 and continued in 1954, but just what flows were required to meet the conditions could not be determined. The U. S. Public Health Service participated in these studies and expanded its efforts in the spring of 1955, the first year that the Roanoke Rapids project was in operation.

It was apparent to all agencies concerned that an expanded and coordinated effort was urgently needed if some of the basic problems of flows and water quality were to be solved and if the very life of the river were to be saved. An appeal was made to Congressman Herbert C. Bonner for assistance. Congressman Bonner arranged a meeting of the representatives of all interested Federal and State agencies, industries, municipalities, and private citizens. The group met at Weldon, North Carolina, on May 2, 1955. The discussions there led to a recommendation for the establishment of a "Steering Committee for Roanoke River Studies." The senior author was chosen as chairman of the Committee and held that assignment throughout the study until the Committee terminated its activities late in 1959.

The Steering Committee was organized with one member from each of the following agencies or interests: State agencies — State Stream Sanitation Committee, Department of Conservation and Development, Wildlife Resources Commission; Federal agencies — Fish and Wildlife Service (U. S. Fishery Laboratory, Beaufort, North Carolina), Corps of Engineers (Office of the District Engineer, Norfolk), Public Health Service (Atlanta Regional Office), Southeastern Power Administration (Regional Office); Private industries — Halifax Paper Company, Roanoke Rapids, and North Carolina Pulp Company, Plymouth; General public — the State senator from the area, sport fishermen of the area, and commercial fishermen of the area.

The representative for the commercial fishermen failed to attend any meetings and their interests were handled by the Department of Conservation and Development. The Virginia Electric and Power

Company was invited to have a representative in the industrial group but declined. The Company did, however, attend all meetings of the Steering Committee and participated in and supported the study throughout. In addition to the efforts of the official members of the Committee and their staffs, active support was given to the program by the National Council for Stream Improvement (a research affiliate of the pulp and paper industries), by the Department of Zoology and Wildlife of North Carolina State College, by the Institute for Fisheries Research (University of North Carolina), by the Branch of River Basin Studies of the Bureau of Sport Fisheries and Wildlife, and by the Robert A. Taft Sanitary Engineering Center.

Members of the Steering Committee soon found that it would not be possible for everyone to become fully informed on all aspects of the problem or to contribute toward the solutions. Three task forces were formed; their assignments were as follows:

> Task Force 1: Water quality and engineering studies. These included determination of the quantity, nature, and pattern of discharges of pulp mill wastes and municipal sewage, together with evaluation of the resultant effects upon water quality in the river. The influences of impoundment and flow releases upon the physical and chemical qualities of the water, and its effectiveness in neutralizing pollutants were studied as a basis for recommending year-around flows to prevent deterioration of water quality.
>
> Task Force 2: Studies related to the spawning of the striped bass, the survival of eggs and fry under existing river conditions. These studies included the determination of the quality and quantity of water necessary to protect the striped bass fishery. This involved both field observations and laboratory studies.
>
> Task Force 3: Studies on the status of the striped bass fishery in the Roanoke River, Albemarle Sound, and tributary streams. Included were the location of spawning areas; migration pattern; survival of young and adult striped bass; collection of data on the catch by sport fishermen and by commercial fishermen; determination of the regulations necessary to conserve the fishery; and habitat improvements needed to assure continuance of acceptable conditions.

Each of the Task Forces promptly held initial meetings to draw up programs of investigation and field study. The Task Forces remained active throughout the life of the Steering Committee or until their final reports were submitted. Each was chaired by the representative of the appropriate State agency on the Steering Committee. Within each Task Force, efforts were pooled whenever possible, and the participating agencies called on for manpower, equipment, and funds. Only one man was employed full-time. The U. S. Public Health Service provided the services of Dr. Frederic F. Fish and the Fish and Wildlife Service provided funds for his expenses. Dr. Fish

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provided field coordination on certain phases of the studies and devoted his personal efforts to Task Force 2. He assisted the Committee by preparing special reports when requested and prepared the final report of the Steering Committee.

One further level of organization was found necessary — a Subcommittee for Operations. This was an executive group composed of the three Task Force Chairmen, the Chairman of the Steering Committee, and Dr. A. F. Bartsch, who represented the Robert A. Taft Sanitary Engineering Center. Dr. Bartsch chaired the Subcommittee. The Subcommittee met four to six times each year to review progress, plan technical phases of the work, process reports, and prepare recommendations for presentation before the Steering Committee. All members of the Subcommittee gave far more of their time and effort than could be readily spared from their other official duties. Dr. Fish also looked to the Subcommittee for general direction of his activities.

The Steering Committee held 11 meetings over a 5-year period and a full record of its transactions is on file with each of the participating agencies. From 25 to 50 people attended each meeting. Many more were present at the public meetings held at Weldon, North Carolina.

In this report, the organization, objectives, and program of the Steering Committee for Roanoke River Studies have been emphasized because little of this information has been generally available. The basic problem faced by the Committee was "How can the water which nature has provided in the Roanoke River be used to meet the varied and increasing demands placed upon it, so as to assure the rights of all legitimate interests and still protect the fishery resources with which the River was so specially endowed?" This was a large order.

In working out solutions to the many problems, the Committee recognized that no one philosophy or special interest could control. There would have to be give and take and above all a willingness to talk and negotiate differences even when at first sight it appeared that there was no common ground for reaching solutions. The Steering Committee found itself in difficult situations many times, and some of the debates held before it make highly interesting and informative reading.

Once the studies were underway, it became apparent that what was done at the Gaston Project, proposed by the Virginia Electric and Power Company as a new hydro-development at river mile 146, could well hold the key to the future of the Roanoke River. This new dam and reservoir occupied all space available for development between the Roanoke Rapids project and the Kerr Dam above. Both Roanoke Rapids and Kerr Dams have bottom-level discharges and are operated as peaking-power plants for the generation of electrical energy. The water coming out of the Kerr Dam was sometimes devoid of oxygen, and often held less than 2 milligrams of oxygen per liter. If the intervening stretch of the river were to be impounded, would it then be possible to provide water of acceptable

quality below Roanoke Rapids, as well as the flows needed for a variety of uses? Most of the studies of Task Force 1 were applied in seeking the answers to this problem. It was not enough to observe and understand existing conditions. The Committee had to know what would happen when these conditions were altered, and recommend measures that could be expected to maintain or even improve water quality for downstream uses. Unless this were done, there would be no opportunity for future development of the river, existing industries would suffer, and the striped bass fishery would be seriously threatened.

One of the study projects proposed and carried out by Task Force 1 was to learn what would occur if a curtain wall or submerged weir were built around the turbine intake at Roanoke Rapids so that water could be taken from the top 25 feet of the reservoir. A comprehensive study plan was developed and carried out during the summer of 1957. Utilizing the old coffer dam as a base, the power company constructed a curtain wall of crushed stone. A full-scale monitoring project was organized to record dissolved oxygen, temperature, and turbidity over a 3-month period. A mass of data was gathered and analyzed by a special committee of experts. The curtain wall did improve the quality of water passed downstream, but certain structural modifications were indicated as to its height, stability of materials, and relation to the flow pattern.

Some of the best brains in the business reviewed the data and gave their recommendation for solving the major problem. The group included Dr. D. W. Pritchard and associates of the Chesapeake Oceanographic Institute as consultants for the Virginia Electric and Power Company; Mr. Milo Churchill, Chief, Stream Pollution Control Section, TVA; Mr. Francis W. Kittrell, In Charge of Stream Sanitation Studies, U. S. Public Health Service; and Mr. Thomas M. Riddick, Consulting Engineer and Chemist for the Halifax Paper Company.

The findings guided Virginia Electric and Power Company in revising and redesigning their proposal for the Gaston project and provided a basis for providing the quality of water Task Force 1 found to be essential. Without this intensive study in which all agencies cooperated it is doubtful whether a solution satisfactory to the principal interests could have been found for the problems of the Roanoke River. The findings led to the construction of a permanent curtain wall or weir in the new Gaston project to assure that water of acceptable quality and temperature would be passed downstream to meet the necessary requirements.

Task Force 1 also completed a comprehensive pollution abatement plan for the Roanoke River and applied its water quality standards in a State classification system to appropriate sections of the stream.

Task Force 2 studied the hatch and survival of striped bass eggs and fry in varying concentrations of waste, drawing samples from the individual mills and from the river where all known pollutants were

mixed. The passage of striped bass eggs at Weldon was recorded for the peak of the 1958 and 1959 spawning season. These jobs required that new equipment be designed and tested and took at least three seasons of work before reliable quantitative data could be gathered and analyzed. The relation of stream flows to fish spawning was also observed. Task Force 2 was not able to complete its studies during the field program of the Steering Committee but continued them under State guidance and issued its final recommendations in 1960(3).

Task Force 3 tackled a variety of problems associated with sport and commercial fishing for the striped bass, as well as with its life history. The staff and facilities of the Fishery Laboratory, Bureau of Commercial Fisheries, Beaufort, North Carolina; the Institute for Fisheries Research at Morehead City; and biologists from North Carolina State College supported by grants from the pulp and paper companies, carried on field work for three full seasons. Their findings were summarized for the Steering Committee, and separate reports were prepared for publication by the participating agencies.

The findings and recommendations of the Steering Committee, with the history of the development of the Roanoke River, were combined in a report of the Steering Committee for Roanoke River studies and issued under date of June 1959(4). Unfortunately, the report has not been published. Final recommendations for stream flows related to the striped bass fishery were not completed at the time that the Steering Committee found it necessary to disband; however, year-around flows for stream sanitation purposes and the provisions believed necessary for inclusion in the license for the Gaston project were completed and accepted.

