WATER TEMPERATURE

INFLUENCES, EFFECTS, AND CONTROL

Proceedings of the Twelfth Pacific Northwest Symposium on Water Pollution Research

November 7, 1963
Corvallis, Oregon
(Reissued April 1967)

UNITED STATES DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration, Northwest Region

WATER TEMPERATURE--
INFLUENCES, EFFECTS, AND CONTROL

PROCEEDINGS

of the

TWELFTH PACIFIC NORTHWEST SYMPOSIUM

on

WATER POLLUTION RESEARCH

Conducted by

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

at the

Pacific Northwest Water Laboratory
Corvallis, Oregon

November 7, 1963

Assembled by
Edward F. Eldridge, Consultant

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AGENDA
TWELFTH RESEARCH SYMPOSIUM

INTRODUCTION

E. F. Eldridge*

As many of you know, this is the twelfth of a series of symposiums sponsored by the Public Health Service during the past six years. These symposiums have been a phase of a Research and Technical Consultation Project initiated in the Portland office of the Service in May, 1957. They have had several objectives: First, to bring together persons of this area who are involved in research in the Water quality field in order that each may become acquainted with the respective interests and research activities of others in this field. Second, to investigate the available knowledge regarding specific water quality problems and to delineate those areas where research is needed to supply new or additional knowledge. And third, to stimulate researchers in all scientific disciplines to conduct such research. In my opinion, the symposiums have successfully accomplished these objectives.

The initial meetings were attended by a comparatively small group (25 to 30) which was conducive to free discussions by most of those present. Because of the apparent interest created by these meetings, attendance has increased until approximately 150 persons were at the last meeting.

Since the Project to which I referred is to be incorporated in the activities of the Water Laboratory of the Public Health Service to be constructed here in Corvallis, future symposiums will be sponsored by this Laboratory. Mr. Curtiss Everts is Director of the Laboratory and, undoubtedly, he will tell you something about the scope and activities planned for this facility.

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TEMPERATURE AS A WATER QUALITY PARAMETER

Curtiss M. Everts*

Everyone engaged in the field of water quality control will quickly recognize temperature as one of the most important measurements of the physical characteristics of water. In fact, the temperatures of surface and underground waters have probably been recorded as often, if not more so, than almost any other physical, chemical or biological measurement made.

The relationships of the temperature of surface waters to the enhancement of fish and other aquatic life, chemical and biochemical reactions, water treatment, the toxicity of contaminants, tastes and odors in drinking water and to the quality of domestic, industrial and agricultural water supplies have been explored by numerous investigators. Until recently much of the data and information obtained have not always been put to practical use. Even now some areas need more precise evaluation and study to clarify the divergent opinions expressed in some reports, to correlate the information that has been obtained so that it may be usefully applied to the problems of water quality control, and to check laboratory results under actual field conditions. It is unlikely that this will prove to be a simple task for as we approach this point it may be expected that conflicts of special interest will arise that will require the judgment of Solomon to resolve.

In the hope that I will not transgress too greatly on the remarks to be made by the speakers that follow, I should like to offer a few examples of the effects of temperature on water use. You are familiar with most of them, but it is believed that mention of them may set the stage for some of the discussion that we hope will take place during the remainder of this Symposium.

Sphaerotilus, a troublesome slime in the surface waters of the Pacific Northwest, is reported to grow extremely well in the waters of the Columbia River at temperatures between 8 degrees and 12 degrees C. These same temperatures are highly suitable for salmon production. At higher temperatures (summer 20-24 degrees C.) poor growth of Sphaerotilus is experienced, but these are temperatures not so suitable for salmon. Interestingly enough growth in the laboratory occurred quite well throughout a range of 10 degrees to 24 degrees C.

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The effects of rises in water temperatures on fish are well known. These include increases in metabolic rates and oxygen requirements, in sensitivity to toxic materials, in reduction in swimming speed, and in increased avoidance reactions.

Drinking water at a temperature of 50 degrees F. and below is usually considered satisfactory. Temperatures in excess of 65 degrees F. are likely to result in complaints, for tastes and odors become more noticeable as temperatures increase. On the other hand, pathogens survive longer at lower temperatures.

When treatment of water is necessary for domestic consumption, floculation and sedimentation rates increase with temperature, and the bactericidal effects of chlorine are greater at temperatures above 20 degrees C.

Agriculturists prefer water at temperatures above 60 degrees F. (15 degrees C.) and this is the sort of environment that the warm-water fishes enjoy. Return irrigation flows usually increase temperatures in receiving streams.

The effects that temperatures have on dissolved oxygen concentrations, on the rates of biochemical oxygen demand, and on aquatic life are well documented and must be reckoned with in any water quality control program.

Thermal stratification in water impoundments will also cause problems, particularly those with low-level turbine intakes. This was well illustrated in the Lower Roanoke River Basin in North Carolina where due to stratification in the impoundments, water released at certain times during the year was deficient in oxygen and adversely affected downstream uses. Use of submerged weirs to draw water of satisfactory quality from a different level is reported to have corrected this problem.

Heat added to water which has been used for industrial and power plant cooling purposes has an adverse effect on aquatic life, and reduces the amount of dissolved oxygen in the water.

Thermal pollution is rapidly becoming a problem in the Delaware River Basin where 3-1/2 billion gallons of water daily (5400 cfs.) are used for thermal electric power in the basin. In the Chicago area where a number of steam power plants use from 50 to 90 percent of water available for cooling on a once-through basis, thermal pollution is reported to be equivalent to the doubling of the organic waste load the Illinois River now receives from the Chicago area.

It should be obvious, therefore, that a rather concentrated effort needs to be expended in gaining more useful knowledge on the effect of water use and watershed activity on water temperatures, so that reasonable objectives can be established, and practical procedures for temperature adjustment and control can be developed. It may even be possible to use temperature variations as a means of forecasting approaching changes in other water quality parameters.

The Federal Water Pollution Control Act makes such an effort a responsibility of the Department of Health, Education, and Welfare. Section 2 of this act directs the Secretary to develop comprehensive programs for eliminating or reducing the pollution of interstate waters and tributaries thereof. In the development of these programs it is required that due regard be given to the improvements necessary to conserve such water for public water supplies, propagation of fish and aquatic life and wildlife, recreational purposes, and agricultural, industrial and other legitimate uses.

This section also 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" and that "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 shall be set forth in any report or presentation to the Congress proposing authorization or construction of any reservoir" including storage for low-flow augmentation.

In carrying out research, and the responsibilities for special studies and demonstration under the act, the Secretary is directed to develop and demonstrate "Methods and procedures for evaluating effects on water quality and water uses of augmented streamflows to control water pollution not susceptible to other means of abatement."

The Public Health Service has a wealth of experience in this field beginning with its studies in the Ohio River Basin in 1938, 1939 and 1940 when the effects of temperature on water quality became increasingly apparent. The work of LeBosquet on the Mahoning River in the vicinity of Youngstown, Ohio, in 1942, where high water temperatures from use and reuse upstream had threatened the shutdown of an important steel mill, resulted in Congressional approval for the release of flood control waters from upstream impoundments for temperature control.

With the potential hydroelectric power development in the Pacific Northwest far from complete, a much more complete understanding must be obtained of the effects of impoundments on downstream temperatures so that suitable preventive or protective measures may be developed for existing storage and incorporated into any new impoundments proposed for the future.

With these facts in mind, the Pacific Northwest Water Laboratory, scheduled for construction under Section 4 of the Federal Water Pollution Control Act, will have, among its chief objectives, a precise study of the effects of multiple-purpose impoundments on downstream water use. We would also expect to carefully investigate the effects of watershed use on water quality. In both of these areas temperature will be a most important area of concern.

This work will not be exactly new to Oregon and the Pacific Northwest for it has already been recognized that at least one of the important contributions that can be made by low-flow augmentation will be that of temperature control. Such a program is included for the impoundments in the Rogue River Basin, and is now under study in the Umpqua River Basin.

Over ten years ago the Pollution Control Council, Pacific Northwest Area, included the control of high temperature wastes as part of its water quality objectives. Similar criteria may be found in the regulations of other water quality control agencies.

Construction of the laboratory is expected to begin in February, 1964 with completion scheduled for the summer of 1965. In the meantime, the task of assembling a competent staff of engineers, scientists, and supporting personnel will proceed as rapidly as appropriations for this purpose will permit. When the staff becomes operational, it will be engaged in a program of research technical assistance on water quality problems in an area which includes Idaho, Montana, Oregon, Utah, Washington, and Wyoming. Training will also be an important function of the laboratory staff.

As one of the arms of the Public Health Service, we would expect to furnish substantial support for any of our activities in the field of water quality control, and would hope that through our efforts and with your help some of the answers on temperature-water use relationships will be found.

EFFECTS OF WATER USES AND IMPOUNDMENTS ON WATER TEMPERATURE

Robert O. Sylvester*

Introduction

The natural temperature rise or fall of a water body is established by a number of meteorological and physical factors. Meteorological factors influencing water temperature are the amount of solar radiation, wind velocity, air temperature and vapor pressure. Physical factors are the surface area exposed, water depth, water temperature, rate of water exchange, mixing afforded, shading from vegetation or land masses, impurities in the water, surface and subsurface inflows, and the temperature of the surrounding land mass. The most important factor is the amount of solar radiation absorbed, which for a given mass of water is a function of the exposed water surface area.

The amount of solar radiation striking a given body of water depends upon the season of the year, geographical location, time of day, elevation, shading, amount of particulate matter and water vapor in the atmosphere, and quantity of indirect solar radiation. On striking a water surface, a portion of the light is reflected, perhaps 5 to 35 percent, depending upon the angle of incidence (1). Light penetrating the water is absorbed at different depths depending upon the wave length of the light and the amount of suspended and dissolved substances in the water which limit the amount of penetration. The longer wave lengths (red and orange) and the shorter rays (ultra-violet and violet) are reduced more quickly than the middle-range wave lengths of blue, green and yellow. The first meter of depth may absorb or extinguish 53 percent (1) of the total incident light where it is transformed into heat.

Water temperature is influenced by land temperature, especially in the case of irrigated areas with their return flows. The specific heat of water is high compared with other materials and it thus becomes a stabilizer of temperature and an important factor in soil temperature. Evaporation from wet soil surfaces together with the relatively high specific heat of the wet soil, will cause it to have a temperature much lower than that of a dry soil under the same conditions. The original source of energy for evaporation is solar radiation which can be divided into three parts: direct solar radiation; heat that reaches the evaporating surface from the air; and heat that is stored in the evaporating body. Part of the incoming solar radiation is reflected from the surface back to the sky and may amount to 25 percent (4) for a surface covered with vegetation. Perhaps 10 to 15 percent of the incoming

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radiation is radiated back to the sky, depending upon the temperature of the earth's surface and of the atmosphere above. The remainder of the solar radiation is used in evaporation and in heating the soil and the air in contact with the soil. When the soil is very moist, more than 80 percent (4) of the net radiation is used in evaporation. When the soil is dry, most of the radiation is used in heating the air.

Heat Budgets

Included in the heat budget for a body of water would be the heat gain from solar radiation, the heat loss by evaporation, the heat gain or loss by conduction, the heat loss by radiation, and the heat contained in the inflow and outflow of the system. With time and a uniform meteorologic condition, a body of water would tend to come into equilibrium wherein the heat losses would balance the heat gains. This condition is approached in large shallow reservoirs and in long streams where the diurnal temperature changes become uniform and of about equal magnitude.

The amount of heat that a body of water will absorb or release can be expressed as follows:

$$H = f(A,M,V)$$

where H = heat loss or gain

A = surface area

M = mixing afforded by advection, wind or channel configuration

V = volume of water involved

The rate of heat release or absorbence can be expressed as:

$$H_r = f(T_a, T_w, W, V_p)$$

where H_r = rate of heat gain or loss

T_a = air temperature

T_w = water temperature

W = wind velocity

V_p = vapor pressure of the atmosphere

Velz (2) presents the following equation for computing heat loss in a body of water. Heat gain can be computed from the same equation by reversing the sign of the air and water temperature; by making solar radiation and conduction a gain; and by subtracting evaporation and radiation.

$$H = \left[0.00722\ H_v C\ (1 + 0.1W)\ (V_w - V_a)\right] + \left[(0.8 + 0.16W)\ (T_w - T_a)\right] + \left[1.0\ (T_w - T_a)\right] - H_s$$

where the first term is heat loss by evaporation, the second is heat loss by conduction, the third is heat loss by radiation and the fourth is heat gain by solar radiation.

H = heat loss in Btu per hour per sq. ft. of water surface

H_v = latent heat of vaporization for a given water temperature

C = a constant ranging from 10 to 15, depending upon the depth and exposure of the water body

W = mean wind velocity in miles per hour

V_w = vapor pressure of water in inches of H_g near water surface

V_a = mean absolute vapor pressure in the overlying atmosphere

T_w = water temperature at the surface, ^oF.

T_a = mean air temperature, ^oF.

H_s = Btu per hour per sq. ft. of solar radiation

Temperature Comparisons

There is a dearth of reported temperature data on Northwest streams obtained prior to man-produced changes in the stream heat budget. Comparison of water temperatures before and after an act of man are subject to question unless all the variables can be held constant in the two periods or can be accounted for by calculation. In a natural stream flowing from an upland to a lowland environment, there will be a normal natural temperature increase or decrease that must be known before artificial causes of temperature change can be evaluated. In the 42-mile stretch of the Wenatchee River between Lake Wenatchee and Dryden, man's activity has produced little effect on the river's natural temperature. Thermograph records (5) of the Chelan County P.U.D. show average monthly natural temperature changes (Table 1) as the river flowed from the upland to the lowland environment. These temperature changes might be considered typical of a moderate-sized stream in the Northwest as most of our streams have storage on the headwaters, although they are not all surface drawoff as in Lake Wenatchee. Raphael (11) (12) has calculated that under natural conditions in August, the Columbia River temperature will rise about 1^{o}F. in a 72-mile stretch below Chief Joseph Dam and about 1^{o}F. in a 50-mile stretch below Rock Island.

Table 1 - Natural Temperature Changes in the Wenatchee River, Lake Wenatchee to Below Dryden, 1956 (5), °F.

	Feb.	April	June	Aug.	Oct.*	Dec.
Lake Wenatchee	34.0	38.1	44.6	57.6	51.6	37.9
Below Dryden	32.8	42.0	46.7	61.4	47.7	36.4
Difference	-1.2	+3.9	+2.1	+3.8	-3.9	-1.5

*Year 1955

In a computer analysis of Lower Columbia River water quality (8), correlation analyses were made between the various quality constituents. Table 2 shows these correlations with water temperature for the entire year of 1960, using the power function equation since it gave the best correlations. If one considers a correlation of 0.55 or above to be significant, then the only significant correlations with temperature, other than dissolved oxygen, on a yearly basis are those involving activity of the biota, such as phosphate, nitrite and nitrate, and chlorophyll. Flow rate very definitely affects water temperature as examined on a month-by-month basis but not on a yearly basis, since low flows occur under both warm and cold climatic conditions as may the higher flows. Feigner (15), in an evaluation of temperature control by low-flow augmentation, concludes that flow requirements increase exponentially with temperature rise.

Table 2 - Correlation of Water Temperature with Water Quality, Lower Columbia River, 1960 1/

Flow	0.22
pH	0.54
Dissolved Oxygen	0.81
Total Solids	0.32
Suspended Solids	0.18
Biochemical Oxygen Demand	0.14
Alkalinity	0.22
Hardness	0.24
Most Probable No. Coliforms	0.29
Sulfate	0.13
Phosphate	0.61
Ammonia	0.40
Nitrite	0.62
Nitrate	0.76
Total Nitrogen	0.55
Pearl Benson Index	0.37
Chlorophyll *a*	0.83

1/ From reference (8), using power function equation $Y = A + B(X) + C(X)^2$. Highest correlation shown with temperature as the independent or dependent variable. Correlations above 0.55 are considered significant.

Figure 1 shows downstream temperature changes in August on four different rivers east of the Cascades which are representative only for the years indicated. The Columbia River in the 450 miles between Grand Coulee Dam and Bonneville rose 5.4°F., the sharpest rise occurring between Pasco and Umatilla due to the warm inflow of the Snake River. In the warm year of 1958, while the Brownlee and Oxbow Reservoirs were first being filled on the Snake River, the mean August water temperature rose to 74°F. at Clarkston. In the more moderate year of 1959, after the dams were in operation, a temperature drop of about 3°F. was observed below the Brownlee Reservoir, rising another 2°F. through the Oxbow Reservoir and then falling off to 69°F. at Clarkston. The Yakima River receives most of its irrigation return flow in the 80-mile stretch between Parker and Kiona where the large majority of the flow in August consists of irrigation return water. Figure 1 shows a temperature rise in this stretch of 12.2°F. to a monthly average of 73.2°F. at Kiona whereas in the preceding stretch of 90 miles, the river temperature rose only 2.7°F. The Wenatchee River in flowing some 40 miles from Lake Wenatchee to Dryden exhibits a gradual temperature rise of 1.5°F. as there is little effect herein by man's activities. This compares closely with the temperature rise in the Upper Yakima River. It should be pointed out that these temperature changes vary, depending upon the year in which the comparisons are made.

Effect on Stream Temperature by Usage

Data are sparse in showing specific changes in river water temperatures from various water uses. Thermal power plants and return of cooling water from various industries are perhaps the chief source of temperature pollution. Hoak (9) reports that the installed capacity of thermal power plants is doubling about every decade. Monongehela River temperatures have risen to 98°F. because of industrial water return, and then cooled to 87°F. in a distance of 1.4 miles. He states that because of the concentration of industry, the heat raised at one point is not always dissipated before another temperature rise occurs. In a study of Columbia River water temperatures between Priest Rapids and Umatilla, Rostenbach (13) concludes that natural climatic and river conditions caused a greater temperature variation in the Columbia River for the 1944-55 period than did the effluents from the Hanford reactors. Oil refinery effluent temperatures observed in the period of 1959-61 in northwest Washington ranged from 72.5 to 83.5°F.

Water, in passing through a municipal water system and subsequently through a sewerage system, experiences a rise in temperature that may or may not be significant, depending upon the size of the receiving water. Table 3 presents temperature data in the Tacoma and the Seattle (Alki) sewage treatment plant effluents. Both plants are of the "primary" treatment type. Although the years of comparison are different, both plants have a similarity in effluent temperatures. Tacoma's water supply is obtained largely from the Green River and Seattle's from the

COLUMBIA RIVER BASIN WATER TEMPERATURES IN AUGUST

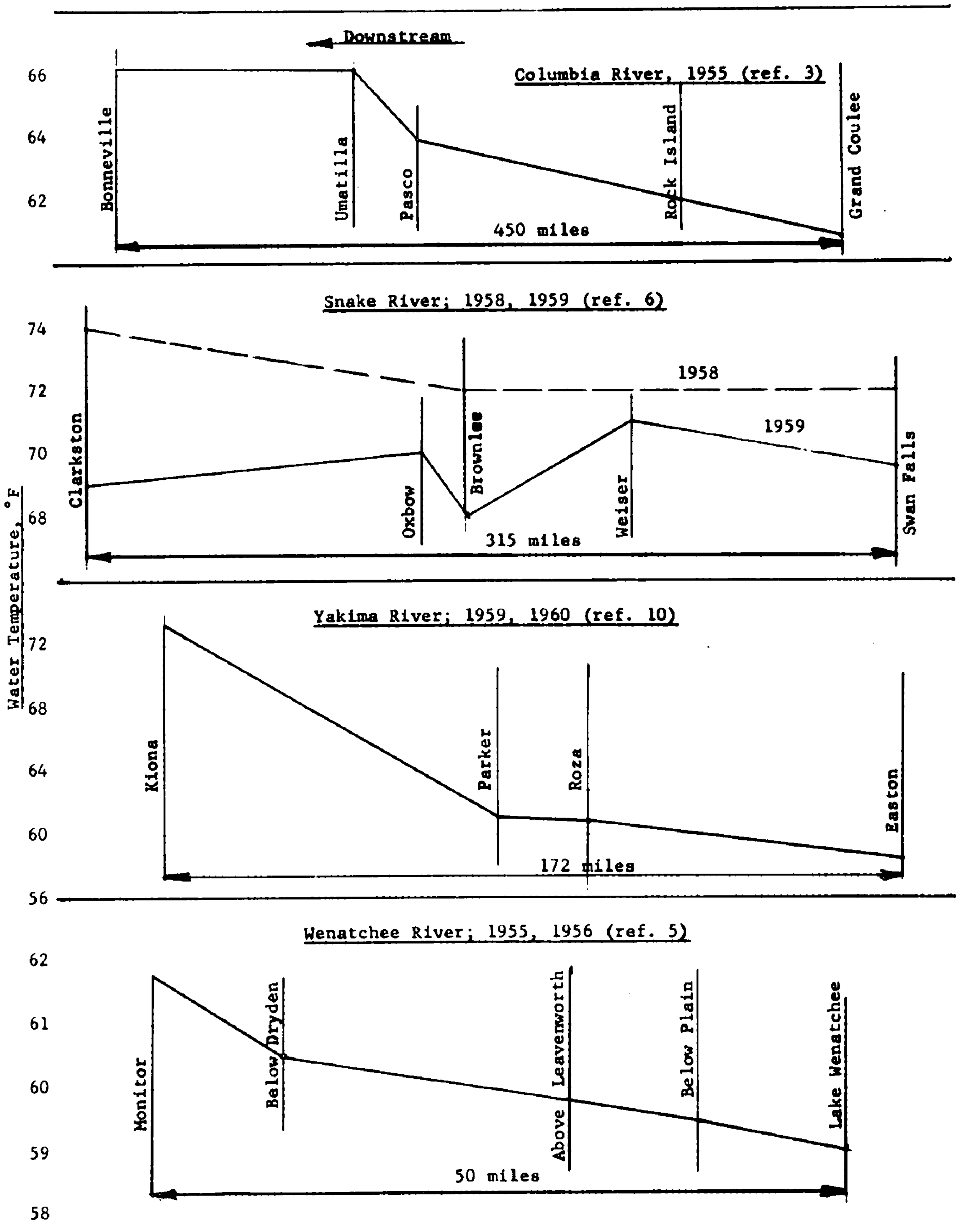


Fig. 1 - Downstream Temperature Changes in August

adjacent Cedar River. The data in Table 3 for Puget Sound area conditions indicate that the treatment plant effluents are warmer than the diverted water by about 14°F. in the winter, 12°F. in the spring, 9°F. in the summer, and 13°F. in the autumn. Additional data are needed on water temperature increase through municipal use.

Table 3 - Sewage Treatment Plant Effluent Vs. River Temperatures, °F.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					Green River Intake							
1961 1/	41	40	41	43	44	48	55	59	50	46	41	42
1962 2/	44	39	39	43	44	50	57	58	58	49	43	39
1963 2/	36	37	41	43	48	54	57	59	60	55	--	--
					Tacoma Sewage Treatment Plant							
1961	54	54	57	59	62	64	64	67	65	62	61	54
1962	55	56	54	59	59	61	63	64	64	62	62	57
1963	57	57	58	57	60	68	67	67	65	61	--	--
					Cedar River Intake							
1960	39.5	40.1	40.6	44.6	48.5	52.8	56.4	54.0	51.1	48.8	43.3	40.3
					Seattle Alki Sewage Treatment Plant 3/							
1960	53	53	52	55	58	60	63	64	62	61	55	55

1/ Prior to Howard A. Hanson Dam Impoundment. Temp. taken daily.

2/ After Howard A. Hanson Dam Impoundment (during period of May to October) thermograph records.

3/ Daily thermometer reading.