The recommendations for stream flows and water quality in relation to the Gaston project were presented to the Federal Power Commission in November 1960, in connection with its review of the Virginia Electric and Power Company's application for a license for this project. After extended negotiations and some modifications to meet operating requirements, the Steering Committee's recommendations were accepted by the Virginia Electric and Power Company and approved by the Federal Power Commission. A copy of these recommendations is included in Appendix II to this report. It should be pointed out here that these recommendations included increased flows over previous license provisions (Project 2009), recognized the need for higher flow schedules during the striped bass season, and most significantly, specified instantaneous and daily dissolved oxygen requirements to maintain the life of the river. This is the first time to our knowledge that such water quality provisions were accepted by a power company and included in a Federal Power Commission license. The license for the Gaston project also included the provision that a permanent curtain wall should be built within 15 feet of the power pool level by the construction agency, as a further assurance of passing water of the desired temperature and quality for downstream uses. The reservoir is now filling (spring of 1963), and only time and scientific study will tell whether the recommendations of the biologists and the engineers, arrived at jointly, were sound

and will accomplish the desired objectives. Certainly, the demands placed upon the reservoir will increase, and any action short of that stemming from the best thinking and available knowledge would be inadequate.

Inasmuch as the John H. Kerr dam holds the key to the seasonal discharge of water into the downstream reservoirs, the Steering Committee, early in its program, recommended that water be stored in the Kerr dam between elevations 300 and 302 feet for the benefit of the striped bass. This would be made available to augment minimum flows that would occur during peaking-power operations and over weekends. The critical period was found to be that time when the striped bass approached their spawning grounds in the Roanoke River. This period begins sometime after May 1 and extends from 2 to 4 weeks, depending upon flows, temperatures, and rainfall (Figure 2). The volume of water provided by the Kerr Dam would be scheduled by the power company to meet the fishery requirements with a minimum loss of generating energy. The plan proposed was found successful and was recommended as one of the permanent operating features.

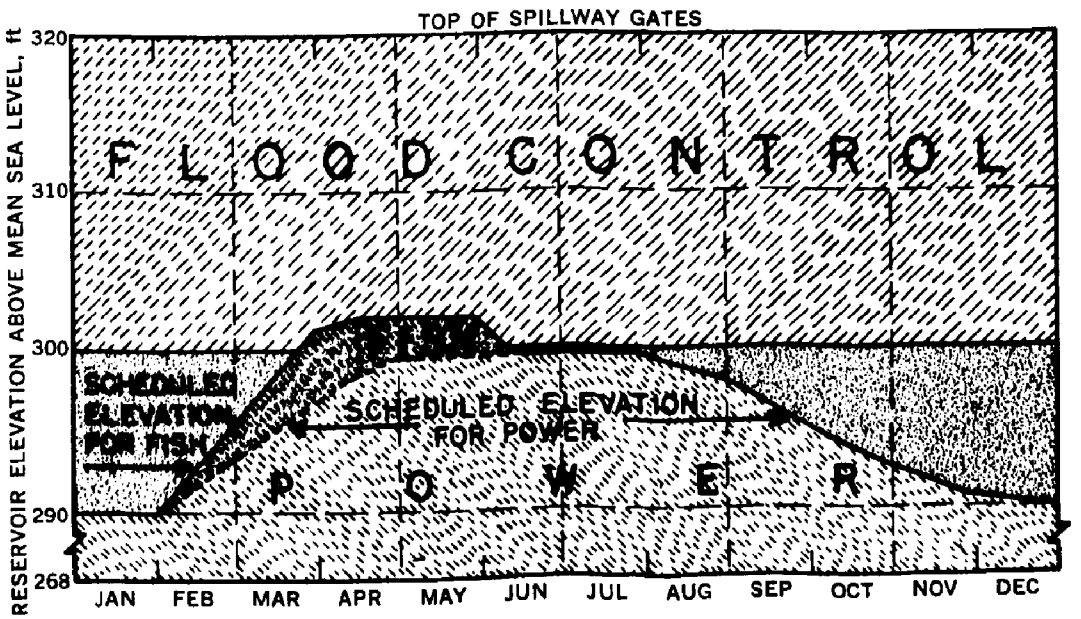

Figure 2 — Proposed and interim use of water storage space, John H. Kerr Reservoir. Courtesy, U.S. Army Engineer District, Norfolk (Ref. 2).

The White River, Arkansas and Missouri

The basin of the White River contains about 28,000 square miles, 60 percent of which is in Arkansas and 40 percent in Missouri. The White River, which is 720 miles long, rises in the Ozark Mountains in northwest Arkansas, flows northward into Missouri, then southward back into Arkansas and empties into the Mississippi River (Figure 3).

The upper half of the White River and tributaries contained some of the most famous float fishing waters in America. The principal species fished for were: smallmouth, spotted, and largemouth bass, walleye, rock bass, other panfish, and suckers. The lower half of the river supported moderate commercial fisheries. The species taken most commonly were: largemouth bass, crappies, channel and flathead catfish, buffalo, freshwater drum, carp, and gar.

After the 1937 flood on the Ohio and Mississippi Rivers, Congress approved several flood control acts that resulted in a comprehensive plan for the White River Basin. The plan consisted of a series of reservoirs in the upper reaches of the river and various channel improvements in the lower reaches.

The Corps of Engineer studies were begun in 1938. Some 15 reservoir sites were considered. Some sites could not be justified economically. Others were strongly opposed by various conservation groups. The 1945 plan proposed 12 reservoirs for flood control, power, recreation, and other uses. The 12 reservoirs would have a total flood pool area of about 350,000 acres and would inundate 751 miles of streams in the heart of the float fishing trip area.

To date, Bull Shoals, Clearwater, Norfork, and Table Rock reservoirs have been completed. Greers Ferry Reservoir is nearing completion and Beaver Reservoir is under construction (Figure 3).

The Norfork Reservoir, which was the first to be constructed, was completed in 1944. A coordinated fish and wildlife study by the Fish and Wildlife Service and the States of Arkansas and Missouri was initiated at about the time the reservoir began filling. Because of personnel shortages during World War II, a comprehensive study was not undertaken until 1946. Two studies were conducted. One considered the values of the reservoir fishery as compared to the loss of stream fishery in the inundated sections. The annual fish and wildlife losses were estimated to be about $40,000 greater than the gains from the impounded waters.

The second study considered the effects of the cold discharges from the hydroelectric reservoirs. It was found that, except for the sucker population, the warm-water fishery was practically eliminated below the dam on the Norfork River.

In 1948, the Norfork Reservoir tailwater was stocked with trout. The stocking was very successful. This resulted in an increased demand for more trout by the fishermen and local interests. When Bull Shoals Reservoir began operation in 1952, it was found that about 30 miles of suitable trout water was provided by the cold discharges of this impoundment (Figure 4) (5).

In order to supply the demands for trout for these new waters cold enough to support trout, it was necessary to construct a hatchery. The Norfork National Fish Hatchery, which is located below the dam, was completed in 1956. The water supply comes from the reservoir. Trout from this hatchery are stocked principally in reservoir tail-

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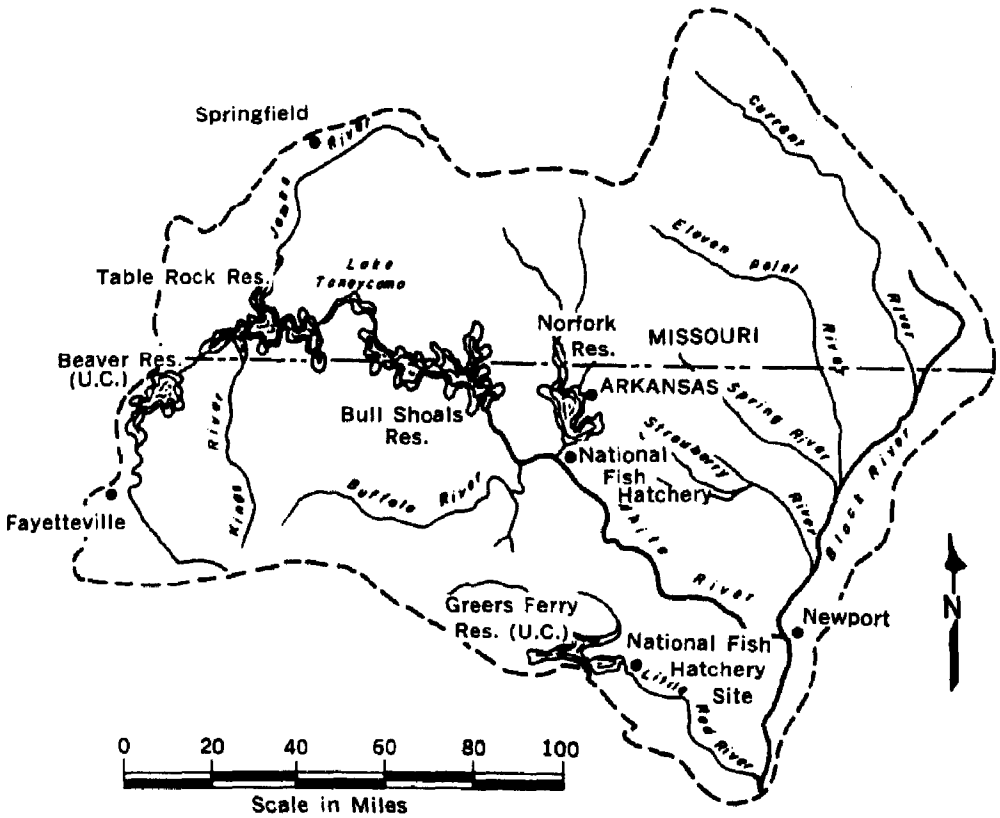

Figure 3 — The White River Watershed, Arkansas and Missouri.