Irrigation Return Flow:

The use of river water for irrigation may have beneficial as well as detrimental effects in regard to water temperature. Water is normally stored to increase the irrigation season base flow of the river above the points of diversion. If this water is stored in fairly deep reservoirs at higher altitudes, it will result in water temperatures above the points of diversion being lower than would prevail under summertime conditions of natural flow. However, downstream from points of diversion where water is diverted so as to decrease the streamflow below its

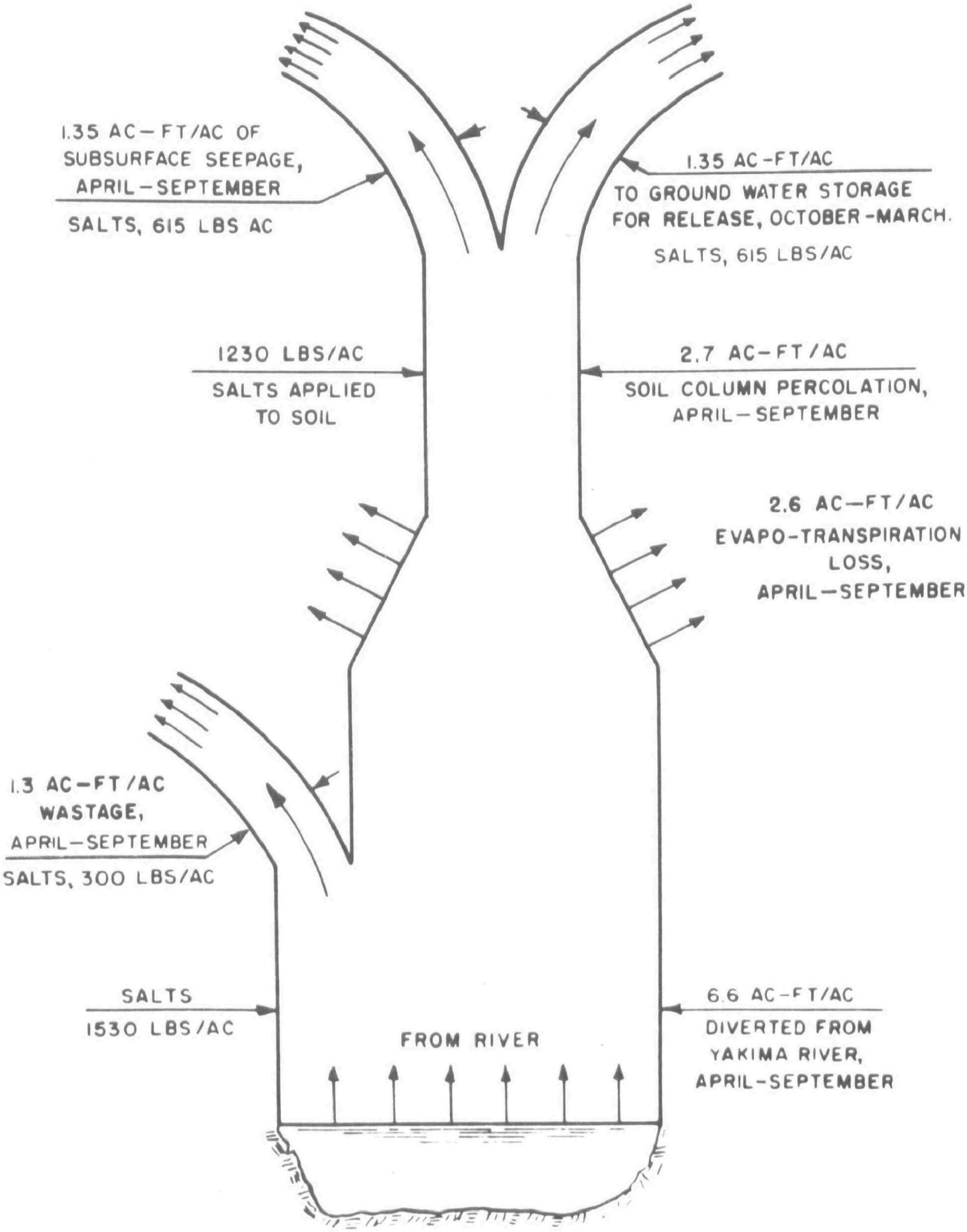


Fig. 2 FATE OF DIVERTED IRRIGATION WATER AND ITS SALTS, YAKIMA RIVER BASIN, 1959-60

normal rate, water temperatures would be raised above those otherwise occurring. The return of spent irrigation waters may raise or lower the receiving stream temperature, depending upon the method of conducting this return flow.

Figure 2 will serve to illustrate the fate of water diverted for irrigation in the Yakima River Basin which can be considered typical of an irrigated area. Of 6.6 acre-feet per acre of diverted water in the April-September irrigation season (10), 1.3 acre-feet per acre is wastage resulting from over-irrigation and from canal spillage. This water returns to the parent river in open drains during which time its temperature is increased. Of the remaining 5.3 acre-feet, 2.6 acre-feet (about 50 percent) is lost to evapotranspiration. This large evapotranspiration loss is responsible for the soil-cooling effect discussed previously. About 2.7 acre-feet per acre of the previously diverted water passes through the soil column into the groundwater stratum where about half of it returns to the parent stream during the irrigation season and the other half returns from bank storage during the non-irrigation season. (The groundwater table rises during the irrigation season and falls during the non-irrigation season.) This groundwater seeps into open drainage channels or is conveyed to open channels via subsurface drains. The great majority of the soil drainage in the Yakima Valley is comprised of open drains.

Table 4 illustrates some of the water temperature changes observed in the Yakima Valley irrigation facilities during August of 1959 and 1960. On the average, water temperature increases of 3.5°F. are experienced in 37 miles of main canal flow.

Table 4 - Irrigation Water Temperature, Yakima Valley, August 1959-1960 -- Mean Values in °F. (10).

Diverted water to Kittitas, Roza, Wapato and Sunnyside Main Canals . .	61.5°
Water after traveling average of 37 miles in main canals	65.0°*
Water in sub-laterals as applied to land; average of 7	63.7°*
Water in sub-surface drains; average of 7	58.4°
Water in open drains as discharged to Yakima R; average of 5 . .	67.0°

*These two figures are not comparable as sampling stations are different.

This is somewhat greater than would have been found in the river for the same flow distance if the water had not been diverted. However, in August, without irrigation flow augmentation, the normal river temperature rise in 37 miles of flow would closely approximate this 3.5°F. temperature rise. Water applied to the land had an average temperature of 63.7°F. and that returned to the river via open drains had an average temperature of 67.0°F., a rise of 3.3°F. Water temperature emerging from sub-surface drains, however, had an average temperature of 58.4°F., a drop of 5.3°F. As previously discussed, this drop in temperature is caused by evaporation heat losses on the soil surface. Thus, if irrigation water wastage can be reduced and if return flows can be conveyed back to the parent river largely by sub-surface drains, these return flows can be beneficial in lowering stream temperatures. During the non-irrigation season the release of bank storage, built up during the irrigation season, will tend to raise otherwise low water temperatures.

Figure 3 shows the seasonal temperature increase in the Yakima River from the point of initial irrigation diversion at Easton to the lower river at Kiona after most of the return flow has entered the river. The figure shows an average water temperature increase during the irrigation season of from 56.4 to 66.2°F. in the 72-mile stretch between Parker and Kiona. This river stretch receives the majority of the return flow and it also contains two areas of very low flows; below the last major irrigation diversion at Parker and below the power canal diversion at Prosser. The power canal diversion discharges back into the Yakima River above Kiona. Figure 3 suggests that the increase in river water temperature between Parker and Kiona, due to irrigation-associated influences, had a maximum value of about 6-7°F. A more rigorous study is needed, however, to validate this figure.

Impoundment Influences on Water Temperature

The impoundment of water will produce various temperature effects on the impounded water temperature and on the downstream water temperature, depending upon:

1. Volume of water impounded in relation to mean streamflow.
2. Surface area of impounded water.
3. Depth of impounded water.
4. Orientation with prevailing wind direction.
5. Shading afforded.
6. Elevation of impoundment.
7. Temperature of inflow water in relation to temperature of impounded water.
8. Depth of water withdrawal.
9. Downstream flow rates during critical temperature period, i.e., an increase or decrease in flow over that occurring naturally.

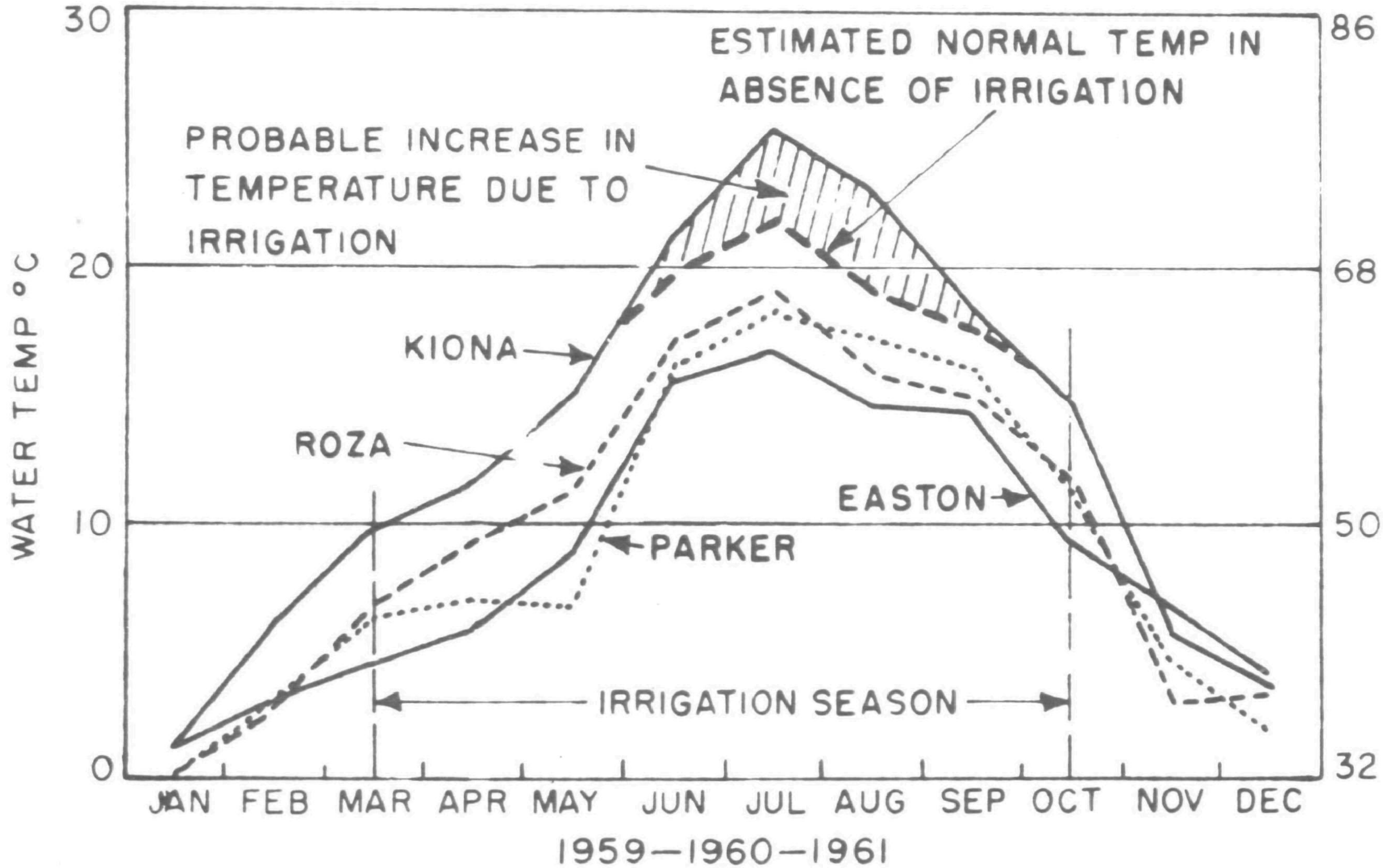


Fig. 3 WATER TEMPERATURES AT YAKIMA RIVER STATIONS.

In general, it can be said that large and deep impoundments will decrease downstream water temperatures in the summer and increase them in the winter, if withdrawal depths are low; that shallow impoundments with large surface areas will increase downstream water temperatures in the summer; that water periodically withdrawn from the surface of a reservoir will increase downstream water temperatures; that a reduction in normal streamflow below an impoundment will cause marked temperature increases; and that "run-of-river" impoundments, when the surface area has not been markedly increased over the normal river area, will produce only small increases in downstream water temperatures.

Andrew and Geen (14), in a study of downstream water temperatures from the proposed Moran Dam on the Fraser River, estimated that the temperature of water discharged from the reservoir through turbine and spill outlets during the period of adult salmon migrations would range from 43°F. on July 1 to 56°F. on September 30. These temperatures are 11°F. colder and 9°F. warmer, respectively, than average temperatures on these dates in the undeveloped river. Churchill (7), in a study of Tennessee Valley impoundments with deep withdrawal depths, observed a lowering of downstream water temperatures as much as 14-15°C. below normal summer stream temperatures.

Raphael (11) (12), in his calculations on the possible effect of the Wanapum and Priest Rapids and the Wells and the Rocky Reach Dams on the temperature of the Columbia River, concluded that in August, the month of the largest temperature rise, the Wanapum and Priest Rapids Dams would cause a temperature rise of 1.5°F. over that occurring with natural flow. The predicted rise for the Wells and Rocky Reach impoundments was 1°F. over the natural temperature rise. He further concludes that "taking the two studies together, it can be seen that the continued development of reservoirs on the Columbia River is doubling the temperature rise of the water as it moves from headwaters to its mouth. It seems inevitable that when the river is fully developed, the maximum temperature of the water will rise even above its present high level. It is estimated that maximum temperatures in the range of 70 to 75°F. at Priest Rapids Dam must be considered in future planning."

Another effect of impoundments on smaller streams is to even out extreme diurnal temperature fluctuations. Figure 4 shows diurnal temperature fluctuations in the Green River above the Howard A. Hanson impoundment of from 12.5-25.5°C. (54.5-78°F.) in the period of July 17-24. Figure 5 shows the even temperature discharge below the dam (and above the Tacoma municipal water intake) where the diurnal temperature fluctuation is about 1°F. This reduction in municipal water intake temperature peaks is, of course, an advantage to the water user.

Figures 6, 7, and 8 show the temperature structure with depth in three dissimilar reservoirs (3). In figure 6, Lake Merwin on the Lewis River is a medium-depth reservoir showing pronounced temperature gradients in all seasons but the winter and early spring of 1938-39. Thus,

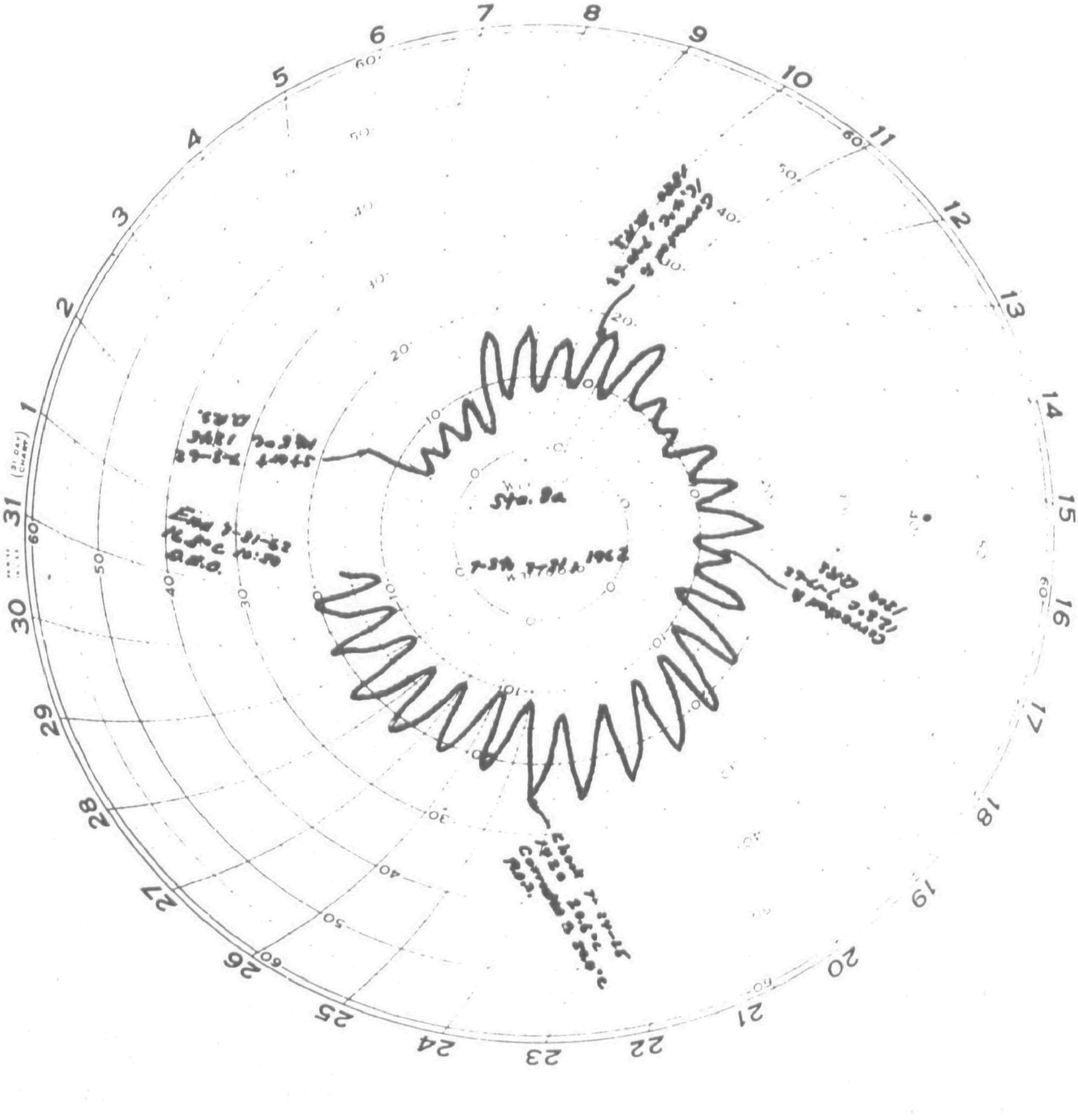


Fig. 4 - Diurnal Temperature Changes on the Green River above the Howard A. Hanson Impoundment

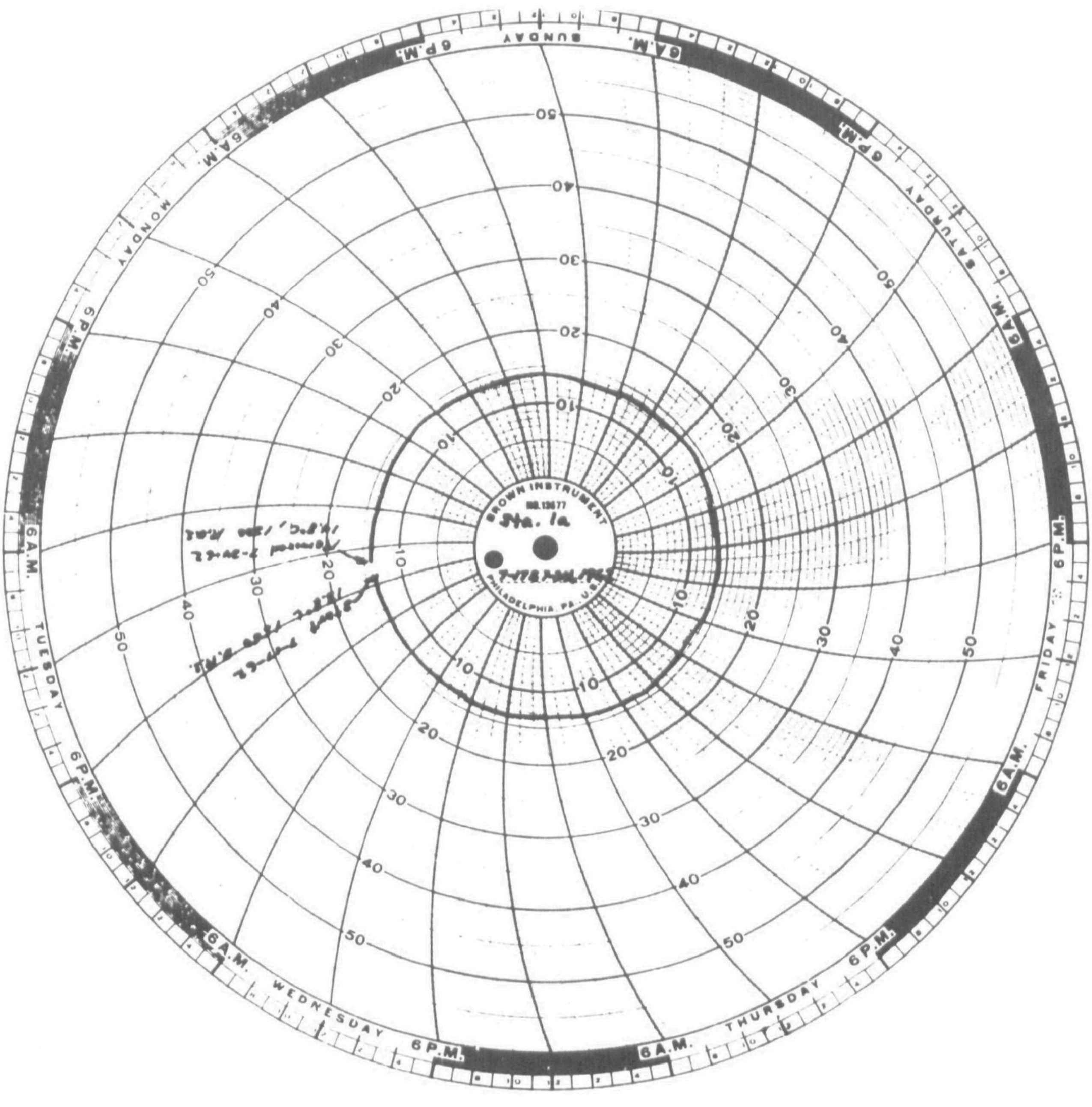
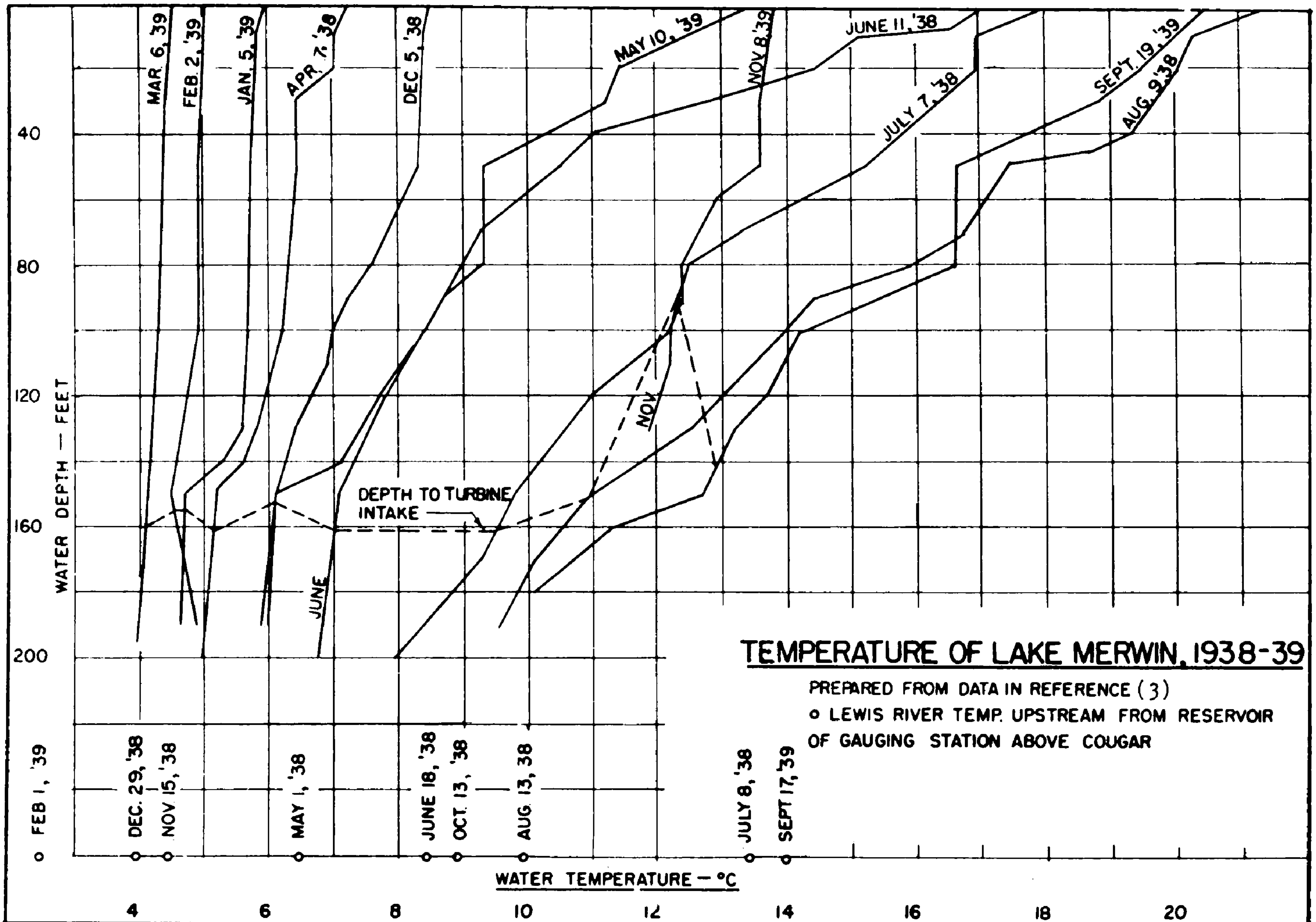


Fig. 5 - Diurnal Temperature Changes on the Green River Below the Howard A. Hanson Impoundment



TEMPERATURE OF LAKE MERWIN, 1938-39
PREPARED FROM DATA IN REFERENCE (3)
o LEWIS RIVER TEMP. UPSTREAM FROM RESERVOIR
OF GAUGING STATION ABOVE COUGAR
WATER DEPTH — FEET
40
80
120
160
200
WATER TEMPERATURE — °C
4
6
8
10
12
14
16
18
20
MAR. 6, '39
FEB. 2, '39
JAN. 5, '39
APR. 7, '38
DEC. 5, '38
MAY 10, '39
NOV. 8, '39
JUNE 11, '38
JULY 7, '38
SEPT. 19, '39
AUG. 9, '38
NOV.
JUNE
DEPTH TO TURBINE
INTAKE
FEB. 1, '39
DEC. 29, '38
NOV. 15, '38
MAY 1, '38
JUNE 18, '38
OCT. 13, '38
AUG. 13, '38
JULY 8, '38
SEPT. 17, '39

Fig. 6

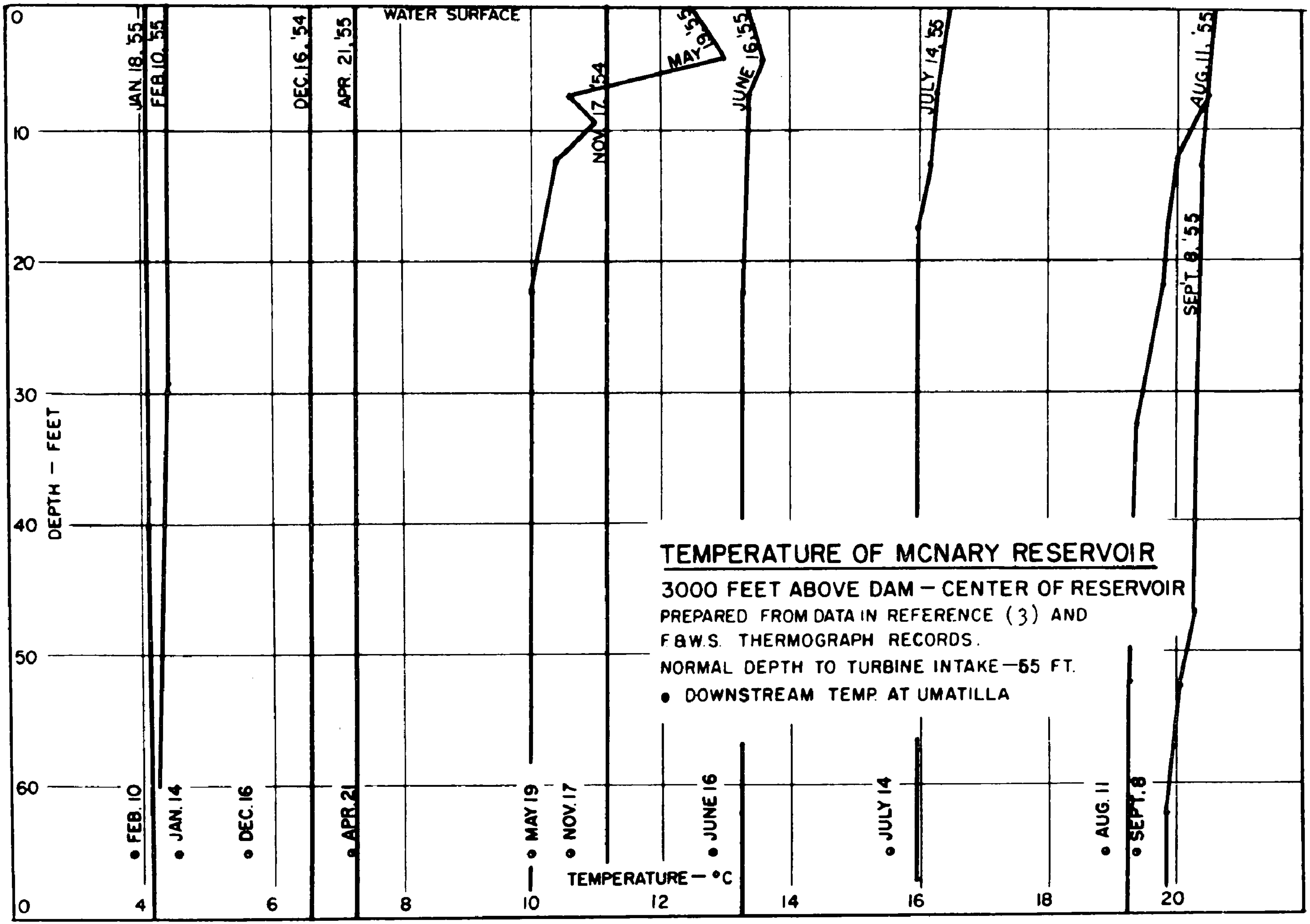
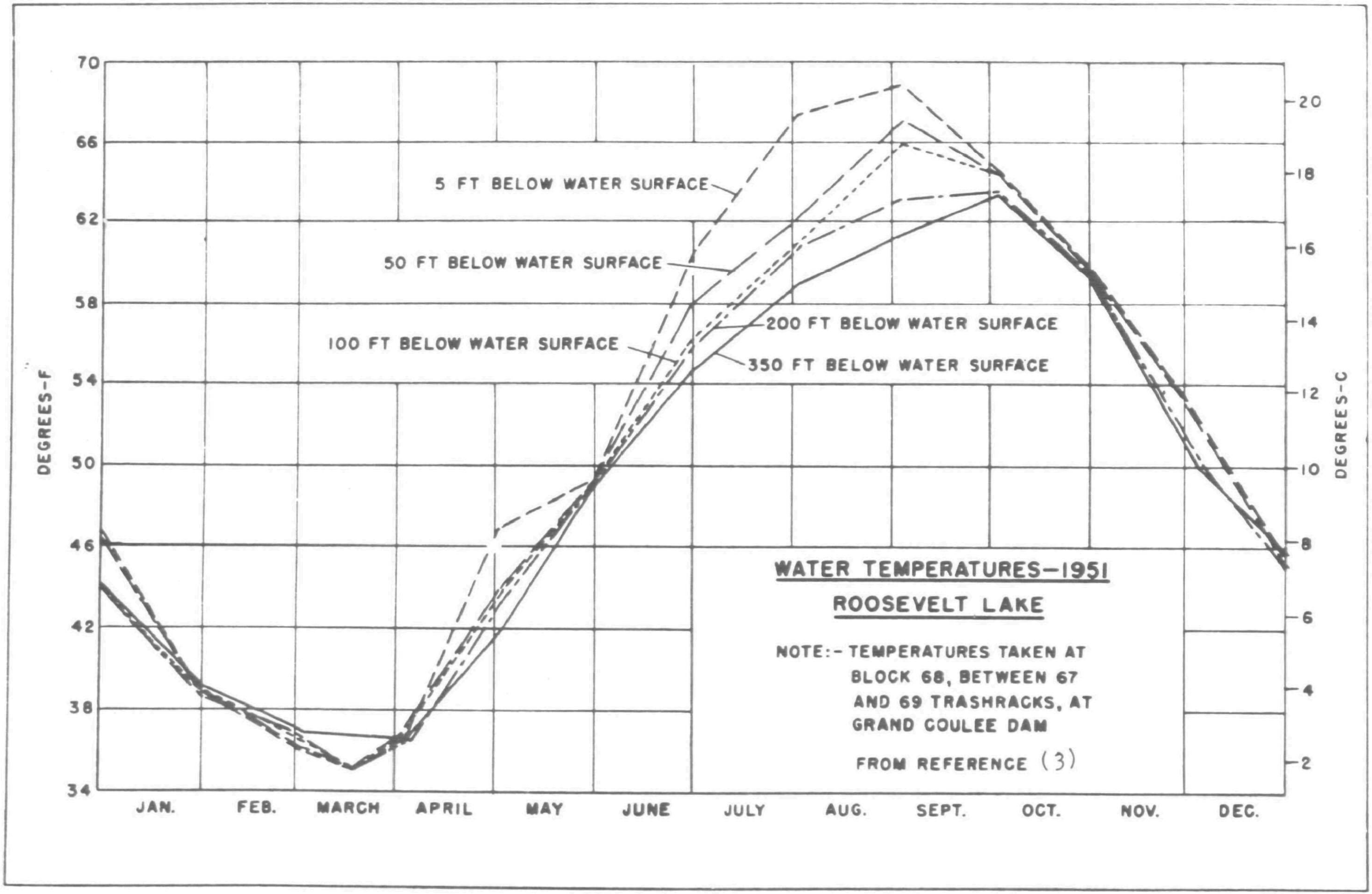

TEMPERATURE OF MCNARY RESERVOIR
3000 FEET ABOVE DAM – CENTER OF RESERVOIR
PREPARED FROM DATA IN REFERENCE (3) AND
F.&W.S. THERMOGRAPH RECORDS.
NORMAL DEPTH TO TURBINE INTAKE – 55 FT.
● DOWNSTREAM TEMP. AT UMATILLA
WATER SURFACE
DEPTH – FEET
TEMPERATURE – °C
JAN. 18, '55
FEB. 10, '55
DEC. 16, '54
APR. 21, '55
NOV. 17, '54
MAY 19, '55
JUNE 16, '55
JULY 14, '55
AUG. 11, '55
SEPT. 8, '55
FEB. 10
JAN. 14
DEC. 16
APR. 21
MAY 19
NOV. 17
JUNE 16
JULY 14
AUG. 11
SEPT. 8
0
10
20
30
40
50
60
70
4
6
8
10
12
14
16
18
20

Fig. 7



WATER TEMPERATURES—1951
ROOSEVELT LAKE
NOTE:- TEMPERATURES TAKEN AT BLOCK 68, BETWEEN 67 AND 69 TRASHRACKS, AT GRAND COULEE DAM
FROM REFERENCE (3)
5 FT BELOW WATER SURFACE
50 FT BELOW WATER SURFACE
100 FT BELOW WATER SURFACE
200 FT BELOW WATER SURFACE
350 FT BELOW WATER SURFACE
DEGREES-F
DEGREES-C
70
66
62
58
54
50
46
42
38
34
20
18
16
14
12
10
8
6
4
2
JAN.
FEB.
MARCH
APRIL
MAY
JUNE
JULY
AUG.
SEPT.
OCT.
NOV.
DEC.

Fig. 8

the water released through the turbines is colder than the upstream water from May through September and warmer than the upstream water from October through April (the August Lewis River temperature shown in Fig. 6 is an anomaly). After construction of a similar reservoir immediately upstream (Yale Reservoir), this was no longer true and the combined effect of the two reservoirs in series (1954-55) is to produce a year-around warming of downstream water as shown in Table 6. The lack of stratification in Figure 7 for the McNary Reservoir is due to the shallow depth of the reservoir and the short detention period for inflowing water. (Slight differences in temperature shown between the downstream temperatures at Umatilla and the turbine intakes at 55 feet of depth is probably due to thermometer calibration or evaporative cooling effects in the turbine tailrace.) The sharp nonconforming thermocline on May 19 occurred at a time when the Columbia River and the Snake River inflows to the reservoir were about equal and the warmer Snake River waters were contained in the upper layers of the reservoir. By June 16, the Columbia River flow had more than doubled that of the Snake and mixing occurred to destroy the temperature gradient.

Roosevelt Lake above Grand Coulee Dam is a very long, deep and narrow reservoir. The temperature gradient between surface and bottom waters is small (Figure 8) except for the summer months when a difference of about 9°F. between surface and bottom was observed in late July, 1951, half of this temperature difference occurring in the upper 50 feet. Minimum temperatures were in March when the deepest water was the warmest, this deep water being the closest to the temperature of maximum density. Maximum temperatures for water withdrawal through the turbines (nominal water depth of 260 feet) was in early October when the pool level had been drawn down for irrigation and power production. Isothermal conditions are shown for January, May, and October when overturns are possible.

Figure 9 is a plot of Columbia River temperatures (3) at Rock Island Dam for the mean of a five-year period before construction of Grand Coulee Dam and a five-year period after construction of the dam. Time periods were chosen when river flows and air temperatures were similar. As shown in Figure 9, Grand Coulee Dam construction has produced warming of the Columbia River at Rock Island between September and March and cooling between March and September. This warming effect was about 7°F. maximum in the winter and the maximum cooling effect in the summer was about 3°F.

Table 5 gives the characteristics of several reservoirs in western and eastern Washington. Table 6 lists the observed temperature changes through these impoundments for different periods of observation. The Yale-Merwin impoundments in series on the Lewis River give a significant temperature rise throughout the year. The Howard A. Hanson flood control-conservation impoundment produced a uniform

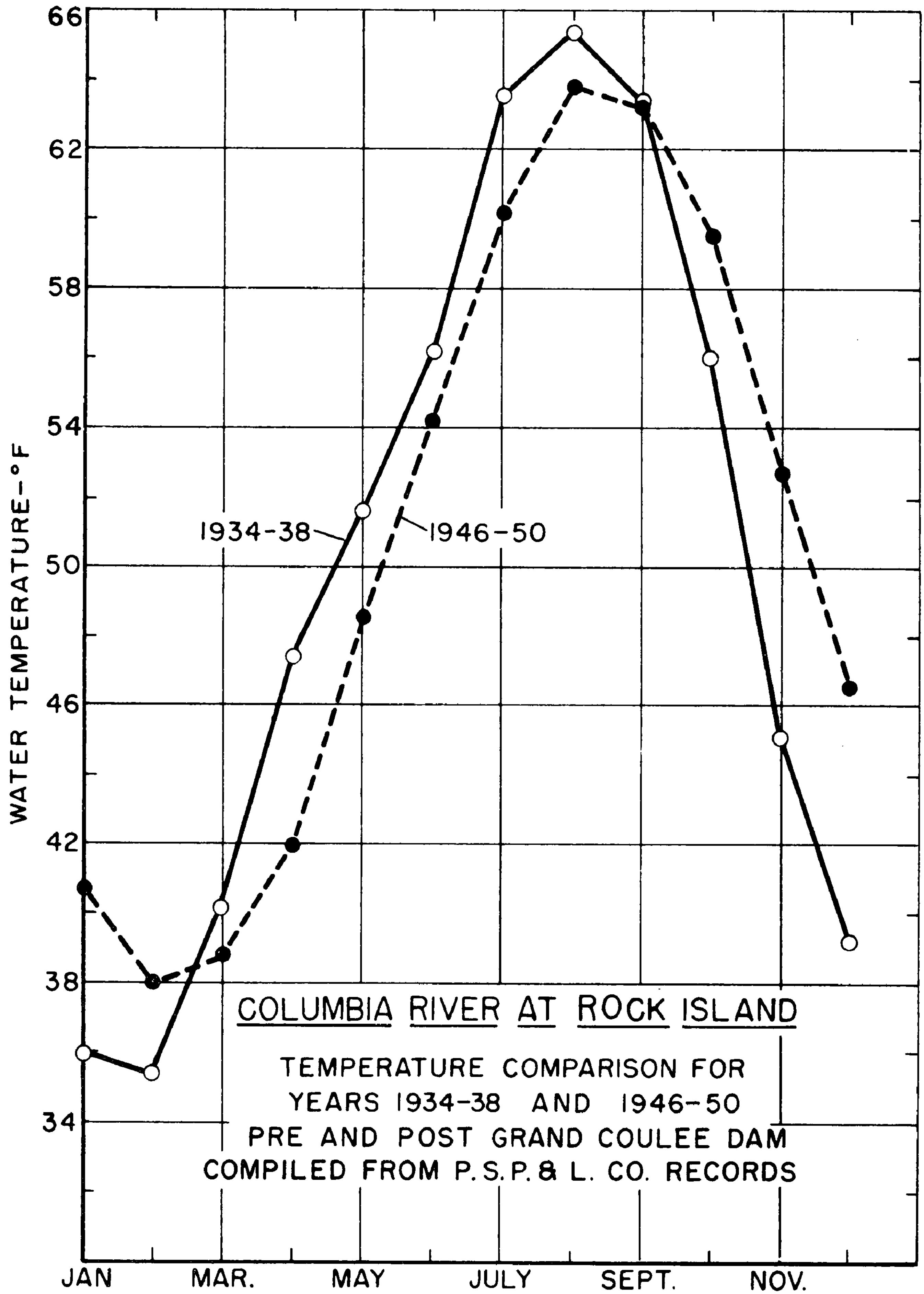

66
62
58
54
50
46
42
38
34
WATER TEMPERATURE-°F
1934-38
1946-50
COLUMBIA RIVER AT ROCK ISLAND
TEMPERATURE COMPARISON FOR
YEARS 1934-38 AND 1946-50
PRE AND POST GRAND COULEE DAM
COMPILED FROM P.S.P.& L. CO. RECORDS
JAN
MAR.
MAY
JULY
SEPT.
NOV.

Fig. 9

temperature rise of about 1.5°F, during the period of conservation storage until October, when the pool was drawn down, and the warmer surface waters raised the flow-through temperature by 3°F. Grand Coulee impoundment water is pumped into the Banks irrigation equalizing pool which is a very broad and shallow pool subject to a maximum of solar radiation in the summer months. Temperature increases exceeded 7°F. through this reservoir from the cold Grand Coulee inlet water to the irrigation water discharge. In Roosevelt Lake, temperature decreases through the reservoir are experienced in the summer until September when the reservoir is drawn down and the warmer upper level water enters the turbine intakes. The effect of Roosevelt Lake in cooling Columbia River water would be more pronounced in Table 6 if the natural temperature increase through the 150-mile reservoir were considered. McNary and Bonneville run-of-river impoundments produce very little warming effect in the summer months, varying from 0 to 0.5°F.

Table 5 - Impoundment Characteristics

Impoundment	River	Average Volume AC - FT X1000	Average Surface Area Acres X1000	Average Depth Feet	Theor. Detention at Average Flow Days
Yale-Merwin	Lewis	747	7,340	101	43
H. A. Hanson	Green	20	0.6	33	10
Banks	Col. Basin	951	24.50	39	140
Roosevelt	Columbia	8,252	70.30	118	35
McNary	Columbia	790	37.90	21	2
Bonneville	Columbia	480	20.30	24	1

Table 6 - Temperature Changes Through Impoundments - Observed Average Monthly, °F. 1/

Impoundment	Average Monthly Temperature Change Through Impoundment								
	Mar.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Yale-Merwin	1.6+	3.0+	5.1+	1.4+	0.8+	3.1+	-	-	4.0+
H. A. Hanson	-	1.5+	1.8+	1.8+	1.8+	1.5+	3.0+	-	-
Banks	-	-	7.0+	7.5+	5.9+	2.0+	-	-	-
Roosevelt	-	-	1.9-	1.9-	0.1-	3.6+	-	-	-
McNary 2/	1.5-	0.1-	0.7-	0.0	0.1+	0.5+	-	0.2+	0.2-
Bonneville	0.2+	-	0.1-	0.1-	0.0	0.0	-	0.0	0.5-

1/ From reference (3), 1954, 1955; except Hanson U. of W. data, 1962, 1963.

2/ Temp. above McNary Dam measured at Pasco. Snake River inflow raises or lowers McNary pool temp.

Summary

A discussion has been presented on the various factors that influence water temperatures in streams, impoundments and on irrigated lands. Data are shown that illustrate the wide range of temperature increases and decreases that are obtained seasonally through water use and its method of use. These data are fragmentary and indicate the need for a thorough study on water temperature patterns as influenced by man's alteration of the natural water environment.

Low water temperatures, commensurate with the maximum productivity of the fishery, should be the goal in water quality management for the following reasons: Low temperatures increase the oxygen capacity of a water body; they slow the rate of biological oxidation (which may not always be desirable); cool water is more palatable in a municipal system; cool water is more valuable to industry for cooling purposes; and the rate of metal corrosion is reduced. Occasionally, cool water is undesirable for certain crops, such as rice.

Future engineering design and redesign or operational changes in existing structures, in consideration of the present trend towards higher river water temperatures, can do much towards reducing or ameliorating this trend.

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DISCUSSION

Q. How did you arrange your chlorophyll rate values? Were these on membrane filters?

A. A cooperative group made this study--the five pulp and paper mills in the Lower Columbia, the Washington Pollution Control Commission, and the Oregon State Sanitary Authority. They collected the algal samples and filtered them on membrane filters, dissolved and extracted the chlorophyll with acetone, and then ran absorbence tests.

Q. The average temperatures that were shown on the graphs--were they taken from the means of the daily temperatures, the mean of maximums and minimums, or do they take into account the whole diurnal cycle?

A. At Rock Island the temperature was read every six hours--midnight, 6 a.m., noon, 6 p.m. We took the mean of those temperatures. Where we had a thermograph record, we tried to balance out the diurnal variations so that we had the same area above as below. In other cases where we were given only the minimum temperature or the maximum, we took the average. We found that in most cases, if you took the minimum daily temperature and the maximum daily temperature and averaged the mean of that, this was very close to working out a thermograph cycle.

WATER TEMPERATURE REQUIREMENTS FOR MAXIMUM PRODUCTIVITY OF SALMON

Roger E. Burrows*

Water temperatures can and do affect the productivity of salmon; the problem, then, is that of defining the temperature limitations. At various stages in the life cycle, productivity must be measured in different ways, either by the number of individuals produced or by the size of fish produced. The effect of temperature on productivity may be measured in a similar manner. Because temperature effects are dissimilar at different stages in the life cycle, it is necessary that these effects be discussed separately for the several stages.