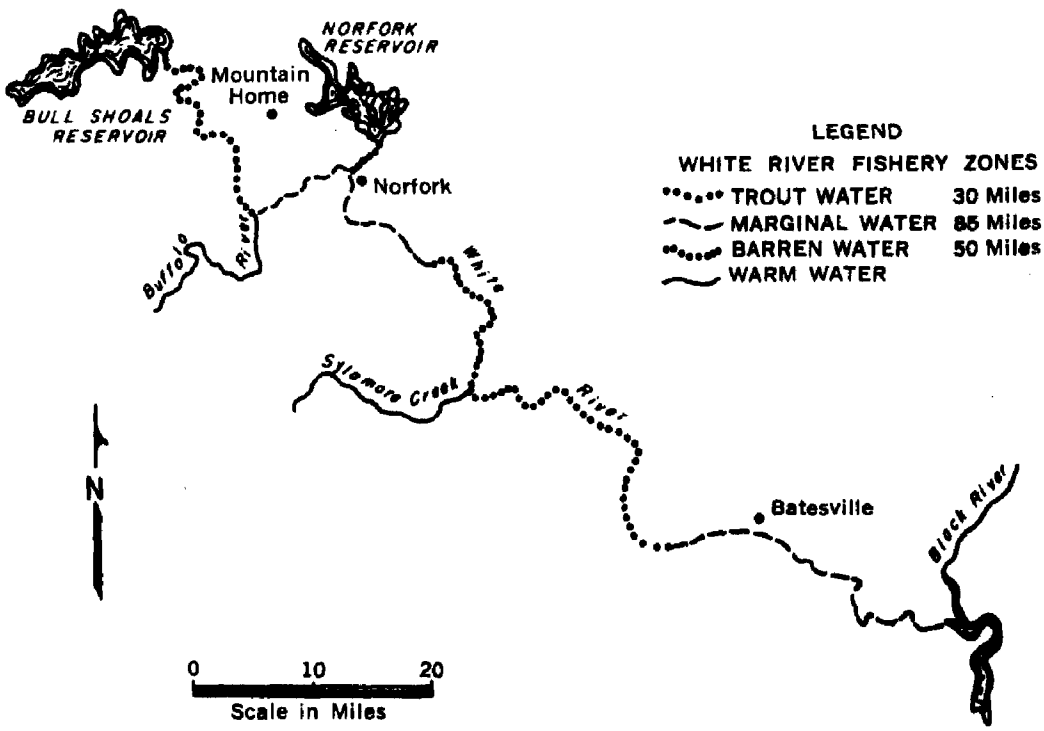

Figure 4 — White River below Bull Shoals and Norfork Reservoirs showing the effects of the colder discharges on the fisheries (Ref. 5).

waters and in the limited trout streams in northern Arkansas and southern Missouri. The present annual production is about 200,000 pounds. The hatchery is now being expanded and by 1964 will be capable of producing 400,000 pounds of trout.

By 1957, trout were being stocked in 91 miles of tailwater streams that afforded 47,792 man-days of fishing(*6*).

During the period from 1946 to 1956, investigations conducted on the effects of bottom discharges from reservoirs in Arkansas, Tennessee, and Kentucky revealed that several downstream warm-water fisheries had been virtually eliminated by cold water discharges. It was found that summer water temperatures were averaging from 10 to 20 degrees Fahrenheit below pre-impoundment temperatures. Management of these modified reaches of the White River still present difficult problems. An extension of the zone of trout stocking has been fairly successful, although expensive. Waters designated as barren in Figure 4 by the 1957 report do support some fish and may be improving.

Based on earlier studies and cooperative studies on the proposed Greers Ferry Reservoir, the Fish and Wildlife Service recommended to the constructing agency in 1957 that multilevel outlets be provided at the Greers Ferry Dam. It was believed that it would be necessary to discharge sufficient quantities of the warmer, near-surface waters to protect the downstream warm-water fishery. The annual value of the downstream fishery was estimated to be $123,000.

The constructing agency estimated that the additional cost for multilevel outlets would be $600,000 and requested that fishery biologists provide a justification for this additional expenditure. As a result of a mixup in communications, funds were not made available for this study until about 2 years after the request was made.

Before the justification study was completed, work had begun on the dam. The results of the study along with a request for the modification of the dam structure to provide for warm water releases were sent to the constructing agency. The constructing agency replied that to incorporate the modifications requested would require a new design and would result in costly delays and the loss of several millions of dollars.

When the public learned that multilevel outlets were not planned and that the downstream warm-water fishery was endangered, a bitter controversy developed between local fishery interests and the constructing agency. Numerous meetings were held in Arkansas, Atlanta, Georgia, and Washington, D. C. Hundreds of letters were written by the interested persons and several newspapers aired the controversy.

As a result of this unpleasant situation, numerous suggestions were made to solve the problem. It was finally decided that the second best action to take would be to develop a trout fishery below the dam. It was found that the downstream areas would provide

about 10 to 15 miles of good trout water, 10 miles of fair trout water, 30 miles of marginal water, and 30 miles of possibly barren water. It will be necessary to construct an $800,000 hatchery to provide trout for anticipated stocking needs in the area.

The most favorable outcome was the assurance by the constructing agency that fish and wildlife matters would be coordinated with the agencies concerned in the future at the earliest feasible stage and continue through the survey, planning, construction, and operation of the project.

The Assistant Secretary of the Army in a letter to the Secretary of the Interior, dated January 9, 1961, stated that, "The difficulties inherent in coordinating fish and wildlife as well as recreation purposes in the development of multiple-purpose water resources projects will continue to require the full cooperation of all concerned."

The Potomac River

The Potomac River basin presents many unusual problems partly because it encompasses mountainous areas, the rolling Piedmont, and the coastal plain, including the Chesapeake Bay estuary. It drains land from four States and passes through the District of Columbia. It is visited by large numbers of people and in many respects will be looked upon as a model watershed development. It has received a great deal of attention from many agencies and must serve a large variety of purposes, with water supply and recreation becoming of increasing importance.

The Potomac River Basin Study(7) is an excellent current example of what the Corps of Engineers call "Partners in Planning." This study, which will be completed in June 1963, "will consider all the beneficial uses of water and must provide a balanced program to satisfy to the maximum possible extent all present and anticipated water requirements in the most efficient and economical manner."

An examination of the various objectives of some of the previous Potomac Basin studies illustrates the evolution of the multiple purpose concept. The first major study was made in the 1920's and specified river development for navigation, water power, flood control, and irrigation. The second study, which was published in 1946, recommended a series of reservoirs for flood control and the generation of hydroelectric power.

In 1956, the Corps of Engineers was directed to prepare a basin-wide plan for flood control, recreation, the development and conservation of municipal and industrial water supplies, and water quality control. The present study should result in a maximum multiple-use development program. It will require considerable effort and cooperation among the various agencies and groups on Federal, State, and local levels.

Federal Agencies. — Department of the Army, Corps of Army Engineers — is in overall charge of the planning, coordination, and major impoundment studies.

Department of Agriculture — is developing a watershed protection and management program and is supplying data on agricultural and rural use in the Basin. The Forest Service is preparing development plans for water projects that will be on National Forest lands.

Department of Health, Education, and Welfare — is making studies of water supply, sanitary water quality, and pollution abatement needs.

Department of the Interior —

1. The Geological Survey is supplying data on sedimentation, streamflow, chemical quality, and ground water resources.
2. The Fish and Wildlife Service is studying the effects of the proposed water development projects on fish and wildlife resources and is recommending measures to gain maximum fish and wildlife benefits.
3. The National Park Service has supplied data on the recreational resources and has evaluated the recreational aspects of the project areas.

Department of Commerce — the Office of Business Economics prepared an economic base study of the Basin.

Federal Power Commission — will supply power value estimates and make hydroelectric studies.

State Agencies. — The States of Maryland, Pennsylvania, Virginia, and West Virginia contain waters that are in the Potomac River system. Various State agencies have certain responsibilities in regard to water developments. In most cases, the State agencies work closely with their Federal counterparts.

Local Agencies. — In addition to the various Federal and State agencies, an advisory group, chaired by the District Engineer, was formed. This group includes representatives from the four States in the basin and the District of Columbia, the National Capital Regional Planning Council, and the Interstate Commission on the Potomac River Basin. The Interstate Commission has been interested principally in pollution control in the Potomac River Basin. The Potomac may well be our most studied river.

THE BUREAU'S PROGRAM IN SPORT FISHERY RESEARCH

The Bureau of Sport Fisheries and Wildlife conducts a fishery research program designed to provide answers to some of the problems encountered in planning and managing reservoirs where fishery resources are significant. The maintenance of satisfactory recreational fishing is frequently one of the objectives in reservoir development. The decline in sport fishing, which is often encountered 5 to 10 years following impoundment, is not inevitable, as has been demonstrated

on some of the TVA reservoirs and in other locations where management programs have helped maintain good fishing.

The Bureau's research program includes projects related to changes in productivity and water quality following impoundment. The requirements of sport and forage fishes for spawning and growth are being studied, as well as the life histories and behavior of some of the principal species. Information is being gathered that ultimately will be useful in advising anglers on characteristics of reservoirs that increase the probability of fisherman success. Methods of gathering and analyzing population data are being developed. The effects of polluting substances will be observed, and the relationships that occur as a result of various water uses will be examined. Limnological studies will be undertaken to learn the effects of water level fluctuation, rate of water exchange, water withdrawal at various depths, and the flooding of standing timber on basic productivity and fish production. The chain effects of a series of reservoirs, which are presently not well understood, will be examined.

Field work is presently underway on Upper Missouri River basin reservoirs, with a project headquartered at Yankton, South Dakota. Another phase of the reservoir study is concerned with the reservoirs and streams of the White River in Missouri and Arkansas. The latter will be headquartered at Fayetteville, Arkansas, where some work is being done in cooperation with the University of Arkansas.