The temperature of the water during the upstream migration and the maturation period of the adult in the lake or stream affect the survival of the adult, and the water temperature at time of spawning affects the survival of the eggs. High temperatures during fresh water residence are conducive to disease development and the subsequent death of the adult prior to spawning. Fish (1948) cites temperatures above 60°F. as conducive to disease development in blueback salmon (*Oncorhynchus nerka*) and temperatures above 70°F. as fatal. Royal (1953) defines normal spawning temperatures of sockeye salmon (O. nerka) as between 45°F. and 55°F. and indicates that temperatures above and below this range are conducive to reduced spawning efficiency either through death of the adults or loss of the eggs. He concludes, "Thus water temperature was indicated as one of the major limiting factors, if not the exclusive limiting factor, in the timing of spawning." The International Pacific Salmon Fisheries Commission (1962), again, reports mortalities as high as 86 percent in sockeye runs of the Fraser River attributed to disease occasioned by water temperatures in excess of 72°F. in certain tributaries.

Burrows (1960) defines the critical water temperature for disease development in chinook and blueback salmon as 60°F. Above this temperature, survival is dependent on the extent of injury incurred by the fish during migration and maturation, the length of the period between the upstream migration and spawning, the incidence of disease organisms, and the type of holding environment.

Warm water temperatures also inhibit spawning activity. Burrows (1960) reports the effect of unseasonably high water temperature as delaying the spawning act.

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Brett (1958) speculates on the role of cold water temperatures as an inhibiting factor affecting the normal endocrine balance necessary for spawning. This speculation is confirmed by Burrows (1960) reporting on the effect of temperature on an exotic race of large summer chinook salmon (O. tshawytscha) which did not spawn when water temperatures dropped below 40°F.

The temperature at spawning not only affects the adult but the survival of the egg as well. Combs[1/] has demonstrated that water temperatures below 42.5°F. at time of egg deposition result in progressively greater mortalities until at 35°F. egg losses are practically complete in chinook salmon and up to 50 percent in sockeye salmon.

The high temperature limitations on eggs at time of spawning have not been clearly defined. It is extremely doubtful that the adult could survive to spawn at water temperatures which would be immediately lethal to the eggs.

The water temperatures most conducive to maximum productivity in the adult salmon during its fresh-water existence range from 42.5°F. to 55°F. Obviously the adult can exist at temperatures beyond this range but not under optimum conditions of survival and egg deposition.

Egg incubation temperatures affect the survival of the eggs, the rate of development, and the size of fish produced. Combs and Burrows (1957) and Combs[1/] have defined the thresholds for normal development for chinook salmon eggs as 42.5°F. and 57.5°F. and for sockeye salmon eggs as 42.5°F. and 55°F. In addition, Combs demonstrated that both chinook and sockeye salmon eggs would tolerate 35°F. temperatures after the 128-cell stage of development was reached.

Water temperatures within the thresholds of normal development affect the growth rate of the embryo. At the higher temperatures the growth rate is accelerated but the size of the fish produced is reduced primarily due to higher maintenance requirements. The size of the emergent fry should, in theory at least, affect the survival rate with the larger fish having the advantage. The time of emergence also can, conceivably, affect survival particularly in species with a short fresh-water residence. Acceleration or deceleration of emergence could place the fish in an unfavorable environment either from the standpoint of available forage or predation activity. Dislocation of the time of migration could result also in unfavorable estuarine conditions and poor acclimation to salt water. Vernon (1958) demonstrates an inverse correlation between temperatures in the Fraser River during

1/ "Effect of Temperature on the Development of Salmon Eggs" by Bobby D. Combs. Manuscript in preparation.

the period of egg and fry development of the pink salmon (O. gorbuscha) and the size of the resultant adult run. The critical period of development as affected by temperature appeared to be during hatching and the subsequent fry stage, December through February. Average temperatures above 38°F. were usually unfavorable. Since no temperature reported was actually lethal to either eggs or fry, it must be assumed that the acceleration of development due to the warmer temperature disrupted the timing of the seaward migration.

The effect of temperature on productivity in the egg and fry stage of development is much more difficult to define than in any other. While the thresholds of normal development are easy to measure, the more obscure effects of temperature, such as its influence on fry size and migration timing, are very evasive to evaluate but may have a profound impact on survival.

When salmon fingerlings have a more prolonged fresh-water residence, the effect of temperature on productivity may be measured by either the number of fingerlings produced or the size of fingerlings produced. The two criteria are not synonymous because the size of the downstream migrant affects survival. Marking experiments conducted with sockeye salmon at the Leavenworth National Fish Hatchery indicated that doubling the weight of the fingerlings at release from 120 to 60 per pound resulted in tripling the adult return. Marking experiments with fall chinook salmon (Johnson, unpublished) indicate higher survivals for the larger fish at release although the results are somewhat obscured by different times of release.

Water temperature, then, to attain maximum productivity in the fingerling must not only remain within the tolerance level of the fingerling but, at least in species with more than a minimum of fresh-water residence, reach the optimum growth level as well. Brett (1952) defines the lethal levels for Pacific salmon fingerlings (Oncorhynchus) as between 32°F. and 75°F. with but slight variation in the upper threshold between species. He also found the preference temperatures for all species to be in the range of from 50°F. to 60°F. The preference temperatures coincide with those for optimum growth.

The response of sockeye and chinook salmon fingerlings to temperature differs. Sockeye grow at a faster rate at all temperatures between 40°F. and 60°F. than do chinook salmon. The growth rates of chinook salmon, however, accelerate more rapidly with temperature increases. For every 10-degree rise in temperature between 40°F. and 60°F. food consumption increases 45 percent in sockeye salmon and 60 percent in chinook salmon, but there is an initial 25 percent difference between the two species at 40°F. While temperature may affect species differently, it is still the prime factor in the determination of growth rate.

Streams or lakes in which optimum growth temperatures are not reached, or for only short periods, will not attain maximum productivity. Similarly, streams or lakes which exceed the optimum range for considerable periods will not attain highest productivity. Water temperatures which remain relatively stable either above or below the optimum range for extended periods are conducive to disease development which may result in a reduction in the number of fingerlings produced.

The food production capacity of a stream obviously affects fish productivity by controlling the growth rate and time of migration. Such food production is dependent to some extent on the temperature regimen. Streams stocked beyond their food capacity induce forced migrations. Chapman (1962) describes the continuous downstream displacement of small silver salmon fingerlings (O. kitsutch) during the first year of fresh-water residence and attributes this premature migration to the aggressive behavior of the larger fingerlings. Kalleberg (1958) suggests that the aggressive characteristic is evolved in salmon and trout to insure an adequate food supply. It may be concluded that food shortages result in forced migrations of portions of the populations not necessarily at sizes and times conducive to optimum survival.

The long downstream migration of salmon fingerlings imposes a gauntlet of predation not normally encountered in other species of fish. One of the factors affecting the degree of predation is the activity of the predators. Water temperature controls the activity of fish predators and, therefore, the degree of predation per fish encountered by the downstream migrants. The preferred or temperature of optimum activity of both the migrant and predator influences migrant survival, particularly at the warmer temperatures. Streams warm more as they progress toward the sea and the salmon migrants, if the warm-up is considerable, may move out of their optimum activity range, thus being placed at a distinct disadvantage in the evasion of resident predators.

Brett (1958), in discussing environmental stress, lists high water temperature as an indiscriminate stress on salmon fingerlings which may be either lethal or loading in nature. A loading stress is defined as any environmental factor which places an undue burden on an organism, necessitating the rapid or steady release of energy. The warm water temperatures, between 65°F. and 75°F., encountered on occasion during migration, place salmon fingerlings under a loading stress. While such conditions may not prove immediately lethal, they may impair the metabolic activity of the animal to such an extent that any additional stress such as pollution may prove synergistic and result in a high level of mortality.

The annual thermal cycle in a watershed determines both the productivity and the species which it will support. Brett (1959) tentatively delineates the thermal requirements for different life processes which characterize Pacific salmon. The work of the Salmon-Cultural Laboratory more precisely defines the requirements in some of these areas of speculation. Review of these requirements in comparison with the thermal cycles existing in lakes and streams indicates that only rarely will the complete thermal cycle coincide with the optimum life cycle requirements for maximum productivity. The thermal pattern of a stream is affected by the weather conditions encountered in the area and by man-made diversions and obstructions. Irrigation diversions can reduce the normal streamflows until the water temperatures become intolerably high.

Dams created for storage or power can become either liabilities or assets depending on how they alter the normal thermal cycle of the stream. Moffett (1949) reports on the favorable temperature conditions created in the Sacramento River by Shasta Dam. Johnson and Brice (1953) describe the adverse temperature conditions created by the delayed discharge of waters from the epilimnion of Dorena Dam. In the latter circumstance, the normal temperature pattern of the stream was reversed with high water temperatures occurring in the fall during the egg incubation period of the salmon.

High power and storage dams with thermal stratification provide opportunity for control of the thermal cycle within a watercourse to the benefit of the salmon population. Such thermal control, scientifically applied, could alleviate to some extent at least some of the detrimental effects of the dams by increasing the productivity of the available stream area.

The effect of temperature on productivity is not confined to the fresh-water portion of the life cycle of the salmon. Davidson (1938) attributes limitations of the geographic distribution of the salmon in part to the ocean temperatures encountered adjacent to the parent stream. Tully et al. (1960) reports an intrusion of warm ocean currents at temperatures approximating 45°F. into the Northeastern Pacific in 1957 and 1958 and attributes this intrusion as the cause for the diversion of the 1958 sockeye run of the Fraser River away from its normal migration path. Gilhousen (1960) points out that not only diversion but delay in maturation occurred in this run and speculates that the fish were displaced into more northern latitudes during their ocean existence, which because of an abnormal lengthening of the light cycle, delayed their time of maturation. Such occurrences indicate that radical disruptions of ocean current patterns could conceivably erect thermal barriers and completely divert a salmon population from its normal oceanic and fresh-water habitat. Other less obvious variations in ocean temperature may have pronounced effects on salmon productivity. Variations in the ocean survival rates of salmon certainly exist.

While our knowledge of the temperature effects on ocean productivity of salmon is rather nebulous at present, information on the requirements for the fresh-water portion of the cycle is rather precise. The temperature requirements for maximum productivity of salmon in fresh water may be defined as follows:

1. Temperatures during the upstream migration and maturation period of the adult should be between 45°F. and 60°F.

2. Spawning temperatures for maximum survival of the eggs should be between 42.5°F. and 55°F.

3. Egg and fry incubation temperatures, after 128-cell stage of development is reached, may vary but should remain within the range of 32°F. to 55°F. The effect of fry size and time of migration on survival in different areas makes it impossible to confine the optimum temperature range more precisely.

4. The range in temperature for maximum productivity in fingerling salmon is between 50°F. and 60°F.

Where dams with thermal stratification make thermal manipulation possible, every effort should be made to produce stream temperatures compatible with optimum productivity.

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DISCUSSION

Q. Have fisheries agencies ever made their wants known about using thermal structure of reservoirs for optimum production of eggs and fry? This can be done.

A. They really did not know what was wanted for quite some time, but they know pretty well what is wanted now.

Q. If you don't speak up, you'll never get what you want.

A. That's for sure. I presume it is entirely feasible to adjust so that water is taken from either the top layers or lower layers of a reservoir without affecting the power production, if there are outlets to do it. But in running all the water through the turbines, there is not much choice.

Q. Isn't it possible, in dam construction, to provide for taking out of different levels?

A. In new dams this can be done, and is being done now. However, in the operation of existing dams, this is not possible. My suggestion is to get letters to people who operate these dams, telling them what your needs are.

A. It seems that it is a glaring defect in our entire fish-management program that we have made no effort to take advantage of the thermal requirements of the fish and to correlate them with the thermal capabilities of management.

A. This is possible only within the limits of the overall objectives of the project, and reservoir operation is only too happy to help out. For instance, recently the Fish & Wildlife requested that we operate the Bumping River Dams to provide for the survival of the fingerlings. This is being done.

A. We had an occasion in California, on the American River, where long after Folsom Dam was constructed the Bureau constructed adjustable louvers for the control of water temperature.

A. The Army Engineers and the Bureau of Reclamation, if they knew the requirements, would at least incorporate structures into dam construction and possibly even now operate dams more advantageously. I don't think that it would be too prohibitive in cost. There are some areas below these streams now which are apparently much more suitable for fish than they ever were before.

Q. There was a report in SCIENCE a few weeks ago about some work on temperature periodicity. Instead of regulating temperature in constant degrees for long periods of time, the investigator took the square waves of temperature in which he changed the frequency by which temperature varied up or down. This seemed to produce dramatic results in survival. This was done, I believe, with the juveniles, but not with the adults.

A. We have found that fish adjust very readily to temperatures of 10 to 15 degrees change.

Q. His point was that maybe the problem of temperature adaptation may be controlled by the frequency with which temperatures are brought up and down and the period at which they stay and then drop.

A. This is not in conflict at all with Brett's work in which he found that where he acclimated fish to a temperature, say of 65 degrees, their lethal level of temperature would rise. Where the fish were acclimated to lower temperatures, say 50 degrees, a sudden rise to 75 would probably kill the fish. Actually this would not have been the lethal level, if the fish had had a chance to accommodate over a considerable period of time.

Q. You mentioned better survival of the juveniles of the larger sizes. Do you mean survival of adults and what about the preponderance of jack salmon?

A. This all depends on what sizes you are talking about. For example, with silver salmon, if you increase the size and hold them for a considerable length of time, you get a preponderance of jacks back. With fall chinook, groups have been released when they were running about 20 to the lb. as contrasted to fish that were running about 100 to 200 to the lb. There have been no indications of a preponderance of jacks back on these fish.

Q. What is the effect of temperature on adults carrying eggs in transportation water--that is, the effect of relatively high water temperature on the development of eggs prior to the fish reaching the spawning area?

A. It doesn't seem to have any effect. On the Grand Coulee, fish were moved in hot water. The adults may die, but if the adults survive, the temperature at which the eggs are taken is the thing that influences the egg itself.

Q. The possibility was mentioned of acclimatizing the fish to a higher temperature regimen where they would not be quite so susceptible to some of the things that would affect them. How long a period of time might be involved in making such an acclimatization?

A. This takes about three weeks, but really it doesn't amount to much as to the adjustment. There is only about 2 degrees difference in the lethal temperatures and lethal temperatures are not, of course, the important temperatures anyway.

Q. Would it affect some of the subsequent life processes that take place where the eggs might be affected by the higher temperature? That is, the stage where the adult is carrying the egg?

A. As far as we know, they are not affected. There are cases where temperatures have been as high as 72 degrees and the eggs were perfectly normal.

Q. Mr. Burrows, you gave a list of ranges of temperatures for various stages of life cycles of fish, and in streams such as the Rogue River all of these stages may be taking place at one time. Is there a range of temperature under such conditions for all of the cycles taking place at the same time?

A. It is difficult to visualize a condition where all of them would be taking place at the same time other than an overlap such as when fingerlings are moving downstream while adults that have not yet spawned are moving upstream. In this case, the temperatures would have to come down to the range that will not affect any particular individual part of the cycle. If the fish is vulnerable throughout any stage and it is not in an optimum habitat, we are going to have to adjust to reach that habitat. Obviously if we have a temperature of 32 degrees that the eggs will tolerate, when we move into a temperature with the adult and it won't deposit eggs at that time, or if spawning has actually taken place and we know that this is the lethal temperature during spawning, then 42-1/2 degrees becomes the minimum temperature. We narrow the limits, in other words.

THE EFFECTS OF TEMPERATURE ON DISEASE IN FISH

Erling J. Ordal and Robert E. Pacha*

Fish are poikilothermic animals; consequently they normally take on the temperature of the water in which they are found. This fact has a profound effect on host-pathogen relationships, since both the host, in this case a fish, and the pathogen, the organism infecting the fish, may be affected differently by the water temperature. Since warm-blooded animals have a temperature regulatory mechanism which holds the body temperature of the animal near to a particular value, it is not feasible to evaluate specific effects of temperature on host-pathogen relationships in such animals. The situation is different with fish, since here the temperature of the host can be placed under direct experimental control.

From the literature it is evident that most fish diseases are favored by increased water temperatures. This has been our experience with most of the diseases of fish which we have studied at the University of Washington. Some of the studies on this problem have been carried out in the University of Washington Experimental Hatchery where water temperatures are under relatively exact control. In these studies, carried out with salmonid fishes, we have found that higher water temperatures drastically increase the effect of such diseases as kidney disease, furunculosis, vibrio disease due to a marine vibrio, and columnaris disease in young fish. Experience with natural outbreaks of a number of diseases in hatcheries, as well as observations of disease in fish in natural waters, tends to confirm these findings with most diseases.

A striking exception to the more or less general experience that increased water temperatures favor outbreaks of diseases in fish is found with the disease sometimes referred to as "low-temperature disease" or "cold-water disease." This disease is due to an aquatic myxobacterium named Cytophaga psychrophila which, as its name indicates, prefers low temperatures. The disease is generally found in young silver salmon in the early spring when water temperatures are low and in some outbreaks causes very heavy losses of young fish. As a rule, when water temperatures increase with the annual warm-up of the water, the disease is self-limiting and disappears.

The effects of temperature on the disease in young silver salmon can be illustrated by an experiment carried out at the University of

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Washington. A stock of young silver salmon from the Dungeness Hatchery suffering from low-temperature disease was brought to the University of Washington Experimental Hatchery and held at 43°F. Each day a considerable number of these fish died. After a week the remaining fish were divided into two groups. While one group was held at 43°F., the second group was tempered into water at 55°. After two days, mortalities in the lot of fish held at 55° ceased, but deaths continued in the fish held at 43°F. until all the fish were lost.

On isolation of the strain of C. psychrophila in the Dungeness fish, it was found that this bacterium was a true psychrophile, failing to grow on culture media except when incubated well below room temperature. However, not all strains of C. psychrophila which are found on fish behave like the Dungeness strain, since some other strains have been found which can cause disease at higher water temperatures. In some cases, the disease persists as water temperatures rise to 55°F. and even higher. In the laboratory it can be shown that some strains of C. psychrophila produce mutants which are capable of growth at higher temperatures, and it is probable that the disease at the higher temperatures is due to these mutant strains.

The occurrence of mutants in some strains of C. psychrophila which are capable of causing disease at a higher temperature illustrates the fact that bacteria can undergo genetic change. When first discovered, C. psychrophila caused serious disease only in young silver salmon. During recent years new strains have appeared, identifiable as C. psychrophila by serological methods, which have been found responsible for generalized infections in young chinook salmon and blueback salmon.

Columnaris disease, due to another myxobacterium, Chondrococcus columnaris, is now well known and recognized as a warm-water disease; and a good deal of attention has been given at the University of Washington to the study of this organism and its effects on populations of fish not only in the hatchery but also in the natural habitat.

Columnaris disease was first described by Davis in 1922 as a new infectious disease of warm-water fishes in the Mississippi River Valley. The disease was found in fish which had been trapped in sloughs along the Mississippi River when flood waters receded, and which subsequently warmed up, and in fish in a hatchery at Fairport, Iowa, at high water temperatures. The disease was found in 15 different species of fish. Although Davis was not able to isolate the organism causing the disease, he observed and described the organisms present in the external lesions on the fish sufficiently well so that there is no question but that the disease which he studied was similar to that known today. Following Davis' report, nothing further is found in the literature until papers by Fish and Rucker, 1943, and Ordal and Rucker, 1944, on the occurrence of columnaris disease in cold-water fishes, i.e., in salmonid fishes, at the Fish and Wildlife Station at Leavenworth, Washington. The building of Grand Coulee Dam made it necessary to relocate the runs of salmonid fishes which were obstructed by the dam. In this operation adult salmon and steelhead trout were trapped at Rock Island Dam and hauled in tank trucks to large holding ponds on Icicle Creek at the Leavenworth Hatchery. There they were maintained until they spawned. The fish were trapped over the period 1939 to 1943 and were placed in the holding ponds in the period 1940 to 1943.

At the Leavenworth Hatchery columnaris disease was first observed in a stock of young blueback salmon in the summer of 1942. Cultures were isolated, and the pathogenicity of the C. columnaris was demonstrated, thus proving that the disease in the young salmon was due to this organism.

Subsequently, columnaris disease was found present in adult chinook and blueback salmon, steelhead trout, white fish, squaw fish, chub and suckers trapped at Rock Island Dam. Pure cultures of C. columnaris were isolated from external lesions and internal organs of some of these fish. Columnaris disease was also found in adult chinook and blueback salmon taken in a moribund condition from the holding ponds at Icicle Creek. It was reported by Fish and Hanavan (1948) that 72.3 to 97.6 percent of the adult blueback salmon and 75.4 to 95.4 percent of the summer chinook salmon in these ponds died before spawning during the four-year period 1940 through 1943. The cause of death in the adult salmon was not established. However, since the fish had been hauled by tank trucks from Rock Island Dam, and since no precautions were taken to prevent infection, it is probable that the majority of these fish had been exposed to columnaris disease during the hauling.

Following the reports on the occurrence of columnaris disease in salmonid fishes and the isolation of the causative agent, epidemics of columnaris disease were reported in a number of regions of the United States ranging from New York to the South to the Pacific Coast (Davis, 1949, 1953). Most of the reports have dealt with the occurrence of columnaris disease in hatcheries or with mass mortalities in natural impoundments, lakes or streams when water temperatures reached high levels.

In some studies carried out in the State of Washington in postwar years it was noted that the strains of C. columnaris isolated in different places varied widely in their virulence, that is, their capability of infecting and killing young fish. A report of these studies was published by Rucker, Earp and Ordal (1953). Thus, it was found that strains of C. columnaris isolated from fish in the lakes and streams and hatcheries of western Washington and from some fish in the Columbia River were of relatively low virulence in that they produced a slowly progressing infection which led to extensive tissue damage only at relatively high water temperatures. Serious epidemics due to these strains occurred only at high water temperatures, ordinarily in excess of 70°F. A number of hatchery outbreaks of this type were observed, and it was noted that although many fish were lost when water temperatures ranged from 70 to 75°F., mortalities diminished or ceased when water temperatures were reduced to 65°F. or below. Outbreaks of columnaris disease due to this kind of strain of C. columnaris occurred a number of times at the Samish Hatchery on Friday Creek in western Washington. These strains were considered to be of low virulence since they failed to infect fish unless the fish were scarified or injured by some means to provide a portal of entry.

In sharp contrast to these strains of low virulence, a number of strains of C. columnaris isolated from fish in holding ponds at hatcheries in the Upper Columbia River Basin in postwar years exhibited extraordinarily high virulence. Tested in the experimental hatchery these cultures killed young salmon in less than 24 hours when fish were exposed to dilute cultures and held at 68°F. As an illustration, an experiment performed with a culture isolated from a salmon at the Entiat Hatchery in the late summer of 1951 might be cited. Twenty uninjured chinook salmon and twenty scarified chinook salmon were exposed to a dilute culture of C. columnaris for two minutes, then placed in a trough of running water at 68°F. at 5:00 p.m. one afternoon. By 9:00 a.m. the next morning 39 fish were dead, and one fish was near death. A similar experiment performed with a culture isolated from fish in the Samish Hatchery, though using smaller numbers of fish, led to no deaths in a period of a week in uninjured fish with half of the fish which had been scarified dying of columnaris disease in that period.