The Bureau's Branch of River Basin Studies reviews plans proposed by the Federal Government or by public or private agencies under Federal permit or license for impoundment, diversion, and other modifications of natural waters, to determine possible effects on fish and wildlife resources. It develops, in cooperation with the State conservation agencies, recommendations for the steps necessary to compensate for damage to fish and wildlife resources by proposed developments and can frequently suggest ways that the projects can be modified to benefit fish and wildlife resources. The maintenance of the required water temperatures, oxygen, and other quality characteristics to meet the needs of fishes, other aquatic species, and recreational interests is of high importance.

The States are giving increasing attention to water quality studies associated with flow regulation. A list of the Federal Aid projects active in this field in 1961 is included as Appendix III.

CONCLUSIONS

Demands for water will undoubtedly double by 1980, and most river systems will be subject to extensive development. Continuing cooperation by all interests will be required in each water development project where flow regulation is involved if the desired water quality is maintained and maximum benefits to the public are to be achieved.

Five cardinal principles of cooperation where flow regulation for quality control is involved are stated as follows:

1. The basic problems must be defined in terms of public need, presently and in the future.
2. The specific requirements of controlling interests and most important uses in terms of water quality must be known and set forth early in project planning.
3. There must be a willingness on the part of all agencies to meet together, to understand differing requirements, and to negotiate agreements on project features.
4. There must be a full exchange of research information as soon as it can be made available.
5. There must be continuing evaluation of recommendations and management methods within broad policy decisions.

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APPENDIX I.

EXCERPTS FROM THE FISH AND WILDLIFE COORDINATION ACT, AS AMENDED, 1958. (16 U.S.C. 661 ET SEQ.)

* * * * * * *

"Sec. 2 (a) Except as hereafter stated in subsection (h) of this section, whenever the waters of any stream or other body of water

are proposed or authorized to be impounded, diverted, the channel deepened, or the stream or other body of water otherwise controlled or modified for any purpose whatever, including navigation and drainage, by any department or agency of the United States, or by any public or private agency under Federal permit or license, such department or agency first shall consult with the United States Fish and Wildlife Service, Department of the Interior, and with the head of the agency exercising administration over the wildlife resources of the particular State wherein the impoundment, diversion, or other control facility is to be constructed, with a view to the conservation of wildlife resources by preventing loss of and damage to such resources as well as providing for the development and improvement thereof in connection with such water-resource development.

* * * * * * *

"(f) In addition to other requirements, there shall be included in any report submitted to Congress supporting a recommendation for authorization of any new project for the control or use of water as described herein (including any new division of such project or new supplemental works on such project) an estimation of the wildlife benefits or losses to be derived therefrom including benefits to be derived from measures recommended specifically for the development and improvement of wildlife resources, the cost of providing wildlife benefits (including the cost of additional facilities to be installed or lands to be acquired specifically for that particular phase of wildlife conservation relating to the development and improvement of wildlife), the part of the cost of joint-use facilities allocated to wildlife, and the part of such costs, if any, to be reimbursed by non-Federal interests.

* * * * * * *

"(h) The provisions of this Act shall not be applicable to those projects for the impoundment of water where the maximum surface area of such impoundments is less than ten acres, nor to activities for or in connection with programs primarily for land management and use carried out by Federal agencies with respect to Federal lands under their jurisdiction.

* * * * * * *

"Sec. 5. The Secretary of the Interior, through the Fish and Wildlife Service and the Bureau of Mines, is authorized to make such investigations as he deems necessary to determine the effects of domestic sewage, mine, petroleum, and industrial wastes, erosion silt, and other polluting substances on wildlife, and to make reports to the Congress concerning such investigations and of recommendations for alleviating dangerous and undesirable effects of such pollution. These investigations shall include (1) the determination of standards of water quality for the maintenance of wildlife; (2) the study of methods of abating and preventing pollution, including methods for the recovery of useful or marketable products and by-products of wastes; and (3) the collation and distribution of data

on the progress and results of such investigations for the use of Federal, State, municipal, and private agencies, individuals, organizations, or enterprises.

* * * * * * *

"Sec. 8. The terms 'wildlife' and 'wildlife resources' as used herein include birds, fishes, mammals, and all other classes of wild animals and all types of aquatic and land vegetation upon which wildlife is dependent."

* * * * * * *

APPENDIX II.

PRESENT AND FUTURE MINIMUM-FLOW REQUIREMENTS STIPULATED IN FEDERAL POWER COMMISSION LICENSE 2009, REVISED 1960

The Federal Power Commission reviewed the application of the Virginia Electric and Power Company to construct and operate a hydroelectric plant at Gaston, on the Roanoke River, North Carolina. The Commission issued their findings and order relative to the Gaston Project on March 25, 1960, to become final 30 days thereafter. The document was issued as an amendment to F.P.C. License 2009, combining the Roanoke Rapids and Gaston Projects.

The new provisions as recommended by the Steering Committee for the Roanoke River studies, and concurred in by the State of North Carolina, the U. S. Fish and Wildlife Service and the Virginia Electric and Power Company, are as follows:

Article 25. Effective with commencement of operation of the Gaston Development, the Licensee shall release sufficient water from the Roanoke Rapids reservoir to maintain minimum flows and pounds of oxygen in the Roanoke River as measured at the point of project discharge to meet the following requirements:

Requirement A: Minimum Instantaneous Flows

Month	Cubic Feet Per Second
January, February, March	1,000
April	1,500
May, June, July, August, September	2,000
October	1,500
November, December	1,000

The above flows are subject to the following special provisions:

(1) These flows may be reduced on weekdays, Monday through Friday, during off-peak hours by not more than 20 percent, but such reduction shall not dispense with compliance with Requirement B.

(2) The average flow for any day shall equal or exceed the minimum instantaneous flow specified for that month.

(3) A minimum instantaneous flow of 2,000 cubic feet per second will be furnished by the Licensee for the period requested by the North Carolina Wildlife Resources Commission, to begin as early as April 1, but not later than April 15, and to continue for at least 60 days but not longer than 75 days in any one year, in accommodation to annual variations in the time and duration of spawning activities of the striped bass.

(4) The reduction in instantaneous flows permitted above shall not apply when special spawning flows are being passed for the benefit of striped bass.

Requirement B: Minimum Oxygen

Discharge from the Roanoke Rapids Development shall be maintained to provide dissolved oxygen at an instantaneous rate of not less than 78,000 pounds per calendar day during the months May through October, except as is permitted under the following conditions:

(1) A reduction not in excess of 34 percent of the instantaneous rate of 78,000 pounds per day will be permitted for periods not exceeding 14 consecutive hours.

(2) Any oxygen deficit so created shall be offset by greater discharges so that a cumulative average rate of discharge of 78,000 pounds per day will be attained within a period up to but not exceeding 16 hours from the beginning of the oxygen deficient flows, and this condition (2) shall again begin to operate as soon as the instantaneous rate again falls below 78,000 pounds per day.

The Licensee shall not be required to compensate through increased flows or other changes in operations for any lessening in the quality of water entering the Gaston Development which may after the effective date of this article be created by Acts of God, or through acts of others than the Licensee, and beyond its reasonable control.

Requirement C:

In the event of temporary emergency conditions arising in performance of Requirements A and B the Licensee will cooperate in good faith with the North Carolina State Department of Conservation and Development, North Carolina State Stream Sanitation Committee and/or North Carolina Wildlife Resources Commission to take such reasonable steps in regard to the reductions permitted by item (1) under Requirement B as may be proper to meet the emergency conditions and in the interest of maintaining during such emergency conditions water quality in keeping with the standards required of class "C" waters by order of the North Carolina State Stream Sani-

tation Committee effective to September 1, 1957. But nothing herein is intended to compel the Licensee to correct conditions which it has not created and no permanent change of operations shall be made without the approval of the Federal Power Commission.

Article 26. The volume of controllable releases of water from the Roanoke Rapids reservoir shall not be permitted to increase to double, or to decrease to half, of any prevailing discharge in less than one hour during the spawning period of striped bass. The spawning period shall be the period from April 1 to June 1 of each year, except as modified upon the recommendations of the North Carolina Wildlife Resources Commission as provided for in Articles 24 and 25.

Article 27. The normal operating level of the Roanoke Rapids reservoir is established at elevation 132 above sea level. (U.S.C. and G.S. datum).

Article 28. The Licensee shall construct, maintain and operate such protective devices and shall comply with such reasonable modifications of the project structures and operation in the interest of fish and wildlife resources, provided that such modifications shall be reasonably consistent with the primary purpose of the project, as may be prescribed hereafter by the Commission upon its own motion or upon recommendation of the Secretary of the Interior, the North Carolina Wildlife Resources Commission, or the Virginia Commission of Game and Inland Fisheries, after notice and opportunity for hearing and upon a finding based on substantial evidence that such modifications are necessary and desirable and consistent with the provisions of the Act; Provided, however, that no modifications of project structures shall be required unless recommendations are made by the North Carolina Wildlife Resources Commission, the Virginia Commission of Game and Inland Fisheries, or the Secretary of the Interior prior to November 30, 1960, or such further time as the Federal Power Commission may prescribe by its order issued prior to November 30, 1960.

Article 29. The Licensee shall consult with the U. S. Fish and Wildlife Service, the North Carolina Wildlife Resources Commission and the Virginia Commission of Game and Inland Fisheries, and on the basis of this consultation shall undertake appropriate measures for preserving and improving fish and wildlife resources of the project area as may be prescribed by the Federal Power Commission upon the recommendations of the Secretary of the Interior, the North Carolina Wildlife Resources Commission, and the Virginia Commission of Game and Inland Fisheries, after notice and opportunity for hearing.

Article 30. The entire project area, except for such portions as may be reserved for reasons of safety and efficient operation, shall be open to free use by the public for the purposes of fishing, hunting, and other recreational pursuits; and the Licensee shall allow to a reasonable extent for such purposes the construction of access roads, wharves, landings and other facilities on project lands the occu-

pancy of which may in appropriate circumstances be subject to payment of rent to the Licensee in a reasonable amount: Provided, that the Licensee's consent to the construction of access roads, wharves, landings and other facilities shall not without its express agreement place upon the Licensee any obligation to construct or maintain such facilities.

Article 32. The Licensee shall be responsible for reregulating additional water discharged from John H. Kerr reservoir either specifically for the protection of the striped bass fishery during the migration and spawning period, or specifically for stream sanitation purposes, in accordance with an agreement or agreements to be entered into by the Licensee and the affected State and Federal agencies subject to the approval of the Commission."

APPENDIX III.

STATE RESEARCH PROJECTS DEALING WITH WATER QUALITY IN RELATION TO FISH AND WILDLIFE RESOURCES

About $1,600,000 annually of Dingell-Johnson Federal Aid Funds are programmed for reservoir research. In addition, most States that have reservoirs, large lakes, and coastal waters, are conducting non-Federal aid research on water quality.

Following are brief descriptions of the 1961 Federal Aid Projects which include water quality studies.

Arkansas F-3-R-6. A survey of possible development of trout waters. To obtain physical, chemical, and biological data on tailwaters of multiple-purpose dams and to collect pre-impoundment fish population data.

California F-18-R-1. Experimental management of reservoirs.

Florida F-8-R-6. River Basin Fisheries Investigations. To evaluate effects on fishery resources of proposed water control structures of the Corps of Engineers in Florida flood control projects.

Idaho F-34-R-4. Water Quality Investigations. To study the effects of pollutants on water quality, formulate water quality standards, and to determine methods of improving water quality.

Kentucky F-16-R-3. Pre- and Post-Impoundment Population Surveys.

F-19-R-1. Pre- and Post-Impoundment Limnological Studies and lake investigations.

Louisiana F-7-R-2. Lake D'Arbonne and Bussy Lake Investigation. To study the biological dynamics of two new reservoirs.

Maine F-8-R-10. State-wide Lake and Stream Investigation. To survey lakes and streams for physical, chemical, and biological characteristics.

Minnesota F-13-R-5. Investigation of Production of Natural Fish Foods. To investigate the relationships of fertility of water and soils to the production of natural fish food organisms with special emphasis on lethal limits for various fertilizers.

Mississippi F-6-R-6. Fisheries Investigation on Flood Control Reservoirs.

F-8-R-4. State-wide Lake and Stream Survey. To obtain information relative to physical, biological, and chemical characteristics.

F-9-R-3. To detect sources of stream pollution and its effect upon bottom organisms, fishes, and chemical qualities of the water.

Montana F-9-R-10. To determine the physical, chemical, and biological characteristics of important fishing waters.

F-23-R-5. To compile data on age and growth, and to study the relation of pollution on bottom organisms.

New Mexico F-22-R-3. To conduct basic surveys; make pre-impoundment studies; . . . cooperate in River Basin Studies . . . .

New York F-22-R-3. Trout: Water Chemistry Relationships.

North Carolina F-14-R-1. State-wide Fish Management Investigations. To survey and classify significant freshwater streams; investigate pollution as it affects sport-fishing waters . . . .

South Carolina F-9-R-2. An Evaluation of Stocking Striped Bass In Reservoirs. To study results of stocking striped bass in selected reservoirs and effects of physical and chemical factors on success.

Tennessee F-5-R-9. Reelfoot Lake Investigations. To evaluate effect of restricted commercial fishing and water level fluctuations; conduct creel census, growth, food, movement, and limnological studies.

F-12-R-7. Large Impoundment Investigations. To determine populations; rate of exploitation; movement; depth distribution of game fishes; seasonal oxygen and temperature profiles; and effect of brush shelters.

Texas F-2 to 9 and 12-R7-9. Fisheries Investigations. Includes pollution surveys.

F-16-D-1. Caddo Lake Circulation Channels. To direct water flows into stagnant areas of Caddo Lake.

Utah FW-5-R-4. River Basin Investigations. To determine fish and wildlife implications of private- and government-sponsored river basin projects, and recommend features for mitigating losses.

Washington F-24-R-7. Environmental Control. To determine the nutrient deficiencies of various bodies of water, methods of adding organic fertilizers, and to study mineral metabolism.

Wisconsin F-60-R-1. Cold Water Fishery Research. To study effects of angling regulations; evaluate habitat development; docu-

ment water quality studies; and to determine survival, growth and yield of various streams.

Wyoming FW-3-R-9. Game and Fish Laboratory Research. (Part) To investigate fish toxicants, water pollutants, and reaction of trout to salinity.

DISCUSSION

W. W. Towne

Director, Columbia River Basin Project
U. S. Public Health Service, Portland, Oregon

It is a pleasure for me to return to Cincinnati. As Joe Flanagan said, these symposia have grown. I recall the Dissolved Oxygen Symposium, with which I had some little connection, that we held some 6 years ago in our small auditorium at the Sanitary Engineering Center. We were crowded, but we were able to conduct the meeting there. I am sure some of the things we have been discussing here were discussed then; we are still talking about them and will be for some time to come.

Dr. King outlined some of the legislation that assigns certain responsibilities in the field of water resources development and water quality control to Federal and State agencies. Since the Public Health Service is one of these agencies, I thought my best contribution here might be to briefly outline some of the cooperative steps that have been taken in the Columbia River Basin. Most of these were initiated and in operation long before I was assigned there, but I am happy to be taking part now in some of these activities, which I think are very progressive steps.

In the Columbia River Basin, as in any other basin, there are some 20 Federal agencies that are interested in water resources development as a result of authorizing legislation. There are at least an equal number of separate State agencies. A Federal agency is authorized by Congress to undertake some activity under specific legislation. To carry out their responsibilities they receive a budget. I think all of us here today recognize the interplay between the areas of responsibility of the several agencies; if one agency, such as the Fish and Wildlife Service or the Public Health Service, is responsible for giving information to some of the other agencies, particularly agencies responsible for the engineering design and construction of these structures, the information must be given in such a form that it can be utilized on a timing schedule that meets the need.

The Columbia River Basin Inter-Agency Committee is composed of the Federal and State agencies concerned with the development of land and water resources in the Pacific Northwest. This area includes the coastal waters of Oregon and Washington as well as the Columbia River Basin because of its interrelated economic and development picture.

The Columbia River Basin Inter-Agency Committee has been very active. It has about 20 active subcommittees. It had a Subcommittee on Comprehensive Planning, on which were representatives from the State and Federal agencies concerned with water resources planning operations. In September 1962, the parent committee recommended that the name of the subcommittee be changed to the Coordinated Planning Subcommittee to emphasize the coordinating aspects of its activities. I would like to read to you a brief excerpt from the report of the Executive Committee recommending this change.

> "The function of the Subcommittee on Comprehensive Planning be broadened to include the coordination of planning for the Columbia River Basin Inter-Agency Committee; further, that this Subcommittee be directed to establish a coordinating task force for each major river basin or group of related basins as the need is determined."

The latter item relates specifically to intensive studies resulting from Federal appropriations to one agency or another to carry out broad, comprehensive planning operations. The Corps of Engineers has just received authorization and budget from Congress to expand their plan and studies on the Willamette Basin. A task force was set up to coordinate the working relationships of the water resources agencies in developing this plan.

> "The objectives of the Coordinated Planning Subcommittee are to provide a forum for the free exchange of information concerning the planning activities of member agencies; work towards the establishment of mutually satisfactory priorities and schedules for water and related land resources planning, and towards the development of fiscal requirements to meet these coordinated planning schedules; . . ."

We think that this is a key item — to coordinate our fiscal requirements.

> ". . . work towards the selection of comparable criteria and procedures, uniform basic data, and consistent projections of future conditions and needs; provide and supervise separate task forces as required for major basin and subregional studies to effect detailed coordination of planning at the working level; and to keep the parent committee fully informed concerning the status and needs of coordinating and planning activities."

The Coordinated Planning Subcommittee has established subbasins into which the various studies fall. We have devised a reporting procedure for the agencies so that we have some idea of the magnitude of their present and future plans. These studies are categorized into five general types:

(1) Comprehensive Framework Plans. These are area studies that provide (a) long-range projections of economic development,

(b) a translation of such projections into demands for water and related land-resource uses, (c) hydrologic projections of water availability both as to quantity and quality, and (d) projections of the availability of related land resources. These studies enable us to outline the characteristics of projected water and land resource problems and the general approaches that appear appropriate for their solution.

(2) Comprehensive Detail Plans. Extension of the Framework Plans to the detail necessary for the Bureau of Reclamation, Corps of Engineers, or the Soil Conservation Service to request authorization of one or more multipurpose reservoir projects in a subbasin.

(3) Special Project Plans. Plans of a narrower geographic and analytic scope, which usually relate to the request for appropriations for one multipurpose reservoir.

(4) State Survey Plans. To bring the states, which are a part of this committee, into the planning picture we must know their resource and land development agencies, their economic agencies, and their plans so that they can be made a part of the overall water resources planning.

(5) Related Water-Resources Activities. In addition to the agencies with responsibility for broad planning, many of the other agencies have supporting types of operations. The Public Health Service is not only a planning agency, but is also responsible for giving certain supporting information on needs for water quality storage to the construction agencies. The U. S. Geological Survey, the Weather Bureau, and the Bureau of Outdoor Recreation also provide supporting information. We need to know their plans, their budget, and what each can contribute to the planning effort. The Coordinated Planning Subcommittee is attempting to compile information within these various categories on the fiscal year in which studies have been or will be initiated, the expected completion date, the percent completed, and the estimated cost of completion. We would like as much estimated budget and scheduling data as possible for the anticipated life of the project. We realize that these estimates are subject to the directives of Congress, but if we are to plan on a comprehensive basis, we must have something to stand with. Practically all agencies have some long-range plan, some idea related to what they hope to do and what they feel is necessary in the next few years in the field of water resources development.