Only limited data are available on the virulence of the cultures of C. columnaris which were isolated during the period of the Grand Coulee fish-maintenance project, although it was recognized in this early period that water temperatures played an important role in the disease. Fish and Rucker (1943) showed that uninjured young fish exposed to a particular culture of C. columnaris for 30 minutes and held at 70°F. died in three days. However, only 24 percent of fish which had been exposed similarly and held at 65°F. died in the 38-day period of the experiment. Rucker and Ordal (1944) carried out another experiment on the effect of temperature on the effect of columnaris disease in young salmon. It was found that uninjured fish exposed to a culture died in 72 hours when held at 71.6°F., while 90 percent of the fish held at 68°F., 45 percent of the fish held at 64°F., and 30 percent of the fish held at 61°F. died in a week. Thus the effect of temperature on an infection of young salmon was well recognized, although these cultures were far less virulent than some of the cultures subsequently studied by Rucker, Earp and Ordal (1953). The occurrence of high virulence strains of C. columnaris in the Upper Columbia River Basin and their apparent absence in the waters of western Washington presented an interesting problem and led to the more recent investigations.

In view of the existing data on damage done to populations of fishes by columnaris disease, the question arose as to the significance of columnaris disease to the fisheries resources of the Columbia River Basin, particularly in view of the impending construction of dams which might serve as points of congestion where transmission of columnaris disease might be expedited.

One reasonable hypothesis that might account for the existence of the high virulence strains in the Upper Columbia River Basin was that salmon became infected with ordinary strains of C. columnaris in the Lower Columbia River, and as they migrated upstream an increase in virulence occurred as the result of some genetic process such as mutation in the strains infecting the fish. Higher water temperatures resulting in increased multiplication of C. columnaris would be expected to increase the likelihood of a mutation to higher virulence.

One way in which to explore the problem was to carry out field investigations on the disease in salmon at various locations in the Columbia River Basin and to develop methodology whereby specific strains of Chondrococcus columnaris might be identified. Such an investigation was begun on a small scale in 1954 and carried out through 1959. The most difficult part of the investigation turned out to be the procurement of samples of fish at various locations in the river, since this required availability of facilities for trapping fish and permission and cooperation of agencies such as the Army Corps of Engineers and the State and Federal Fishery Agencies. Sampling was carried out at Bonneville Dam, at McNary Dam, and at Rock Island Dam on the main Columbia River; at Roza Dam, at Prosser, and at Horn Rapids on the Yakima River; at Tumwater Dam on the Wenatchee River; and at Zosel Dam on the Okanogan River. Samples were obtained at these locations when time and the necessary cooperation and availability of trapping facilities made it possible. Since at this time there were no barriers in the Lower Snake River, sampling was carried out in 1955 and 1956 with the cooperation of the Fish Commission of Oregon by use of fyke nets in conjunction with a study of patterns of migration of salmon and steelhead trout in the Snake River.

Fortunately for this investigation there were thermograph records of water temperatures available from approximately 1944 at a number of locations in the main Columbia River and in its major tributaries. These records were available because of the farsightedness of Mr. Kingsley Weber of the U. S. Fish and Wildlife Service and his associates who recognized that water temperature might be an important factor which affects runs of salmonid fishes. Unfortunately for the investigation, the thermographs which had been employed were wearing out, and coincident with the period of the columnaris study, most of them were taken out of service and were not replaced. By 1958 most of the Fish and Wildlife thermographs were out of service, and by 1959 all were removed. Though some water temperatures were taken by other agencies, all records of water temperatures used in the present study were obtained from the Fish and Wildlife Service.

Relatively high water temperatures prevailed in the main Columbia River during the period of the Grand Coulee Salmon Relocation Project. This is illustrated in Figure 1, where mean water temperatures at Rock Island Dam are plotted for the months of June, July, and August for the period 1933 to 1959. Relatively warm water temperatures prevailed during much of the 1939 to 1943 period when upstream migrants were trapped at Rock Island Dam. This situation was followed by a decline in water temperatures until minimum water temperatures for July and August were reached in 1954 and 1955. After these minimums, the temperatures again rose, reaching a secondary maximum in 1958, and then declined rather sharply in 1959.

Water temperatures in the main Columbia River in the summers of 1941 and over the period 1955 through 1959 are given in Figure 2. The water temperature at Rock Island Dam in 1958, the warmest of recent years, approached but remained less than that in 1941. The Snake River becomes warmer than the Columbia River during the summer months. This river normally reaches a temperature of 65°F. late in June and quickly exceeds 70°F. where it remains throughout the summer months. In 1955, an exceptionally cold year, the warm-up was delayed approximately two weeks. The pattern of behavior of the Snake River is given in Figure 3 where 6-day averages of daily maximum water temperatures are plotted for the summer months. The Lower Yakima River and the Okanogan River warm up in a similar fashion, with the warm-up in the Yakima River usually occurring earlier than in the Snake River.

As indicated in Figures 1 and 2, the field investigations from 1954 through 1958 covered a period of increasing water temperatures in the main Columbia River, with a sharp decline occurring in 1959. Particular attention was paid to blueback salmon since the patterns of migration were known and migration occurred mainly in the latter part of June, July and early August. This period also coincided with the time when assistance was available from students at the University.

It is not possible to completely document the findings in the period allowed for this talk. However, it was found during the period 1955 through 1957 that columnaris disease was to all practical purposes absent from salmon and other fishes at Bonneville Dam. In 1956, for example, only two cultures of C. columnaris were isolated from 543 fish examined between July 26 and September 11. In 1957 only one culture was isolated from 140 fish examined in this location. In 1955, when permission to sample fish at Bonneville Dam could not be obtained, approximately 300 scrapfish were taken from the mouths of the tributaries between Bonneville and McNary Dams, and only four cultures of C. columnaris could be isolated from these fish. None of these strains exhibited high virulence. In contrast, the incidence of columnaris

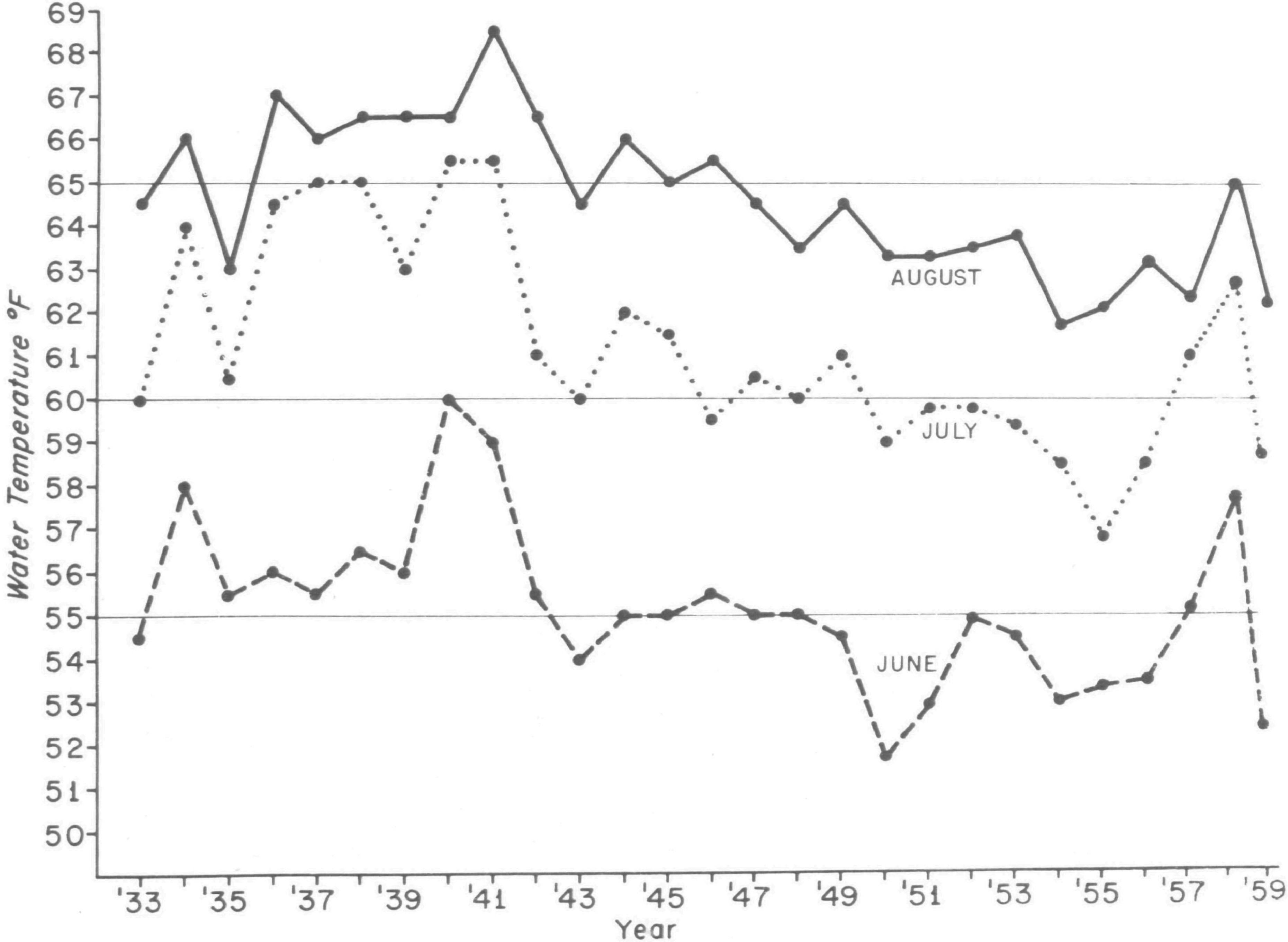

Fig. 1. Columbia River at Rock Island 1933-1959. Mean monthly water temperatures.

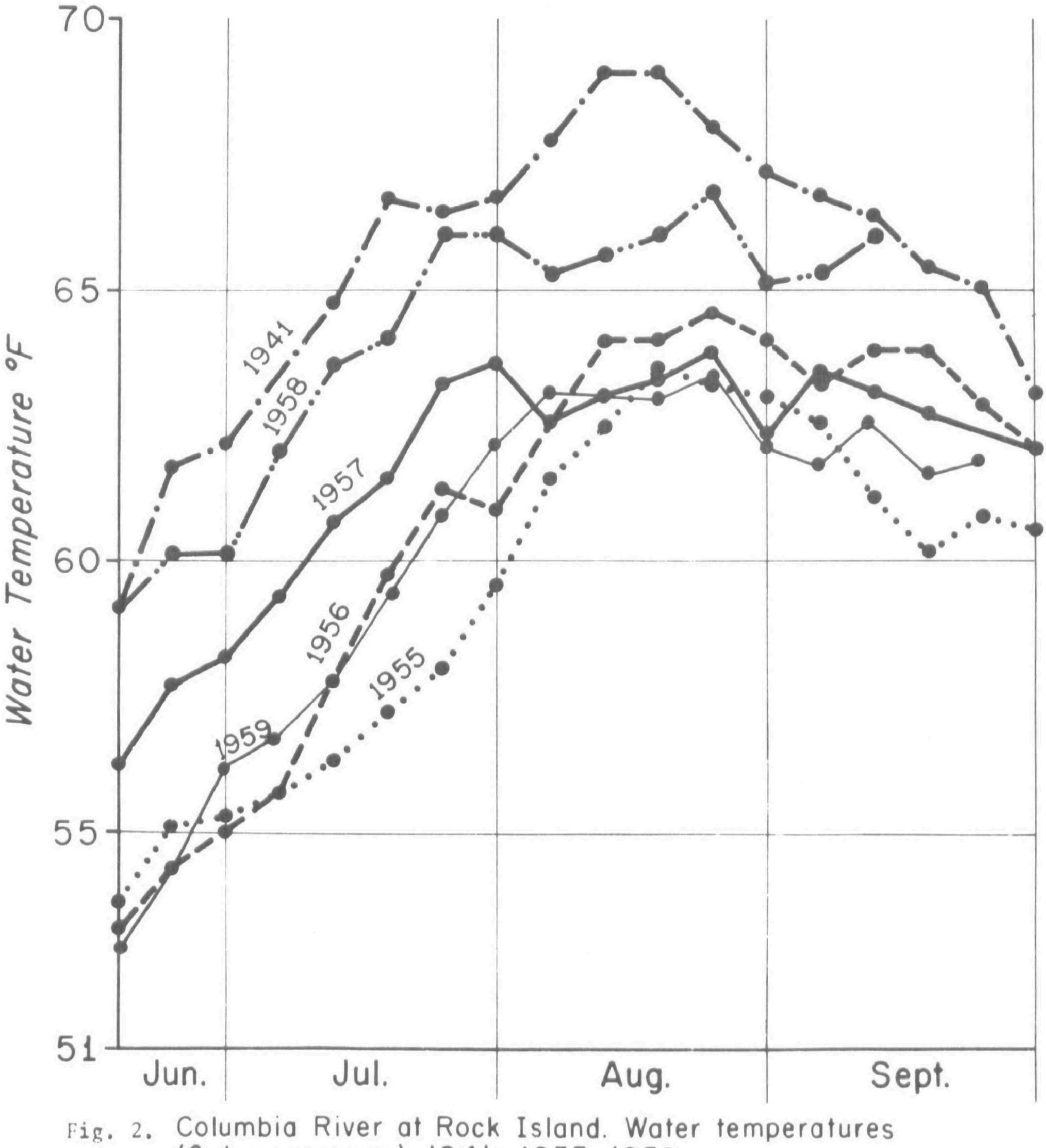

Fig. 2. Columbia River at Rock Island. Water temperatures (6 day averages), 1941; 1955-1958.

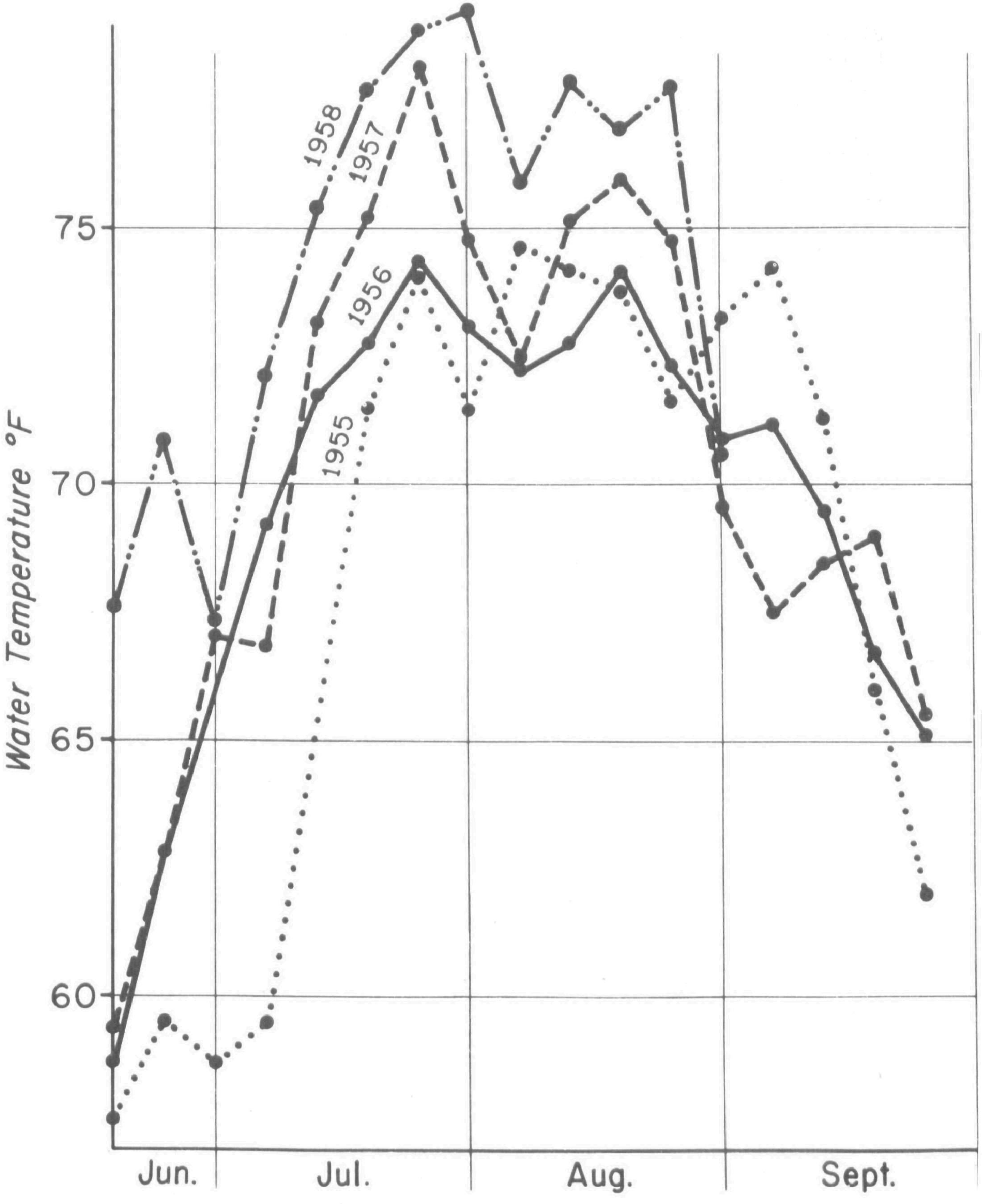

Fig. 3. Snake River at Sacajawea. Water temperatures (6 day averages), 1955-1958.

disease in fish taken in the warm waters of the Snake River near Clarkston in July and early August of 1955 and 1956 ranged from 20 percent to 75 percent in the chinook and blueback salmon sampled by fyke nets operated by the Fish Commission of Oregon. It was subsequently reported by Thompson, et al. (1958) that 34 percent of the blueback salmon captured by fyke nets in the Snake River in 1955 and 50 percent of the fish captured in 1956 exhibited recognizable columnaris disease.

A small run of blueback salmon enters Redfish Lake in Idaho. The number of adult salmon reaching the weir at Redfish Lake during the period 1955 to 1959 is shown in Table 1. It can be seen that the run decreased from 4,361 fish in 1955 to a low of 55 fish in 1958. Evidence obtained by personnel of the Oregon Fish Commission, together with data collected in field studies carried out during this period, suggests that the decrease in fish reaching Redfish Lake was due to mortalities in these fish as a result of infection with columnaris disease. By comparing the temperature data plotted in Figures 1 and 2 with the data presented in Table 1, it can be seen that the decline in fish reaching Redfish Lake is paralleled in an inverse fashion by water temperatures in the main Columbia River. Since the water temperatures of the Snake River rather consistently reached values in excess of 70°F., it would appear from these findings that the water temperatures in the Columbia River below the Snake River junction played a role in determining the incidence of columnaris disease.

Table 1

Counts of Adult Blueback Salmon Crossing the Weir at Redfish Lake*

Year	1955	1956	1957	1958	1959
No. Blueback Salmon	4,361	1,381	571	55	290

*Data from Bjornn (1960)

In this connection, some studies carried out during the summer of 1957 are interesting. In this summer columnaris disease was essentially absent from salmon at Bonneville Dam. When first sampled at McNary Dam July 10 and 11, 1957, 52 blueback salmon were examined; 27 showed lesions characteristic of columnaris disease; 17 pure cultures were isolated from these fish. Eight additional cultures were isolated from other species of fish. Many of the lesions of the blueback salmon were tiny and, therefore, most likely of recent origin. Hence, it seemed probable that these fish had been infected either while in the ladders at McNary Dam, or while massed before the dam. This might account for the relatively high incidence of columnaris disease in the blueback salmon taken from the Snake River, although the development of the disease would, of course, be favored by the high water temperatures in the Snake River.

In 1955, one of the coldest years on record, samples of blueback salmon were taken during the period of migration over Zosel Dam on the Okanogan River. At the very first part of the run the incidence of columnaris disease was 1.5 percent. Near the end of the run the incidence was 42 percent as determined by isolation of pure cultures. As noted before, water temperatures in the Okanogan River during the summer months are comparable to those in the Snake River.

In 1956 only one trip was made to Zosel Dam. This was during the latter part of the blueback run, and 55 percent of the fish taken were found to be infected with columnaris disease. In 1957 columnaris disease was found common even in the early part of the run of blueback salmon. In 1958, an exceptionally warm year, difficulties were experienced in obtaining blueback salmon from the Okanogan River during the normal period of migration; and the run was a failure. However, a large number of blueback salmon were found dead or dying of columnaris disease in the Similkameen River, a cooler tributary of the Okanogan River, where these fish had taken refuge.

From the studies in the Snake River and the Okanogan River it seemed evident that columnaris disease offered a real hazard to salmon in the warmer tributaries, but the evidence indicated that the water temperatures in the main Columbia River represented an important factor in determining incidence and effects of the disease in fish in the tributaries.

Beginning with the 1957 season, more attention was paid to the question of the virulence of the strains of C. columnaris isolated from fishes of the Columbia River watershed, since it was expected that high virulence strains would be more dangerous to salmonid fishes than low virulence strains of C. columnaris. The facilities at the University of Washington had been improved so that it was possible to carry out analyses of virulence on a number of strains.

As noted before, in 1957 columnaris disease was essentially absent from salmonid and other fishes examined at Bonneville Dam. Eight of the 17 strains isolated from blueback salmon at McNary Dam on July 10 and 11, 1957 were analyzed for virulence immediately after isolation, and five of these strains were found to be of high virulence in that they killed young salmon in less than 24 hours when exposed to a dilute culture in water. Sampling at Rock Island was limited to two trips on July 16 and 24, 1957, at water temperatures of 61 and 64°F., respectively. In spite of these relatively low temperatures, 15 pure cultures of C. columnaris were isolated, all from blueback salmon. Since columnaris disease was not found in scrapfish at this location, the blueback salmon must have been infected while downstream. On subsequent analysis for virulence, most of the Rock Island strains were found to be of the high virulence type.

One of the tools employed for the study of columnaris disease in fishes of the Columbia River Basin was a system of serological analysis. This is a method whereby strains of a particular organism can be distinguished from each other. The method is widely used in epidemiological studies on certain diseases of man.

It was found that all strains of C. columnaris had a common or species antigen. This antigen was assigned Arabic numeral 1. Seven additional antigens were found. These were designated by the Arabic numerals 2, 3, 5, 6, 7, 8, and 9. These antigens were present or absent or found present in different combinations in the strains which were investigated.

One useful result of the development of a system of serological analysis was that it was possible to show that wide variations in virulence existed within a given serological type of C. columnaris. This is illustrated in Table 2 where the virulence of a number of different 1957 isolates of C. columnaris containing antigens 1, 3, 8, and 9 are compared.

Codes in this table illustrate the locations in which these cultures were isolated. M is McNary; R is Rock Island; T is Tumwater; O is Okanogan; and BL is Bumping Lake or Tieton Reservoir. The strains were all isolated in 1957, and it may be noted that strains of high virulence belonging to this serological type were isolated at a number of locations. Interestingly enough, the strains of lowest virulence were isolated from the Tieton Reservoir on the Naches River, a body of water which cannot be reached by migrant fish, where a mass epidemic of columnaris disease occurred in kokanees or silver trout at a high water temperature. Large numbers of dead and dying fish were found on the lake or on the shores. Tested in the laboratory, these strains all exhibited low virulence. By present standards, this means strains which failed to kill in four days or failed to kill at all when tested by the contact method, that is, by exposure to dilute cultures of C. columnaris for two minutes and subsequent holding at 68°F. An interesting finding based primarily on the work in 1957 is that high virulence strains occurred in many serological types. As a matter of fact, in 1957 high virulence strains of C. columnaris were found in seven of the serological types which were present in the Columbia River.