Just a closing word: We that are associated with comprehensive planning for water quality control in the Columbia River Basin feel that this is one basin where planning can result in maximum dividends. Much of this area is still relatively unpolluted so that preventive measures can ensure continued good water quality. All of us recognize that prevention is cheaper than cure. Furthermore, it is easier to keep an undegraded resource at a high level and put into it some reserve for the future than it is to bring a downgraded water resource back to where it might have been if preventive actions had been taken.

DISCUSSION FROM THE FLOOR

Mr. Bell, U. S. Public Health Service: As a native Arkansan, I cannot miss the opportunity to put in a plug for the fishing industry of the state, even though I regret the lack of cooperation between the U. S. Fish and Wildlife Service and the construction agencies on the White River Basin Reservoirs. If anybody wants to retire to a good fishing place, go to north Arkansas. It is really good.

Mr. Morris, U. S. Public Health Service: The list of people who are here and that we have heard from includes the Public Health Service, Corps of Engineers, Federal Power Commission, Fish and Wildlife Service, Weather Bureau, Department of Agriculture, Bureau of Outdoor Recreation, Coast and Geodetic Survey, Housing and Home Finance Agency, Bureau of Reclamation, State governments, Federal commissions such as ORSANCO, municipalities, industrial interests, public and private utilities, and private land owners.

I wonder, Mr. Towne, have we not reached the point where some formal coordinating agency is necessary to put the diverse and often overlapping interests under one agency to act as a clearing house and coordinate these water resources activities?

Mr. Towne, U. S. Public Health Service: There is a bill before Congress now directing a centralization of water resources planning.

I think — and this is entirely personal, I do not speak for the Public Health Service — I think the whole field of water resources development is so broad, and involves such diversified interests that operation under a single planning agency would be very difficult. The Public Health Service, for example, is basically responsible for development of facts relative to water quality from which those people who determine how the water is to be used can arrive at sound judgments.

As for putting everything under one head, I am somewhat fearful that there is no one individual, and maybe no small staff within one organization, that can objectively view the importance of all the various segments of water resources development. Maybe it is better to have specialists in separate agencies who can speak on the importance of their activities. Some activities might be inadequately emphasized if they were under one head. It is human nature for a person to develop his own personal interests, and administration by a single water resources agency would lean, I think, to one area or another.

I have given this considerable thought. Coordination between agencies may be slower or somewhat less efficient than a more autocratic method, but in a democratic country such as ours the final decisions are made by the public, and they need the best facts; I doubt whether a small group could marshal all the facts and present the broad picture as well as the specialists in flood control, in water pollution control, in land use, and what not.

Mr. McDermott, U. S. Public Health Service: I would like to speak as a representative of the Advanced Waste Treatment Unit of the Basic and Applied Sciences Branch at the Robert A. Taft Sanitary Engineering Center. I have been considering some cost figures while listening to the talks. The picture obtained is interesting enough that I want to use it to present a point and pose a question. Assume a situation where the BOD of the stream is 15 milligrams per liter and it is necessary to reduce this to 7.5 milligrams per liter. Assume further that the BOD of the water released from storage is 5 milligrams per liter. Under these assumptions, for each 1,000 gallons of water in the stream, 3,000 gallons of dilution water would be required to produce a mixed water with a BOD of 7.5 milligrams per liter. If the cost of providing the dilution water is assumed to be 2 cents per 1,000 gallons, then the cost of upgrading the quality of the original river water would be 6 cents per 1,000 gallons.

I would like also to point out a problem in storing water for waste water dilution in the Western states. In many areas there is a shortage of irrigation water and even of domestic water. I can foresee difficulty in getting people to accept release of water for quality control if water for their livelihood is in short supply. These comments lead to a question as to what cost levels or range of costs are generally encountered in streamflow regulation; in other words, what are the costs that advanced waste treatment methods must meet to be competitive?

Mr. Towne: I fully agree with your comment on the objections that will probably be raised to streamflow regulation in the West, but we do not claim that low flow augmentation, or flow regulation, is the most economical means of achieving a degree of quality control that we can reasonably accomplish by waste treatment now. The fact that money is being made available for advanced waste treatment research shows that the Public Health Service recognizes the importance of furthering treatment capabilities rather than providing dilution indefinitely. It may be some years, however, before effective application of advanced waste treatment methods can be realized.

In Oregon, the Governor and the Water Resources Board have stated that Oregon does not have enough water to use it for pollution abatement, i.e., in lieu of treatment. We do not propose flow regulation in lieu of treatment. The Water Pollution Control Act requires that we utilize treatment insofar as possible. As advances are made in research and new knowledge assures higher degrees of treatment, some of the water that is being stored at this time for quality control can well be used for other purposes. This has been the history of any water resources development. Until the Water Supply Act of 1958 permitted the inclusion of storage for anticipated municipal and industrial water supply in multiple-purpose reservoirs we were not able to provide for future needs. Before that time someone had to enter into a contract for repayment before capacity could be provided in a project. We have all seen reservoirs built that created a water demand that could not be paid for in advance. Then the water could not be taken from the reservoir because it was allo-

cated to other uses. I think the state water pollution control agency, the state water resource agency, or the state engineer, whoever is allocating water, should reserve this water for quality control as long as it is needed. I do not think any of us are advocating the use of flow supplementation where treatment can be effective.

Mr. McCallister, U. S. Army Engineers: This rather sticky question of competition for water has arisen and, I'm afraid, it has gotten me out of my chair. There has been a lot of technical discussion here on problems associated with quality control, but I have heard essentially nothing until just now on how you determine its value, and how you choose between competing uses in the allocation of storage for quality control.

I discussed one of our activities with a Bureau of the Budget man a few months ago. We were involved in basin planning, and he asked me the question: "Since it is commonly accepted that you don't have sufficient storage sites in the State of Michigan to satisfy all the needs, how will you determine the storage allocations for the various uses of your multipurpose reservoirs in your basin planning?"

I said, "Well, providing that the cooperating agencies furnish us data in a form that is usable for the determination of the value of including each purpose on an incremental basis in competition with other purposes we are going to do the best we can to optimize the projects."

This has been mostly a technical discussion on how to achieve the best quality of water from flow regulation; I would like to raise a question as to the true value of flow regulation in light of the possibility, and the probability in many cases, that it is going to preclude, or at least limit, other uses such as water recreation, irrigation, and uses of that sort?

Too many times we look at the interests of our own agency as being, like motherhood, the interest that has to be preserved and raised above all others. We try to ensure that everything we say is fully considered in the reports of the receiving agency. But think of the poor man who has to take our evaluations and recommendations in the form that we hand them to him — and I'll direct this to the Public Health Service since this is a Public Health Service sponsored symposium — who has to take the Public Health Service' evaluations of the benefits of flow regulation and fit them into a scheme for optimizing the benefits from all the possible project purposes. You report that certain flows are required, that you have investigated possible alternative measures of providing equivalent quality control, that you estimate it will cost so much to provide this quality control, and that it is worth it. Now, does this mean you have a B/C ratio of one to one for quality control, or does it mean you have a B/C ratio of infinity?

In other words, when we try to compare the value of the benefits from using a unit of storage for water quality control with the value

of using it to maintain a fishery, or for water supply, or for flood control, or for any of the other uses, we are in difficulty.

If we have to reduce or eliminate some uses because of limited storage capacity or limited runoff, how can we compare the value of a unit of storage for quality control with a unit of storage for some other purpose? Is flow regulation for water quality control to be placed on a pedestal and considered worth the cost, regardless of the value of competing uses? Recreation benefits from fishing are similarly presented by the Fish and Wildlife Service; i.e., they present fishery benefits in terms of a certain amount of storage being worth so much.

Senate Document 97 considers setting a dollar value on the loss of life from floods. It seems to me that if the construction agencies are being pressured to consider these kinds of values and to consider secondary benefit values, it is imperative that we have a common denominator in our consideration of these things so that when we apply a project formulation procedure we can pick the combination of allocations that will maximize the benefits for the people in the basin and in the country as a whole.

Perhaps this should be the subject of another symposium. How can we work together, realizing that we do have competition for water and that determining how a project of competing uses should be formulated is almost impossible if every agency says, "This is what you should put in your project," saying in effect, "We don't care about the other possible uses." Yet the Corps of Engineers has to report to Congress as to what combination of uses, allocations of facilities, and resultant benefits should be ascribed to a particular project at a given site.

Mr. Bell: Thank you, sir. That is a most fundamental question, and I can assure you it could be the subject of another symposium.

Mr. McLean, U. S. Public Health Service: We hope there will be another symposium that will include economic considerations. We do not feel the time is quite right for that now. We recognize the necessity of means to discriminate between the several desirable purposes for which storage can be provided. This meeting is directed toward better answers to technical problems in water quality control. Subsequent meetings may contribute to better answers to the problems of economic evaluation of the benefits provided by quality control.

WHERE WE STAND ON STREAMFLOW REGULATION FOR QUALITY CONTROL

K. S. Krause

Chief, Technical Services Branch, Division of Water Supply and Pollution Control, Public Health Service, Washington, D. C.

This meeting is unique inasmuch as it is the first symposium on streamflow regulation for quality control. The willingness of such a high proportion of those attending to stay through this final presentation indicates a very vital and continuing interest in this subject.

I would like to ask just one simple question: Did the symposium accomplish what it set out to do? First of all, its stated purpose was to facilitate exchange of information on the effects of streamflow regulation on water quality; secondly, to review available knowledge on the effects of streamflow regulation on water quality; thirdly, to discuss studies presently in progress on quality control problems associated with streamflow regulation; and, finally, to explore research needs in the field of streamflow regulation for quality control. I hope you will agree with me that we can answer this question with a resounding "Yes."

Mr. Stein referred to some of the early discussions of certain legal matters as furnishing more heat than light. I believe in this symposium we have had more light than heat. I do not intend to review each paper in trying to sum up this particular symposium. I am reminded of the student psychologist who taught his pet flea to jump every time he said, "Jump!" But this psychologist had a research bent, so he decided to see how well the flea would jump if he removed some of his legs. He removed the hind pair of legs and told the flea to jump, and the flea jumped. "Well," he thought, "this is fine. What will happen if I remove another pair?" So he took off another pair of legs, and he told the flea to jump, and again the flea jumped — rather feebly, but he jumped. "Ah," he said, "what will happen if I take the last pair off?" So he removed the last pair of legs from the flea. He again told the flea to jump, but the flea just quivered a little bit and stayed put. He shouted a little louder; still the flea did not move. Then the student psychologist reached this conclusion: "Fleas must hear through their legs!"

I am sure our conclusions would be on much firmer ground if our systems analysis were more complete or we had Dr. Fiering to push the buttons. But philosophizing a bit, one of our famous educators made the observation that we can never expect to know everything, and a man must make decisions based upon the knowledge that he has. Certainly knowledge and experience prepare each of us to make faster and better decisions, but in our complex society the cost of errors in decision is great and ever increasing. I am sure a child could make decisions on almost any subject, and some would be good. I believe, however, that we must strive to push the proportion of correct decisions as much towards the hundred percentile

as we can at this moment in history. The farther we proceed towards this goal, the tougher each increment of progress becomes.

We are dealing with a complex subject, one that has far-reaching technical, economic, and social ramifications. We cannot afford not to examine our knowledge before making decisions. If there is one earth-shaking conclusion I have reached here at this meeting, it is that even problems have problems.

But what have we accomplished?

Forty persons have presented topical discussions covering a vast array of subject matter, all pertinent to streamflow regulation for water quality control. These might be grouped generally as dealing with administrative, policy, hydraulic, hydrological, chemical, biochemical, thermal, physical, and engineering evaluation types of problems. We have touched on both the legal and economic ramifications of streamflow regulation. Both are sufficiently important to be the subjects of separate symposia in the future. We have touched on decision-making tools that we hope will put all of the former information into proper perspective. I am sure we have not heard the last of this.

Now to some observations:

1. Fluctuations in water quality are serious economic and productive factors to industrial, municipal, agricultural, fishery, and recreational water users.

2. Reservoirs now in operation for quality control purposes have shown themselves to be useful tools for adding oxygen, for thermal control, for damping fluctuating inorganic loads, and for neutralizing mineral acids both in the reservoir and downstream. Reservoirs have also effectively reduced microorganisms at downstream water intakes.

3. Reservoir management for maximum water quality improvement shows promise for stabilization of thermal, organic, and inorganic quality.

4. Flow augmentation can have adverse as well as beneficial effects on downstream quality.

5. Reservoir storage and its resultant effects on water quality must be studied on a case by case basis. We are cautiously optimistic about the potential usefulness of flow regulation.

6. Reservoir outlet design features play an important role in the quality of water emerging from reservoirs.

7. Proper control of land runoff and preparation of reservoir storage sites may markedly improve water quality in storage.

8. Simulated hydrology and mathematical techniques for estimating quality will help us to identify our deficiencies and permit us to concentrate on overcoming the most significant weaknesses in our knowledge.

9. Analysis of the effects of storage and flow control should be made on an entire river basin to properly evaluate the accumulated advantages and disadvantages, since time and location of events are important and often controlling factors in whether the benefits outweigh the liabilities.

10. Streamflow regulation may be our only practical method of improving water quality in some areas and instances.

Dissolved oxygen and its association with water quality has been given major attention in this meeting. But, let us not forget that there are other and perhaps equally important quality parameters. A new science of water resources seems to be emerging. It is a strange looking creature, but so is a camel; yet he functions very effectively.

There are some challenges ahead, too. First, we need to be able to simulate conditions in an impoundment prior to construction so as to be able to predict results of storage on water quality. Second, we need to improve our techniques for measuring water quality, especially our techniques for automatically monitoring the quality. Third, we need to resolve problems of conflicting interests associated with water storage and releases; some of these problems are legal. Fourth, we need to develop operating criteria that will give the greatest efficiency to river basin control systems to achieve the maximum water use and re-use for all legitimate purposes. Fifth, we need to improve our use of economic forecasts as a basis for estimating future water needs. Sixth, we need to develop more effective structural designs for hydropower intakes that can select the water, and hence the quality, that will be discharged. And finally, by way of a little thought teaser, we need to seek a common denominator for comparing efficiencies of not just one system, but several systems. I am suggesting that we look to basic energy in the physical and chemical area as a possibility for this common denominator. We need something to give us a benchmark by which our choices can be effectively made.

Gentlemen, it has been a pleasure to be here with you, to hear so many fine papers, and to have so much active participation in the discussions. I am sure that the symposium proceedings will provide a wealth of information for you; I know they certainly will for us.

BANQUET SESSION

Master of Ceremonies: **Maurice LeBosquet**
U. S. Public Health Service

PUBLIC EXPECTATIONS

Dr. Maurice K. Goddard

Secretary, Pennsylvania Department of Forests and Waters
Harrisburg

Your program chairman is a very clever man! He advised me that my topic would be of my own choice, and then, to make sure that I would not get too far off-base and discuss something like "Streamflow Regulation for Quality Control in Outer-Space," he suggested that a broad view of the objectives of the general public, since these objectives are the basis of our establishment and desire to maintain quality objectives, might be a good subject for a stimulating address. So be it. I can take a hint!

In my mind the general public really has but a single objective insofar as water quantity and quality are concerned. And, it is not even strictly an objective, but rather, an expectation. The general public expects that someone, his government or his water company, will see to it that he is delivered adequate supplies of good water for all of his uses and to meet all of his demands. Pure water, and plenty of it at all times, is considered by the American public as its right and heritage. About the only time the general public becomes actively concerned is when, for some reason, that delivery is curtailed, or the quality of the water deteriorates to a point where it becomes distasteful or unusable.

When either or both of these things happen, the general public usually asks just three questions: Why did it happen? Who or what was responsible? What is being done, and by whom, to correct the conditions? Somebody is then expected to come up with quick and satisfactory answers!

That somebody is usually the head or administrator of the agency or agencies charged with the responsibility of ensuring the availability of, or the protection of, water supplies. His answers, of course, come from those unsung heroes — the scientists, engineers, and technicians on his staff.

The general public's lack of concern about the services it expects until those services are interrupted is well known, and that lack of concern is not confined to things pertaining to water. The trait is simply inherent in human nature.

The public, then, is only aroused collectively when a change in some existing condition, either natural or man-made, disturbs its comfort or status quo. Do not misunderstand me, I am not deriding this trait — I have a profound respect for the general public. After all, I serve it, and I am a part of it.

Now, let us divide the general public into its components — you and I — the John Q. Citizens who make up the whole. Taken as an individual, John Q. has many facets — his thinking and viewpoint

on any subject may be guided by either his vocation or his avocation, or may be colored by both. He, too, may be aroused when his normal comfort and status quo are disturbed, but, when his avocation is directly affected in any manner, he is even more likely to make his desires known. In order to do this effectively, he bands together with other, similarly affected individuals having the same avocation, and a new organization is born.

This point is well illustrated in the following statements extracted from a report, in pamphlet form, recently issued to the people of Pennsylvania by the Pennsylvania Department of Health, and entitled, "People and Water, Water and People."

"Like the torrent of an onrushing stream that cannot be stopped, when people speak, they must be heard.

"Although clean water is the goal of the people, they may seek action for different reasons. The sportsman wants a stream he can fish in, and if the stream is polluted, he must know the reason why, and what can be done about it. When nature is destroyed needlessly, the sportsman feels like a kettle of water boiling over.

"But, he is not alone in his deep feelings.

"Industries that need water for their livelihood cannot countenance a clean stream becoming abased, nor can polluting industrial plants withstand the ire of the people, when the people understand that water pollution can be stopped. Industrial groups in Pennsylvania have taken concerted action to protect streams.

"Civic groups, women's clubs, the community councils see the polluted stream from a different point of view. Many of the groups act for clean streams simply because the cause is right. Others see the threat of beauty destroyed, still others recognize that water pollution is a health and economic threat."

In Pennsylvania, those of us who are charged with the responsibility of assuring that adequate supplies of good water are available at all times to the public are always on the look-out for new weapons in our fight to clean up our streams and keep them clean. We consider streamflow regulation for quality control to be a promising new weapon. It is a comparatively new term, representing a change or equalization of basic emphasis.

While improved quality was inherent in the concept of low-flow augmentation for downstream water supply, the basic emphasis in providing low-flow augmentation was to increase quantity. We recognized, of course, that such releases would, under most conditions, also improve downstream water quality during low-flow periods. Storage and streamflow regulation for water quality control simply means, then, that now extra quantities of water will be stored for subsequent release for further purification of the river after maximum waste treatment. We realize that it is a supplementary measure to be used in conjunction with, and not in lieu of, necessary waste treatment.