The ecological and epidemiological studies on the problem of columnaris disease in fishes of the Columbia River Basin through 1959 have been reported by Ordal and Pacha (1960) and cannot be presented in detail here. However, it was possible to conclude that due to the

Table 2

Variations in Virulence in Strains of C. columnaris of Antigenic Composition 1, 3, 8, 9 and Bacteriocin Type D

Strain	Virulence (Hours for 100% mortality in test fish)
1-M57-22	24
1-M57-29	18
2-M57-27	22
3-M57-5	94+
4-M57-4	139
1-R57-2	22
1-R57-17	22
2-R57-21	20
2-T57-2	16
4-T57-7	114
2-057-20	22
3-057-37	72
1-BL57-1e	222
2-BL57-3a	196
2-BL57-8c	222+

occurrence of high virulence strains of C. columnaris in the Columbia River Basin, columnaris disease has become one of the major factors contributing to the decline of the runs of salmon and steelhead trout. In years of high water temperatures catastrophic mortalities due to Columnaris disease can occur in adult salmon prior to spawning. In colder years, a larger proportion of adult salmon survive to reach the spawning grounds, but carry high virulence strains of C. columnaris, if present in the river, into lakes and streams supporting populations of young salmon and steelhead trout. In light of present knowledge of columnaris disease in the Columbia River Basin, it is probable that the major damage to runs of salmonid fishes as a result of infection by strains of C. columnaris of high virulence is not normally the killing of adult salmon before spawning but rather the killing of young salmon and steelhead trout in the lakes and streams supporting these fish. Salmonid fishes such as blueback salmon, spring and summer chinook salmon, and steelhead trout, all of which normally remain in lakes and streams for a period of a year or more before migrating to sea are therefore particularly susceptible to destruction by high virulence strains of C. columnaris.

That columnaris disease was a serious threat to runs of blueback salmon was evident from the investigations on columnaris disease in the summers of 1957 and 1958. However, in the absence of counts of downstream migration, no data became available on damage to juvenile salmon. As pointed out by Ordal and Pacha (1960) in a report on work supported by the Fish and Wildlife Service, the full impact of columnaris disease could not be determined until the return of the progeny of the 1957 and 1958 runs as adults in 1961 and 1962. That these runs were badly damaged is indicated in Table 3.

Table 3

Adult Blueback Salmon Counts
at Bonneville Dam
1957 to 1963

1957	82,915
1958	122,389
1959	86,560
1960	59,713
1961	17,111
1962	28,179
1963	60,027*

*Counts up to August 1.

Termination of support by the Fish and Wildlife Service for the program of investigation of columnaris disease and its effects on the fisheries resources of the Columbia River Basin left a number of questions unanswered.

Although it was now established that columnaris disease represented a serious threat to natural runs of salmonid fishes in the Columbia River Basin, the question of the source of the strains of C. columnaris, in particular, the high virulence strains, was not yet resolved. The hypothesis that high virulence strains originated from low virulence strains in salmon infected in the lower river during the course of migration was disproved, and the available evidence indicated that the high virulence strains originated in the Columbia River Basin somewhere between McNary and Rock Island Dams (Ordal and Pacha, 1960). Since both the Snake and the Yakima Rivers warm up early in the season, long before the Columbia River, it was considered entirely possible that these might be the source of the high virulence strains. Emphasis in the earlier studies had been on salmon, but the disease had also been found in scrapfish, particularly in scrapfish at McNary Dam during the course of the blueback migration, and in the scrapfish observed in the Lower Yakima River. In colder years, the disease had been found at Rock Island Dam in salmon, but not in scrapfish. Hence, it was considered possible that the disease originated in scrapfish.

In an effort to learn the actual source of the strains of *C. columnaris* infecting fish in the Columbia River Basin, field trips were carried out to the Yakima, Snake, and Columbia Rivers early in 1962 with support from the Atomic Energy Commission. The first trip to the Lower Yakima River was on May 24, 1962, when water temperatures were 59°F. On this trip 63 out of 113 scrapfish obtained at this site showed lesions suggestive of columnaris disease, and pure cultures were isolated from 35 of these fish. During the first three field trips to the Lower Yakima River conducted at weekly intervals when water temperatures ranged from 56°F. to 60°F., 310 fish were examined and 123 pure cultures of *C. Columnaris* isolated from individual fish. Field trips were begun to Ice Harbor Dam on the Lower Snake River on June 7. The water temperature at this time was 53°F. One culture was isolated, but in the following week 13 cultures were isolated at a water temperature of 59°F. In the following three weeks a large proportion of the scrapfish examined showed evidence of columnaris disease. Two cultures of *C. Columnaris* were isolated from scrapfish at McNary Dam on May 31, 1962, when the water temperature was 54°F. At McNary Dam difficulties were experienced in getting fish for examination, and columnaris disease was not found to be widespread until July 11, when 33 pure cultures were isolated from 83 fish examined. Water temperatures on this date were 64°F.

On analysis of virulence of a number of strains of *C. columnaris* isolated at these sites in the earliest part of the season, it was found that cultures of all grades of virulence were present. The presence of low virulence strains in fish taken in the Lower Yakima River, the Lower Snake River, and at McNary Dam at water temperatures ranging from 53°F. to 60°F. indicated that these strains must have originated at some location where warmer water occurred. Such a region might also provide an environment where build-up in virulence could occur through some genetic mechanism since multiplication of bacteria infecting a poikilothermic animal would be favored by higher water temperatures. Since water temperatures at Rock Island Dam on the main Columbia River did not exceed 52°F. over the period May 24 to June 5, 1962, during which 123 pure cultures of *C. columnaris* were isolated from individual fish in the Lower Yakima River, and the water temperatures in the Lower Snake River did not exceed 53°F. during this period, natural waters from these streams could not have been the warmer water in which columnaris disease first developed.

The regions of the Columbia River fed by the warm effluents of the Hanford reactors represent locations where initial infection of fish by *C. columnaris* and build-up of virulence of strains of *C. columnaris* might occur. A second possibility, suggested by personnel of the General Electric Company, is that a number of warm sloughs on the Hanford Reservation may be the areas where initial infection of fish and development of high virulence strains of *C. columnaris* take place.

To obtain evidence on this problem, field studies were instituted in the early spring of 1963 in order to compare cultures isolated from fish in the sloughs on the Hanford Reservation with those from the fish entering the Lower Yakima River. Field studies were begun in the Lower Yakima River on April 9, 1963, at a water temperature of 48.2°F., with the cooperation of Fish and Wildlife personnel, and continued at approximately weekly intervals. Through the cooperation of personnel of the Atomic Energy Commission and the General Electric Company, it was possible to obtain samples of fish, mainly by gill net, from a number of sloughs and ponds on the Hanford Reservation. Sampling was initiated on April 23, 1963, when water temperatures in the sloughs and ponds ranged from 50°F. to 55°F.

As a result of these studies it was found that columnaris disease was far more prevalent and cultures of C. columnaris isolated nearly a month earlier from fish taken in the Lower Yakima River than was the case with fish taken in the Hanford sloughs and ponds. Cultures of C. columnaris were isolated from nine fish taken in the Lower Yakima River on April 24, 1963, at a water temperature of 56.3°F. Over the period April 9 to May 27 a total of 108 cultures of C. columnaris were isolated from 629 fish examined at water temperatures below 65°F. Most of these were scrapfishes though the fish examined included some salmonid downstream migrants. Over the period April 23 to May 16 a total of 605 fish were examined in the sloughs and ponds on the Hanford Reservation. Columnaris disease was not found in these fish. Two cultures of C. columnaris were isolated on May 22, 1963, when water temperatures at the points of sampling ranged from 58.1°F. to 67°F. Over the period April 23 to June 5, 1963, when sampling was temporarily terminated by flood waters in the Columbia River, 849 fish were examined and five pure cultures of C. columnaris obtained.

Though analyses of virulence and of serological type have not yet been carried out, the results of the field investigations in 1963 confirm the findings in the spring of 1962, and it is not possible to avoid the conclusion that the infected fish during the early season enter the Lower Yakima River after exposure to the warm effluents of the Hanford reactors.

At present, the evidence indicates that warm-water-loving fishes or scrapfishes resident in the Hanford area seek the areas of warm water in the Hanford effluents. There is some evidence from studies in western Washington which indicates that scrapfishes carry low virulence strains of C. columnaris over the winter season. Hence, when these fish enter the warmer water these strains may develop and cause infections in the fish. Spontaneous mutation to high virulence may occur during multiplication in warm water, or incorporation of radioactive materials may induce mutations to high virulence. Once infected, it is entirely possible that these fish may seek areas of colder water, and under these circumstances multiplication of low virulence strains may cease whereas the high virulence strains of _C. columnaris_ are capable of attacking and killing fish at lower temperatures. Once high virulence strains of _C. columnaris_ develop, there would be an opportunity of transmission of the disease from fish to fish. Although data on migration patterns of scrapfishes in this area are scanty, the occurrence of columnaris disease in scrapfishes taken in the Lower Yakima and Snake Rivers, and subsequently at McNary Dam, can be accounted for by the fact that as the water rises in the late spring months the fish either seek the calmer waters of the Yakima or Snake Rivers or are swept downstream to McNary Dam where they may accumulate in the ladders and provide a source of infection of migrant salmonid fishes.

In conclusion, there are a number of problems yet to be solved. One is the question of whether the temperature or the radioactivity of the Hanford effluents is responsible for the development of high virulence strains of _C. columnaris_. A second, which should be of importance to experts in fisheries, is to determine whether high virulence strains of _C. columnaris_ survive from year to year in some intermediate host. A third is consideration of the possibility that high virulence strains of _C. columnaris_ are transported to other watersheds by transfer of stocks of salmonid fishes. Finally, consideration should be given to the possibility of lowering the water temperatures of the Lower Snake River by proper construction and operation of dams which are in the planning stage or under consideration. With construction of Lower Monumental Dam and other dams on the Lower Snake River, there will be multiple points of congestion where transmission of columnaris disease to the important runs of salmonid fishes in the Salmon River will be expedited, unless water temperatures are materially reduced during the summer months.

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TEMPERATURE STUDIES ON THE UMPQUA RIVER, OREGON

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The temperature study on the Umpqua River system is an essential part of a comprehensive study now being undertaken for the development of the Umpqua Basin's water resources. Central to the plan of development envisaged by the U. S. Army, Corps of Engineers, the agency responsible for the comprehensive study, are three reservoirs to be located on the South Umpqua River, Cow Creek and Calapooya Creek. Their function is to regulate flows in each of the streams for purposes of flood control, irrigation, municipal and industrial water supply, fish and wildlife enhancement, recreation and water quality control.

One of the problems which needed consideration under the comprehensive plan of development related to stream temperature conditions. Summer temperatures in many of the streams in the Umpqua Basin exceeded tolerable limits for fish life and were unfavorable to the maintenance of water quality. It was therefore recognized that a major function of any proposed development was the control and enhancement of stream temperature conditions. Capability of the proposed reservoirs for exercising such control had therefore to be established. Information was also needed on thermal structure in the reservoirs to enable the planning of outlet facilities for maximum utilization of the thermal stratifications for stream temperature control. Moreover, the improvement of stream temperature conditions had to be determined in order to fully evaluate resulting benefits. Assessment of these benefits was considered essential for determining economic feasibility of the plan of development.

To satisfy these planning needs, temperature evaluations were required to answer the following questions:

1. In what amounts and at what temperatures will water be available in the reservoirs during summer months, the season of critical stream temperature, for average as well as critical water years and temperature years?

2. For given reservoir release rates, from what levels should water be drawn to achieve maximum control of downstream water temperature throughout the entire critical period?

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3. For given release rates and temperatures, what maximum stream temperatures will occur downstream from the reservoir, for average as well as critical years?

A number of Federal and State agencies have been cooperating in carrying out the temperature study, the evaluations and temperature forecasts being the particular responsibility of the State Water Resources Board.

For several reasons the energy-budget method was adopted for making the necessary temperature forecasts. The method is sound theoretically and basic methodology had already been developed. It had been used by McAlister 1/ for temperature predictions on the Rogue River similar to those needed for the Umpqua River. Raphael 2/ had employed the method on reservoirs and rivers in California and Washington. Although there is room for refinement, the method as presently used is expected to yield reasonably accurate results.

The method is based on the identification and evaluation of the energy exchange processes between a body of water and its environment. In the energy-budget equation for the body of water, all the items of energy gain and energy loss are combined into a single algebraic expression. Solution of the equation for any given set of conditions gives the value of energy change of the water and, hence, its temperature change.

The modified energy-budget equation as used for lakes and streams states that for a given interval of time:

$$Q_\theta = Q_s - Q_b - Q_e - Q_h + Q_a$$

where Q_θ = net change in energy in the body of water.

Q_s = net incoming solar radiation.

Q_b = effective back radiation from the water surface.

Q_e = energy loss due to evaporation.

Q_h = energy loss by conduction from water to air.

Q_a = energy advected into the water by tributary streams, precipitation, etc.

1/ Rogue River Basin Study by W. Bruce McAlister, 1961.

2/ Prediction of Temperatures in Rivers and Reservoirs by Jerome M. Raphael, Journal of the Power Division. Proceedings of the American Society of Civil Engineers, July, 1962.

Although the energy-budget equation was known as far back as 1915 when Schmidt used it to estimate the annual evaporation from the oceans, the difficulty in evaluating many of the terms has restricted its application. That the classical energy-budget equation needed modification was established by the exhaustive Lake Hefner Study 1/ carried out in the early fifties. This study also developed information which enabled the evaluation of energy-exchange processes with a greater degree of confidence. Accuracies approaching ± percent were obtained for evaporation from Lake Hefner for periods greater than seven days using the energy-budget method as compared to the water-budget method. Reference will be made later to a verification study which was carried out on the Willamette Coast Fork by the agencies who are participating in the Umpqua study.

The following is a brief description of the terms of the energy-budget equation and the data required to evaluate them:

a. Q_s - Net Solar Radiation

Between sunrise and sunset, the body of water receives energy directly from the sun in the form of short-wave radiation. Of the total radiation incident on the water surface, a small portion is lost by reflection and scattering. The rest of the energy is absorbed by the water and is identified in the energy-budget equation as Q_s, net incoming radiation. Radiation values for Roseburg, which is centrally located, are assumed to be applicable for all locations in the Umpqua River Basin. In the absence of recorded values, average monthly solar radiation for Roseburg is taken from maps prepared by Sternes, adjusted for measured values available for Medford. For the verification of these values, experimental radiation integrators were maintained during the past summer at selected stations. Data obtained has yet to be evaluated.

b. Q_b - Effective Back Radiation

The body of water constantly loses energy through the emission of long-wave radiation. Energy loss is computed by applying the Stefan-Boltzmann radiation law, using an emissivity factor of 0.97. A constant gain in energy occurs through the absorption of long-wave radiation emitted by the atmosphere. Atmospheric radiation received at the water surface is also expressed in terms of the Stefan-Boltzmann law, but includes an atmospheric radiation factor to allow for vapor pressure

1/ Water Loss Investigations: Lake Hefner Studies, Technical Report, Geological Survey Professional Paper 269, 1954.

and cloud cover. It is estimated that only 97 percent of this radiation is absorbed by the water.

Expressions for energy exchanges through long-wave radiation are usually combined into one which gives the effective back radiation. Under certain circumstances, however, the exchange will result in a net gain in energy to the body of water.

The equation is as follows:

$$Q = 0.97\sigma(T_w^4 - T_a^4)\ \theta$$

where Q_b = effective back radiation

σ = Stefan-Boltzmann constant

T_w = absolute temperature of the water

β = atmospheric radiation factor

T_a = absolute temperature of air

θ = time

c. Q_e - Energy Loss Due to Evaporation

The evaporative process removes energy from the body of water in the form of latent heat of vaporization, the loss being identified by the term Q_e. This loss of energy is computed by means of an empirical equation which was found to agree with data collected at Lake Hefner.

The equation for lakes and reservoirs is as follows:

$$Q_e = 0.34\ U(e_w - e_a)\ \theta$$

where Q_e = energy loss in Btu/ft^2

U = wind speed in miles per hour

e_w = vapor pressure of water in saturated air at the temperature of the water surface, in millibars

e_a = vapor pressure of water in air, in millibars

θ = time in hours

This equation also gives the energy gain due to condensation. When applied to streams, a coefficient of 0.57 is used instead

0.34, to allow for the higher rates of evaporation from streams.

d. Q_h - Energy Transfer by Conduction

Conduction of sensible heat occurs between the body of water and the air whenever a temperature difference exists between them. The rate of conduction depends upon the temperature differential and the wind velocity. Energy change is identified in the energy-budget equation by the term Q_h. Values are determined with the aid of the Bowen Ratio, which gives a relationship between loss of energy from evaporation and the loss from conduction. This ratio, combined with the expression for the energy loss by evaporation, states that:

$$Q_h = 0.138 \ U(t_a - t_w) \ \theta$$

where Q_h = Energy transferred by conduction in Btu/ft^2

U = Wind in miles per hour

t_a = Temperature of air in degrees Fahrenheit

t_w = Temperature of water in degrees Fahrenheit

θ = Time in hours

The constant 0.138 allows for barometric pressure which is assumed for the Umpqua Basin to remain constant at 29.5 inches of mercury during summer months.

e. Q_a - Advected Energy

When water is added to a reservoir or stream, the energy contained in that body of water is increased by the energy content of the added water. Similarly, water removed causes a decrease in the energy content of the lake or stream. Energy change by this process is referred to as advected energy and is represented in the energy-budget equation as Q_a. Quantities and temperatures of inflow and outflow are required to compute this term.

Data Sources and Analysis

The energy-budget method may well be criticized for its excessive data requirements. Extensive meteorologic, hydrologic and other physical data are required before the energy-budget equation can be resolved for a given reach of stream for a specific period.

Data for the Umpqua River study was obtained from a number of agencies, both from published and unpublished records. Where needed information was not available it was secured through special studies which were undertaken. Data was collected and processed as follows:

A. Meteorology

1. Solar Radiation

Average solar radiation for Roseburg was obtained from Sternes radiation maps of Oregon. Values were adjusted with the aid of Weather Bureau records for Medford, the nearest pyrheliometer station to Roseburg. Average net daily values corrected for reflected solar radiation were computed for 10-day periods. One-half of the daily radiation was assumed to occur between 0700 and 1200 hours and the other between 1200 and 1700 hours. Data was collected during the summer from experimental radiation integrators consisting of relatively small insulated pots containing water. Two of these integrators were located at pyrheliometer stations at Medford and Corvallis while three were located in the Umpqua Basin, at Roseburg, Tiller and Riddle. The data collected, which has not yet been evaluated, is expected to provide verification of radiation values adopted for the Umpqua Basin.

2. Solar Altitude

Mean altitude of the sun was determined for each ten-day period from declination values taken from the solar ephemeris corrected for the latitude at Roseburg. Daily average was obtained by multiplying the mean altitude by 0.75.

3. Sky Cover

Mean sky cover at Roseburg was obtained from Weather Bureau records, which gave the information in tenths of sky covered for the period between sunrise and sunset. These values were assumed to hold for the period from midnight to midnight. Values were average for ten-day periods.

4. Relative Humidity

Relative humidity at Roseburg was taken from Weather Bureau records, and mean values were determined for the periods 0000-0700, 0700-1200, 1200-1700 and 1700-2400 hours for each ten-day period.

5. Mean Winds

Mean wind speeds for Roseburg were taken from Weather

Bureau records. Values in miles per hour were tabulated for periods identical with those adopted for relative humidity values.

6. Air Temperature

Using Weather Bureau records for Roseburg, average air temperature values were determined for the hours 0000-0700, 0700-1200, 1200-1700, and 1700-2400. A set of values was obtained for each ten-day period.

7. Barometric Pressure

Barometric pressure for Roseburg was taken from Weather Bureau records.

8. Evaporation

A pan evaporation station was set up at Roseburg in co-operation with several agencies and data was collected during the past summer.

Tables containing meteorological and other data were prepared in a form convenient for making energy-budget computations. Table 1 is one such table.

B. Reservoirs

1. Streamflow

Streamflow data for the reservoir sites was obtained from U. S. Geological Survey, Water Supply Papers.

2. Pool Elevation

Depth-capacity curves prepared by the U. S. Army, Corps of Engineers, reservoir inflow rates taken from U.S.G.S. Water Supply Papers and reservoir release rates specified by the Corps of Engineers enabled monthly pool elevations to be estimated.

3. Water Surface Area

Monthly water surface areas were determined from Corps of Engineers' area-capacity curves and estimated pool elevations.

TABLE 1

METEOROLOGICAL DATA

PERIOD			Q_s*	β	e_a	U	t_a
Month	Day	Hour	Net Solar Radiation BTU/ft²	Atmospheric Radiation Factor	Mean Vapor Pressure mb	Mean Wind Velocity mph	Mean Air Temperature °F
JUNE	1-10	0000-0700	0	.86	12.5	3	53
		0700-1200	990	.85	12.4	6	64
		1200-1700	990	.86	13.6	10	72
		1700-2400	0	.86	13.4	6	61
	10-21	0000-0700	0	.86	12.3	3	54
		0700-1200	1040	.86	12.4	6	65
		1200-1700	1040	.86	12.7	11	73
		1700-2400	0	.86	13.4	6	62
	21-30	0000-0700	0	.84	12.7	3	55
		0700-1200	1090	.84	12.6	8	66
		1200-1700	1090	.84	12.9	12	76
		1700-2400	0	.84	13.3	7	64
JULY	1-10	0000-0700	0	.82	12.3	2	55
		0700-1200	1170	.83	13.3	6	69
		1200-1700	1170	.83	13.0	12	81
		1700-2400	0	.83	13.1	6	66
	10-21	0000-0700	0	.83	13.1	3	57
		0700-1200	1090	.83	14.2	7	71
		1200-1700	1090	.83	13.9	12	86
		1700-2400	0	.83	13.8	6	69
	21-31	0000-0700	0	.82	12.6	3	57
		0700-1200	1110	.82	13.6	8	72
		1200-1700	1110	.81	12.2	14	87
		1700-2400	0	.82	13.3	7	70
AUGUST	1-10	0000-0700	0	.82	11.9	3	54
		0700-1200	970	.83	13.0	7	70
		1200-1700	970	.83	12.7	12	83
		1700-2400	0	.83	12.8	6	68
	10-21	0000-0700	0	.83	12.1	2	54
		0700-1200	890	.83	13.0	7	68
		1200-1700	890	.83	11.9	12	82
		1700-2400	0	.84	13.1	7	67
	21-31	0000-0700	0	.83	11.8	3	53
		0700-1200	860	.84	13.0	7	68
		1200-1700	860	.83	12.2	12	80
		1700-2400	0	.84	12.9	6	65

* Total daily solar radiation is divided equally between the two daylight periods.

4. Inflow Temperature

Temperature of reservoir inflow was taken from records of hydrothermographs stationed at the reservoir sites.

C. Streams

1. Streamflow

U.S.G.S. Water Supply Papers provided flow data based on gaging records. Flow in ungaged tributaries was estimated on the basis of drainage areas and unit yield rates.

2. Water Temperature

Stream temperature data was taken from hydrothermograph records. Instruments were located on the principal streams in the Umpqua Basin, the earliest installations taking place in 1960.

3. Time of Travel

Time of travel was determined in the field for three discharge values for each stream except Calapooya Creek. Only one determination was made for this stream. Discharge values were selected for damsites to represent, as far as possible, the range of reservoir releases adopted for the temperature study. Travel time was measured with the aid of a tracer technique. A fluorescent dye, Rhodamine-B, was introduced into a stream at a known time and point of introduction and the time taken by the dye to reach downstream points was observed. Sampling was done at these points with a fluorometer. Stream gaging measurements were carried out simultaneously so that travel time was related to stream discharge for every reach. A plot for each of the reaches was then made of travel time versus discharge. From these plots travel time values were taken for stream discharge rates equal to reservoir release rates adopted for the study. These values enabled curves to be drawn of elapsed time versus stream miles for constant discharge rates equal to reservoir release rates. Figure 1 illustrates curves plotted for the South Umpqua River for the discharge rates of 700, 1200, and 1600 cubic feet per second.

4. Water Surface Area

Water surface areas were determined for each river mile from a number of aerial photographs taken at different times. With the aid of U.S.G.S. Water Supply Papers pertaining to

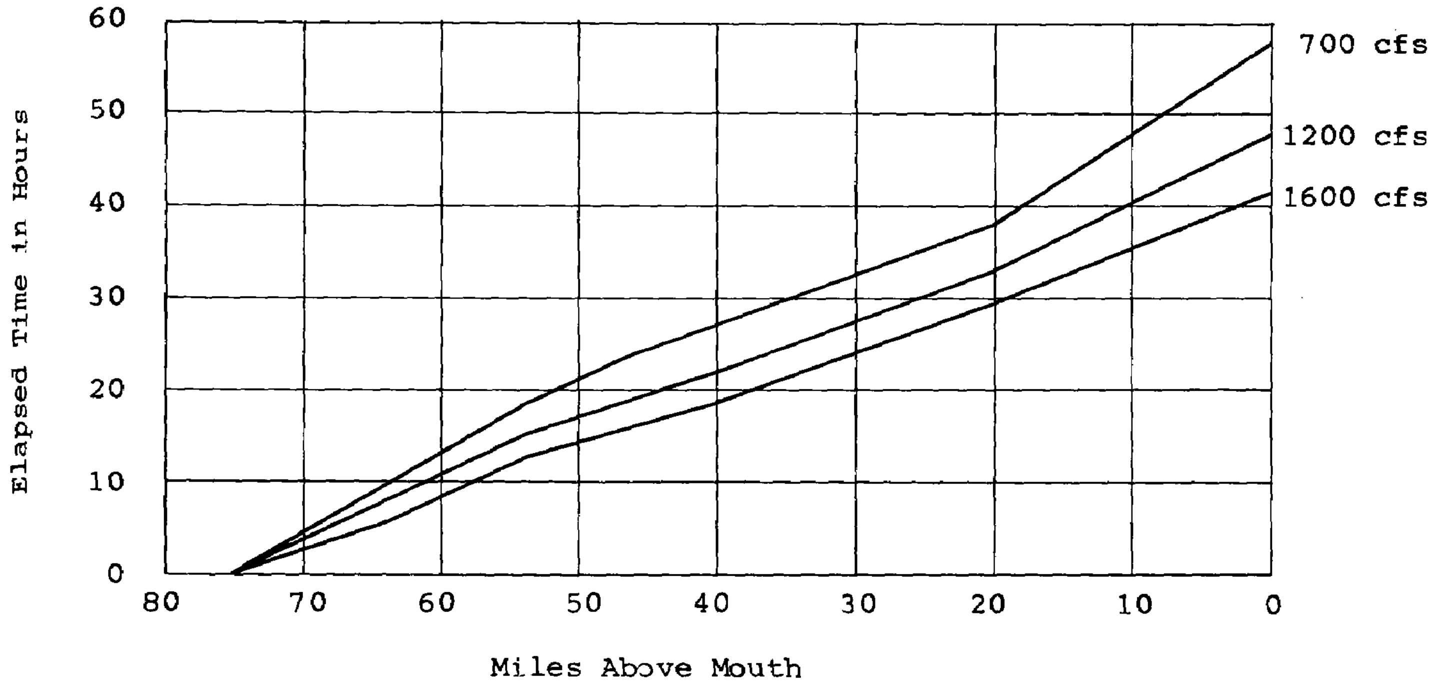

FIGURE 1 - Time of Travel of South Umpqua River

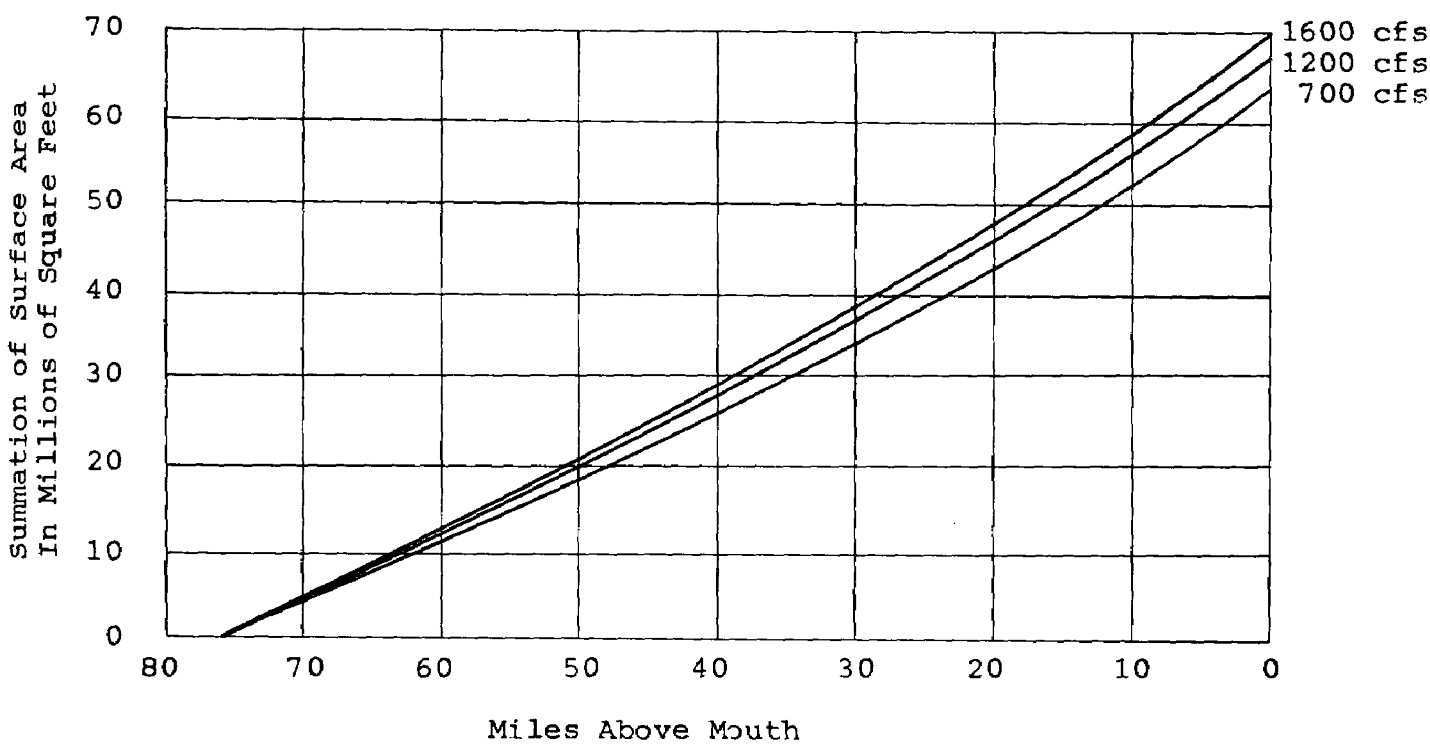

FIGURE 2 - Water Surface Area of South Umpqua River

the time of each photograph, stream discharge values were estimated for each river mile to correspond with each surface area determination. Plots were made for each river mile of surface area versus discharge. From these plots, surface area values were taken off for the constant stream discharge rates adopted for the study. Curves were then drawn of cumulative water surface area versus stream mile. Figure 2 illustrates the curves prepared for the South Umpqua River.

Reservoir Temperature

Temperature analysis of reservoirs required a knowledge of their physical characteristics and method of operation. The proposed reservoirs were relatively deep, depths at full pool being 380, 210 and 220 feet respectively for Tiller, Galesville and Hinkle reservoirs. Annual regulation cycle called for evacuation in the fall to provide storage space for flood control. Reservoirs were to be filled during winter and spring, the period of minimum stream temperature, and were expected to attain full pool elevations by the end of spring. During summer, reservoirs were to be evacuated, withdrawals being made from zones of relatively cool water for purposes of stream temperature control.

Very little is known about changes in thermal conditions within deep reservoirs, particularly when operated for modification and control of stream temperature. Several assumptions had, therefore, to be made in undertaking temperature evaluations for reservoirs in the Umpqua Basin. At the beginning of summer, each reservoir was assumed to have a constant temperature throughout, with the exception of the surface layer, which will be discussed presently. With the advance of summer, the development and downward movement of thermoclines were assumed. Validity of this assumption is borne out by records available for comparable reservoirs.

Two factors were recognized as the primary causes of reservoir temperature changes during summer months. They were:

1. Energy exchange processes identified in the energy-budget equation; and

2. Evacuation of water from selected elevations in the reservoir.

Analysis of these two factors, therefore, formed the basis of temperature determinations in the Umpqua reservoirs. Thermal conditions were determined for each of the summer months for various reservoir depths, for selected meteorologic and hydrologic conditions and for selected withdrawal schedules.

Evaluation of the energy-budget equation required a knowledge of reservoir surface temperature. No temperature values were available for similar reservoirs that would have served as a guide. In arriving at a reasonable assumption, it was argued that, because of the slow rate of heat transfer by conduction, reservoir surfaces responded directly to meteorological conditions regardless of reservoir depths. From the temperature standpoint, the surface layer of a reservoir was, therefore, assumed to be analogous to a shallow pond exhibiting no thermocline characteristics. Temperature in such a body of water is known to be ambient, following the diurnal meteorologic cycle. Surface temperatures of the reservoirs were, therefore, assumed to correspond to the ambient temperatures of shallow ponds subject to the same meteorological conditions. This assumption was not expected to cause any significant errors in energy-budget computations for reservoirs. In the absence of temperature observations for shallow ponds in the Umpqua Basin, values were taken from hydrothermograph records for Cow Creek where thermal conditions, in the summer, were known to approximate those governing ponds.

Gain in energy for the reservoir was determined for each ten-day period by the energy-budget equation. Computations were made on the basis of the four elements into which a 24-hour period was divided so as to allow for the diurnal cycle. A sample computation is given in Table 2. Energy gain for each month was obtained by totaling the gains for the appropriate ten-day periods.

Reservoir gain in energy for each of the months of June, July, August and September was then distributed within the reservoir by depth so that resulting temperature-depth curves were comparable to curves available for certain western Oregon reservoirs. A trial-and-error procedure was adopted for this purpose. Changes in reservoir thermal structure resulting from the energy exchange processes at the surface were thus determined. A typical temperature-depth curve is illustrated in Figure 3 which shows average thermal conditions in Tiller Reservoir at the beginning of July.

Modifications to thermal structure resulting from reservoir withdrawals were determined by a simple procedure. Water withdrawn from a certain elevation was assumed to be at the temperature prevailing at that elevation at the time of withdrawal. Knowledge of the quantity and temperature of water withdrawn during each of the summer months permitted the correction of temperature-depth curves, which had been prepared as described in the previous paragraph. The procedure is illustrated in Figure 4. The modified temperature-depth curve for a given month, used in conjunction with the capacity-depth curve for the reservoir, enables determination of the quantity and temperature of water available in storage for temperature control during the following month.

TABLE 2

ENERGY BUDGET COMPUTATION
FOR TILLER RESERVOIR
Period July 1 - 10

TIME		0000-0700	0700-1200	1200-1700	1700-2400	0000-2400
(for ten days)	hours	70	50	50	70	240
RESERVOIR						
Volume	ac. ft.	350,000	350,000	350,000	350,000	350,000
Surface Area	acres	2,850	2,850	2,850	2,850	2,850
Inflow	ac. ft.	580	420	420	580	2,000
Release	ac. ft.	3,500	2,500	2,500	3,500	12,000
TEMPERATURE						
Inflow	° F	61	61	66	66	
Release	° F	45	45	45	45	
t_w (Surface)	° F	70	69	72	74	
SOLAR RADIATION						
Q_s (Table 1.)	BTU/ft^2	0	1,170	1,170	0	23,400
LONG WAVE RADIATION						
t_w (Surface)	° F	70	69	72	74	
t_a (Table 1.)	° F	55	69	81	66	
B (Table 1.)	%	82	83	83	83	
θ	hours	70	50	50	70	
Q_b	BTU/ft^2	2,770	1,105	745	2,065	6,685
EVAPORATION						
U (Table 1.)	mph	2	6	12	6	
e_w	mb	25.0	24.2	26.7	28.6	
e_a (Table 1.)	mb	12.3	13.3	13.0	13.1	
θ	hours	70	50	50	70	
Q_e	BTU/ft^2	1,015	1,865	3,905	3,710	10,495
CONDUCTION						
U (Table 1.)	mph	2	6	12	6	
t_a (Table 1.)	° F	55	69	81	66	
t_w (Surface)	° F	70	69	72	74	
θ	hours	70	50	50	70	
Q_h	BTU/ft^2	290	0	-745	465	10
ENERGY GAIN						
$Q_s-Q_b-Q_e-Q_h$	BTU/ft^2					6,210
$Q_s-Q_b-Q_e-Q_h$ (for entire res.)	OTU*					283,000
ADVECTED ENERGY						
Inflow	ac. ft	580	420	420	580	
Inflow Temp.	° F	61	61	66	66	
Q_a (from inflow)	OTU	10,820	12,180	14,280	19,720	63,000
Release	ac. ft	3,500	2,500	2,500	3,500	
Release Temp.	° F	45	45	45	45	
Q_a (from release)	OTU	-45,500	-32,500	-32,500	-45,500	-156,000
Q_a (net)	OTU					93,000
TOTAL ENERGY GAIN						
Q_θ	OTU					190,000

* OREGON THERMAL UNIT = Quantity of heat required to raise one acre-foot of water 1° F.

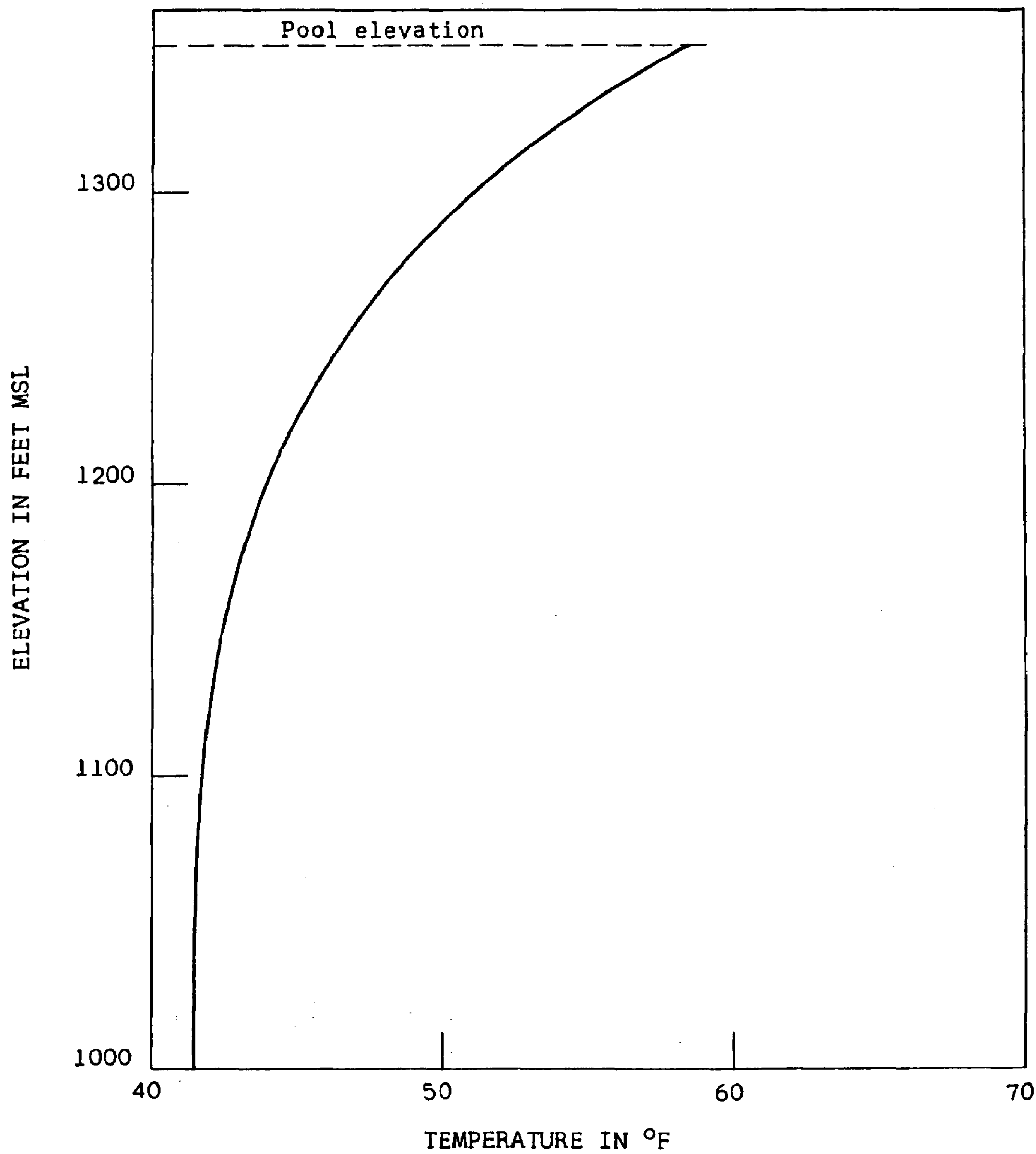

FIGURE 3. Estimated temperature gradient of Tiller Reservoir for July 1st.

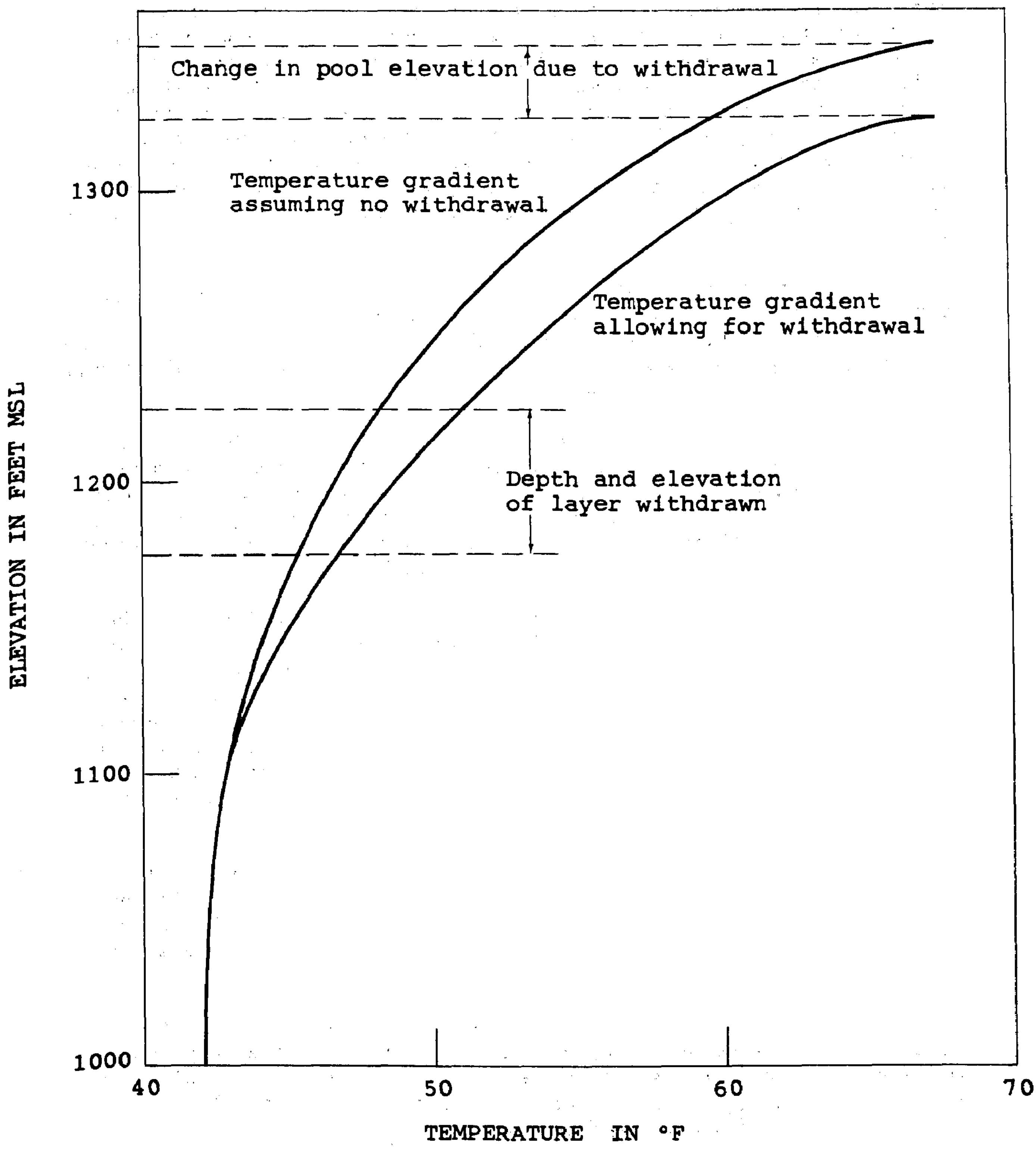

FIGURE 4. Effect of reservoir withdrawal upon temperature gradient.

Stream Temperature

Computational procedure for streams differed in some respects from that used for reservoirs to allow for differences in their physical characteristics. For a stream, it was necessary to determine maximum and minimum daily temperatures of parcels of water from the moment they left the reservoir to the time they reached the mouth of the stream. Energy exchange processes had, therefore, to be evaluated for relatively short periods so that the response of the stream to diurnal variations of meteorological influences was accurately ascertained. Allowance had to be made for stream velocity and changes in stream width since they determined the period and areal extent of exposure of the body of water moving downstream.

To satisfy these requirements and yet keep the number of energy-budget computations to a minimum, the following time intervals were adopted: 0700-1200, 1200-1700, 1700-2400 and 2400-0700 hours. The end of the second period marked the point of maximum daily temperature while the end of the fourth coincided with the minimum.

Certain assumptions were made in evaluating energy changes for streams. One was that thermal gradients were absent due to complete mixing of the water. Streambeds and banks were assumed to have no influence on the water temperature. Energy contributions by thermal discharges, biological and chemical processes and the conversion of kinetic energy to thermal energy were disregarded as being minor.

Stream temperatures were determined for summer months only, the period of critical temperature. The procedure is illustrated in Table 3 which shows the evaluation of the various terms in the energy-budget equation for a specific case. The example deals with a hypothetical discharge of 1200 cubic feet per second from Tiller Reservoir entering the South Fork Umpqua River at 0700 hours. A probable gain in temperature of 5.7°F. is indicated by the computation, when temperature of water released is 45°F. and meteorological conditions are those normally encountered during the period July 1 to 10.

With the aid of specially prepared nomographs and tables, it was possible to expedite the procedure illustrated in Table 3. Reference should also be made to a computer program set up at Oregon State University as part of this study for solving the energy-budget equation for streams.