Some 30 years ago, the Commonwealth of Pennsylvania constructed the Pymatuning Dam and Reservoir on the Shenango River in western Pennsylvania for water supply and flood control, the former being furnished to downstream communities and industries through low-flow augmentation. The project has since become a major recreation center as well. More recently, the amended decree of the United States Supreme Court, dated June 7, 1954, in the Delaware River Case, provided for a River Master to supervise the diversions of water from the Delaware River Basin by New York City for water supply, and the compensating releases from the New York City water-supply reservoirs to augment the flow of the Delaware. Even more recently, the U. S. Army Corps of Engineers' comprehensive study and plan for the development of the water resources of the Delaware River Basin to the year 2010, which was completed in 1960, provided for meeting downstream water supply needs through low-flow augmentation. And, about the same time, my own Department completed water resources development plans for the Brandywine and Codorus Creek Basins in Pennsylvania, covering the same period and providing upstream storage for release to meet downstream water supply needs.

In all of these cases, the first consideration was to make increased quantities of water available during low-flow periods. Possible benefits from improved quality of water during the same period, while recognized, were considered secondary to the main quantity objective.

Figure 1 shows the components of flow in the Delaware River at Montague, New Jersey, from the latter part of May to October, 1962. This Figure is reproduced from the Delaware River Master's 1962 report. Incidentally, Montague is across the river and just a little downstream of Milford, Pennsylvania, the headquarters of the Delaware River Master.

You will note from the Figure that we had drought conditions in the Delaware River Basin during the summer months and that about 64 percent of the total flow of the Delaware measured at Montague during July, August, and September was made up by the compensating releases from the New York City water supply reservoirs. During the month of July, 72 percent of the total flow came from those releases. It does not take much imagination to picture what the condition of the Delaware River would have been, both quantity- and quality-wise, if this water had not been released to the river during those critical periods.

While Pennsylvania and New Jersey fought hard to prevent the out-of-basin diversion of Delaware River water to New York City, we have since found that the cloud did have a silver lining. Without the upstream storage provided in the New York City reservoirs and the compensating releases, the Delaware would have been in grievous trouble more than once since 1955, when the Pepacton and Neversink reservoirs went into operation. Even more improvement can be expected when the third reservoir, Cannonsville, is completed and operating.

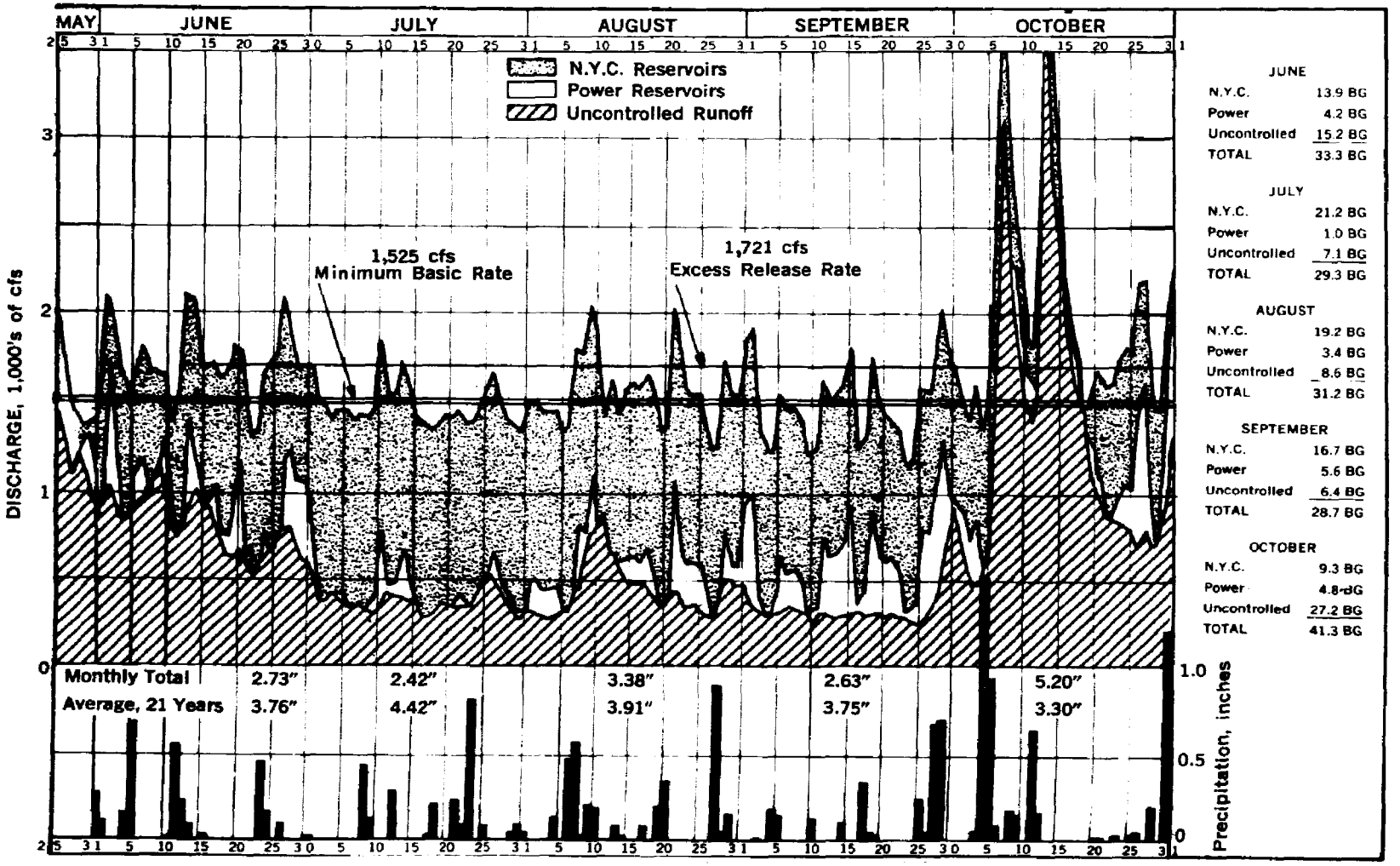

Figure 1 — Components of flow in the Delaware River at Montague, N.J. 1962.

As you all know, one of Pennsylvania's major pollution problems stems from acid mine drainage, a problem shared by a number of our sister states. We have, in fact, approximately 2,300 miles of acid streams. Our summary statement of present and anticipated water problems to the Senate Select Committee on National Water Resources in 1959 pointed out that while we have been relatively successful in preventing further deterioration of our streams by mine drainage — we have been about holding our own since 1945 — the problem of discharges from active and inactive mines located along already acid streams had certainly not been solved.

One of our recommendations in that statement is very interesting:

"On watersheds where acid mine drainage cannot be eliminated or adequately reduced at the source, study is needed to determine the practicability of, and the advantage to be gained by (a) the impoundment of such drainage during peaks of high acid flow with subsequent regulated release of the acid waters so that downstream adverse effects will be eliminated, or (b) the impoundment of clean waters in dams on clean streams, tributary to acid-polluted streams, and the release of such waters to augment the flow and neutralize the effects of acid mine drainage in the receiving stream."

The waters of the West Branch Susquehanna River are highly acid from its headwaters to the vicinity of Lock Haven, Pennsylvania, where they are usually neutralized by the flow of a large, non-acid tributary, Bald Eagle Creek. You will note that I qualified that statement by saying that they are "usually" neutralized at that point.

The fact is that when heavy rains over the headwaters of the West Branch have missed the Bald Eagle watershed we have had heavy fish kills almost as far down the West Branch as its confluence with the North Branch at Sunbury. Upon the completion of the last two reservoirs of the four-reservoir system for flood control in the West Branch Basin, we will have a unique opportunity to change this situation.

The Corps of Engineers is considering the storage of acid waters in the Curwensville Reservoir, now under construction on the upper main stem of the West Branch, and plans releases to aid in preventing downstream fish kills and in neutralizing water sufficiently to make it suitable for many industrial uses. At the Blanchard Dam and Reservoir on Bald Eagle Creek, now under planning, provision will be made for storage of nonacid waters for water quality control. Coordinated operation of the two reservoirs for water quality control promises great improvement in the quality of the waters of the West Branch Susquehanna River.

It was, of course, the 1961 amendment to the Federal Water Pollution Control Act that officially added this new aspect of pollution control by recommending that consideration be given, in the planning of any reservoir, to the inclusion of storage for the regulation of streamflow as a means of water quality control. Obviously, too, that amendment is directly responsible for this symposium —

we are here because the public expects us to make the best possible and most efficient use of our new weapon, and we are exploring the means of doing just that. Previews of the Corps' comprehensive study and plan for the development of the water resources of the Potomac River Basin, soon to be released, indicate that for the first time in a major river basin plan consideration is being given to storage of water for quality control. Estimates of the quantity of water that will be needed in the various segments of the basin by 2010 will include the quantities needed to ensure water of good quality through streamflow regulation. The estimates, of course, presuppose that maximum waste treatment will be provided.

Earlier, you will recall, I mentioned that when John Q. Citizen's avocation is directly affected he is likely to make his desires known. In closing, therefore, I wish to present the plight and complaint of one Angus, a citizen of Scotland, as it appeared in a news-story from the town of Largs, Scotland, on March 14 of this year.

Angus complained to the Town Council that the taste of the town's water supply was so bad that he was forced to travel 30 miles to Glasgow for bottled water to mix his drinks. The harried municipal water engineer explained that the heavy snow melt was carrying the taste of heather from the hills into the town reservoir, and then added that the taste would soon disappear and that, in any case, it would not harm the man's whiskey.

So you see, Ladies and Gentlemen, while John Q. expects us in America to keep his water clean, Angus Q. expects our counterparts in Scotland to keep his whiskey tasty!

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BIBLIOGRAPHIC: SYMPOSIUM ON STREAMFLOW REGULATION FOR QUALITY CONTROL, CINCINNATI, OHIO, APR. 3-5, 1963. J. E. McLean, Chairman. Robert A. Taft Sanitary Engineering Center. PHS Publ. No. 999-WP-30. June 1965. 420 pp.

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