Table 3 indicates that the average water temperature, for the reach of river being analyzed, has to be estimated at the very commencement of the analysis. This temperature is needed for evaluation of the terms Q_b, Q_e and Q_h in the energy-budget equation. In cases where the computed average differs substantially from the estimated value, the energy-budget computation is repeated, using a new esti-

TABLE 3

ENERGY BUDGET COMPUTATION
FOR SOUTH UMPQUA RIVER

STREAM SECTION	
Beginning River Mile	77.0
Ending River Mile (from Figure 1).	69.0
PERIOD	
Month	July
Day.	1st - 10th
Hour	0700 - 1200
θ	5 hrs
DISCHARGE	
Q (average for Stream Section).	1200 cfs
TEMPERATURE	
Initial.	45°F.
t_w (estimated average for section)	48°F.
SOLAR RADIATION	
Q_s (Table 1)	1170 BTU/ft^2
LONG WAVE RADIATION	
t_w	48°F.
t_a (Table 1)	69°F.
β (Table 1)	83%
θ	5 hrs
Q_b	14 BTU/ft^2
EVAPORATION	
U (Table 1)	6 mph
e_w	11.3 mb
e_a (Table 1)	13.3 mb
θ	5 hrs
Q_e^*	-34 BTU/ft^2
CONDUCTION	
U (Table 1)	6 mph
t_a (Table 1)	69°F.
t_w	48°F.
θ	5 hrs
Q_h	-87 BTU/ft^2
TOTAL ENERGY GAIN	
Q_s	1170 BTU/ft^2
Q_b	14
Q_e	-33
Q_h	87
Q	1277 BTU/ft^2
TOTAL TEMPERATURE GAIN	
Q	1277 BTU/ft^2
A (Figure 2).	6.7 x 10^6 sq ft
Q	1200
θ	5 hrs
Δt	5.7°F.
FINAL TEMPERATURE.	50.7°F.

* Q_e in this case is energy gain due to condensation

mated value. In the example shown in Table 3, the assumed average of 48°F. is in close agreement with the computed average of 47.8°F.

Table 3 shows further that the value of Q_t is determined firstly for a water surface of unit area, in this instance a square foot. This value is then applied to the surface area of the reach of stream under analysis, 6.7×10^6 square feet in the example. The final temperature in one reach, 50.7°F. in Table 3, is taken as the initial temperature for the next lower reach.

In the Umpqua River studies, temperatures were computed for reservoir releases occurring at 0700, 1200, 1700 and 2400 hours. For each stream, computed temperatures were plotted against river miles and curves drawn connecting maximum and minimum points, respectively. These curves were taken as the limits of the diurnal temperature range for the particular conditions considered. It is proposed to develop such curves for three discharge values and an appropriate range of initial temperatures with respect to each of the three reservoirs. Curves are to be plotted for average as well as critical years for each ten-day period from June 1 to August 31. These evaluations have been held in abeyance until field data collected this summer becomes available.

As mentioned earlier in the paper, a verification study was undertaken on the Willamette Coast Fork. The purpose of the study was to determine the reliability of methodology adopted for temperature analysis of streams. Preliminary evaluations of data gathered for the Willamette Coast Fork indicated close agreement between computed and observed stream temperatures during the day. At night, observed values were less than computed values. The study demonstrated the reliability of the method, at least for the meteorological and other conditions experienced during the study.

There is considerable room for improvement in the energy-budget methodology as currently used for both reservoir and stream temperature determinations. A simplification in computational procedure, which will reduce man-hours without sacrificing accuracy, is particularly needed. Current knowledge on evaporation from streams and on surface temperatures in reservoirs appears to be inadequate for precise temperature determinations. The need exists for an expansion in the collection and publication of meteorological data required for energy-budget studies.

Acknowledgements

The guidance and inspiration received from Malcolm H. Karr, Chief Engineer of the State Water Resources Board of the State of Oregon, under whose supervision the Umpqua Temperature Studies were carried out, and the loyal cooperation of Robert T. Evans and Bruce A. Tichnor, who assisted in the computations, are gratefully acknowledged.

DISCUSSION

Q. Do you feel that stream turbulence may have any effect on evaporation?

A. Yes, because most of our equations have been obtained from lakes and the lakes, in general, may be fairly placid and of a given surface area. We feel that the river, in general, is quite turbulent, having a very rough surface; in fact, most of our streams on the West Coast are for large distances white-water rivers and we feel that the extra surface area which is involved here will be a considerable factor in increasing the evaporation above and beyond what is presently being estimated.

Q. How do you justify the use of solar radiation data from only one point when you are considering a whole basin or a length of stream maybe 70 or 80 miles long?

A. Solar radiation is a function of cloud cover. The solar radiation hitting a latitude would be constant, if the sky were clear. We felt that, in the Umpqua Basin, Roseburg is centrally located in the area that we are considering, and it would provide us with an average value that could be attainable with the degree of accuracy that we are aiming at.

Q. Do you believe that the use of pyrheliometers would be advantageous in the collection of solar radiation data to supplement the readings at only one point in the basin under investigation?

A. We have had some experimental radiation integrators installed in a number of places. They are, you might say, modified Cummings radiation integrators--small insulated pots. One is located in Corvallis alongside a pyrheliometer and another one at Medford, also alongside a pyrheliometer, and we have a few scattered in the Umpqua Basin. Unfortunately, we have not yet evaluated this data, but we hope that this will give us an indication of whether our assumption or our adopted practice of using the Roseburg values are adequate.

TEMPERATURE PHENOMENA AND CONTROL IN RESERVOIRS

Jerome M. Raphael*

Abstract

The variation of temperature in reservoirs with time and with distance from the surface can be predicted with confidence, using a heat-budget approach, if proper account is taken of the varying influences of meteorological phenomena, the geometry of the reservoir, the position of the outlets, and the volume of the inflow and outflow. The reservoir can be considered to be made up of a number of horizontal layers each having the average temperature of the portion of the temperature gradient in that layer. Heat moves into and out of the layer chiefly by means of water transported into and out of the layer. Some heat is transferred between layers by conduction, which is another way of saying molecular diffusion, but this amount is physically so small in comparison with the amount of heat moved by mass transfer that it can safely be neglected in any engineering computation.

In the typical reservoir, water leaves the reservoir through an outlet works or penstock. The water that leaves the reservoir is drawn not only from the layer directly in line with the outlet, but also to some extent from layers above and below. Any water drawn from a low elevation must be replaced by waters from layers above, and in this manner heat is transferred downward from the surface to lower-lying layers. Water flowing into the reservoir at a given temperature is considered to dive down beneath warmer and lighter layers until it hits a colder layer, and then to mix with this layer.

At the surface itself, a tremendous amount of heat is transferred. The primary agent here is solar radiation. Incoming short-wave radiation is attenuated by passage through the atmosphere, and diminished by clouds and reflection from the surface of the reservoir. The amount of incoming radiation is dependent upon the hour of the day, the day of the year, and the altitude and latitude of the reservoir. The warmed water surface radiates heat to outer space as long-wave radiation and the atmosphere likewise radiates to the surface of the reservoir as long-wave radiation. The net interchange of long-wave radiation is termed effective back radiation and is generally net radiation to space. Some heat is lost from the surface of the reservoir by evaporation, which is affected by the vapor pressure of the atmosphere, the wind velocity and the temperature difference between water surface

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and the air. Some heat is gained from the atmosphere by direct conduction between air and water. And finally, some heat may be gained directly from rainfall.

In an engineering calculation of these surface temperature effects, a finite surface layer must be considered. Experience in swimming in deep lakes has shown the great temperature differences between the water at the immediate surface and that lying only a few feet beneath the surface. However, it can readily be visualized that this daytime phenomenon must change greatly at nighttime. As air temperature decreases, there will come a time when the surface skin of water is cooler than the air. Thus the surface itself is cooled to a temperature slightly less than the water immediately below it. Being heavier, this water sinks through the warmer water and the warmer water is in turn cooled at the surface. Thus, there are set up local convection currents which tend to stabilize a finite layer of water of nearly uniform density at the surface. In calculations made using data obtained at Shasta Reservoir, temperatures computed using a 10-foot surface layer corresponded most closely to temperatures measured at the reservoir. Use of a thinner surface layer gave temperature fluctuations which did not seem representative of those measured. Thus, a 10-foot surface layer has been utilized in a number of predictions of reservoir temperature.

Time intervals for these predictions should be as short as practicable if detail is needed of maximum and minimum temperatures. With 3-hour intervals, diurnal variations are easily shown. With daily intervals, detail is lost, but averages are easily obtained for gaging the effect of various operating criteria on the temperature of the reservoirs.

Recognition of temperature as a parameter of water quality is so recent a phenomenon that there are only a few engineering works designed to deliver water at a predetermined temperature. These usually involve either a number of outlets at different elevations in a dam, or a device that can be used to mask off all inflow except that from an elevation in the reservoir at the desired temperature. It must be recognized that as a corollary to this it is necessary to have practically continuous monitoring of the variation of temperature with depth in the reservoir in order to be able to determine the quantities of water to draw at various elevations.

METHOD OF COMPUTING AVERAGE RESERVOIR TEMPERATURE

Peter B. Boyer*

On Reservoir Temperatures

Introduction

Recent emphasis on the effect of water temperature on fish, irrigation, and recreation led the Portland District, Corps of Engineers to the examination and study of reservoir and river temperatures and related data. The study is continuing, but sufficient progress has been made to report on the analysis and results. Specifically, this report discusses the procedure used for reproducing or determining the month-end average reservoir temperatures. Essentially, the method consists of solving a "heat-storage" equation, known also as "heat-balance" and "energy-budget". The equation is employed as a guide in keeping an inventory of the basic data, assumptions, appraisals, and computations. The terms of the equation are defined by the ordinarily observed meteorologic factors. All work is conveniently arranged, symbolized, and referenced in Table 1.

Observed Reservoir Temperatures (Detroit and Lookout Point Projects)

Since 1954, Portland District, U. S. Corps of Engineers has been reading thermohms, installed on the upstream face of Detroit and Lookout Point Dams, to obtain general information on the reservoir temperature and specifically on the temperature of water entering the powerhouse intake. The temperatures are recorded daily from August 1 to November 15 and weekly during the remainder of the year, between the hours of 4 and 8 p.m. For this study, it is assumed that the water temperature at a thermohm equals that at the same level in other parts of the reservoir. 1/ The observed temperatures for 1958 are plotted in three different forms, shown by Figures 1, 2, and 3. The patterns are typical of other years. Examination of the patterns reveals the following temperature characteristics in Detroit and Lookout Point Reservoirs:

* U. S. Army, Corps of Engineers, Portland District, Portland.

1/ Dorena Reservoir is also equipped with thermohms at 10 feet apart. However, water temperatures were observed only during 1951 and 1952.

TABLE 1. REPRODUCTION OF 1958 MONTH-END AVERAGE RESERVOIR TEMPERATURES, DETROIT PROJECT, OREGON

By Heat-Storage Equation: $T_2 = (S_1T_1 + I\ T_1 - O\ T_o + 0.03\ A\ H)\ /S_2$

LINE	SYMBOL	ITEM	UNIT	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	REMARKS	
1	S_1	Res. content	SFM	4170	3559	4662	5435	6535	7317	7403	7047	6720	5810	4353	2895	At begin. of mo.	
2	T_1	Ave. Res. temp.	°F	40												See line (32)	
3	$S_1\ T_1$	Res. heat content	SFM-°F	166.8	141.2	194.5	227.7	285.7	342.3	370.0	376.3	370.2	321.2	231.0	133.4	In 1000. See line (30)	
4	I	Inflow	SFM	4210	5130	1765	3350	2405	1635	925	655	635	755	4095	3350	During month	ADVECTIVE ENERGY
5	T_i	Av. inflow temp.	°F	40	40	39	41	47	51	56	57	53	48	45	42		
6	$I\ T_i$	Heat inflow	SFM-°F	168.4	205.2	68.8	137.4	113.0	83.4	51.8	37.3	33.7	36.2	184.3	140.7	In 1000.	
7	O	Outflow	SFM	4800	3820	1015	2250	1650	1545	1270	970	1550	2165	5490	3455	During month	
8	T_o	Av. outflow temp.	°F	40	40	41	41	42	43	44	47	50	55	50	43	From fig. 1 or 2	
9	$O\ T_o$	Heat outflow	SFM-°F	192.0	152.8	41.6	92.3	69.3	66.4	55.9	45.6	77.5	119.1	274.5	148.6	In 1000.	
10		Sky cover by clouds	Tenths	9.2	9.2	7.8	7.5	6.5	7.2	1.9	2.6	5.9	5.9	8.3	9.1	USWB, Salem, Ore.	
11	P	Possible sunshine	%	17	19	41	47	57	47	93	87	53	53	28	19	From fig. 5	
12	S_i	Incident solar rad.	Ly/dy.	99	150	280	395	512	478	707	623	372	273	139	87	From fig. 5	SOLAR HEAT
13	S_r	Reflect. (clear sky)	"	38	39	38	40	46	47	45	41	39	38	39	35	Nearly same each yr.	
14	$P\ S_r$	(11) x (13)	"	6	7	16	19	26	22	42	36	21	20	11	7	Cor. for sky cover.	
15	S_a	Absorbed, $S_i - P\ S_r$	"	93	143	264	376	486	456	665	587	351	253	128	80	Ave. for mo.	
16	T_a	Air temperature	°F	40	45	43	47	61	63	71	71	61	56	44	44	Obs'd at Detroit Dam.	
17	T_w	Water surf. temp.	°F	41	45	45	49	64	66	75	76	67	62	51	45	Assumed	L.W. HEAT
18	R_n	Net. L.W. Rad. Loss	Ly/dy.	103	95	106	109	127	129	144	151	147	141	136	101	$R_n = R_w - 0.87\ R_a$; table 2	
19		Rain: 0.1 or more	Days	16	18	10	17	7	14	0	2	8	5	18	16	Obs'd at Detroit Dam	
20	E_p	Pan evaporation	Inches.	0.65[1]	1.42[1]	2.25[1]	3.71[1]	6.84[2]	5.40[2]	10.02[2]	9.21[2]	4.11[2]	3.02[1]	0.62[1]	0.29[1]	[1] Medford [2] Detroit Dam	EVAPO. HEAT
21	E	Res. "	"	0.3	0.7	1.4	2.2	4.5	4.2	8.0	7.7	4.4	3.5	1.0	0.5	Assumed	
22	H_e	Evapo. heat, 49.5 E	Ly/day	15	35	69	109	223	208	396	383	218	173	50	25	Ave. for mo.	
23	$T_w - T_a$	(17) - (16)	°F	1	0	2	2	3	3	4	5	6	6	7	1		
24	U	Wind speed	mph	7.4	6.3	7.3	7.6	6.3	6.3	7.0	7.0	7.9	6.1	8.5	6.6	USWB, Salem, Ore.	CONV. HEAT
25	H_c	Conv. heat, $0.89\ U(T_w - T_a)$	Ly/dy.	6	0	13	13	17	17	25	31	42	32	61	7	Ave. for mo.	
26	H	(15)-(18)-(22)+(25)	Ly/dy.	-31	13	76	145	119	102	100	22	-56	-93	-119	-53	Ave. for mo.at res.surf.	
27	A	Res. surf. area	Acres	2200	2280	2630	2970	3340	3500	3450	3320	3070	2630	2080	1800	Ave. for mo.	
28	.03 AH	Total over res. surf.	SFM-°F	-2.0	0.9	6.0	12.9	11.9	10.7	10.4	2.2	-5.2	-7.3	-7.4	-2.9	In 1000.	
29	$IT_i - OT_o$	(6) - (9)	SFM-°F	-23.6	52.4	27.2	45.1	44.7	17.0	-4.1	-8.3	-43.8	-82.9	-90.2	-7.9	In 1000.	
30	$S_2\ T_2$	(3) + (28) + (29)	SFM-°F	141.2	194.5	227.7	285.7	342.3	370.0	376.3	370.2	321.2	231.0	133.4	122.6	At end of mo.; In 1000.	
31	S_2	Res. content	SFM	3570	4662	5435	6535	7317	7403	7047	6720	5810	4353	2895	2785	At end of month	
32	T_2	Ave. res. temp.(30)÷(31)	°F	39.6	41.7	41.9	43.7	46.8	50.0	53.4	55.1	55.3	53.1	46.1	44.0	" " " "	
33	T_2	Observed ave.	°F	39.6	41.6	41.6	43.7	46.9	50.0	54.2	55.7	56.7	52.9	45.3	43.0	Weighted by storage.	

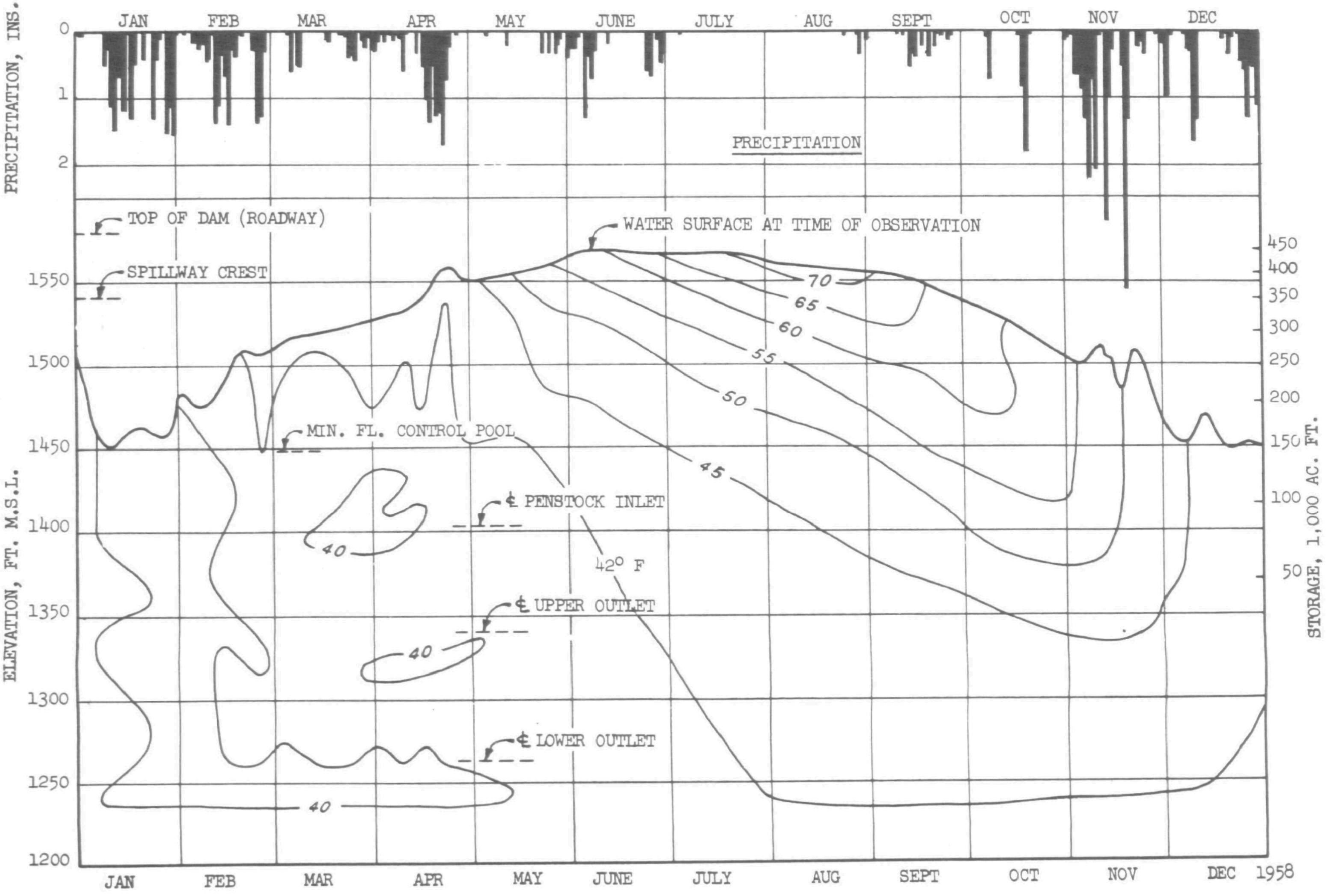


FIG. 1 WATER TEMPERATURE AND PRECIPITATION, DETROIT RESERVOIR, ORE.

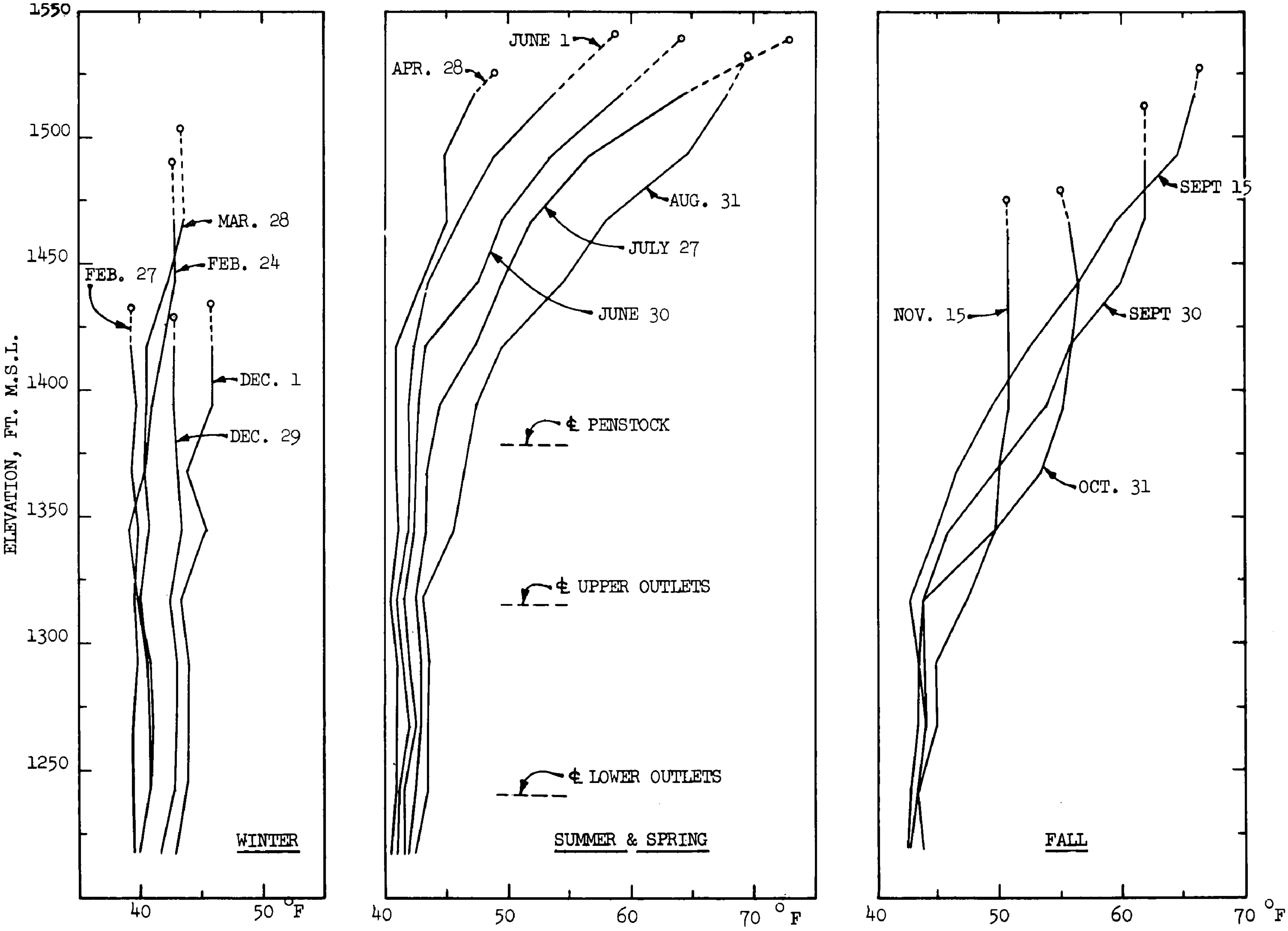


FIG. 2 OBSERVED 1958 TEMPERATURE PROFILES, DETROIT RESERVOIR, ORE.

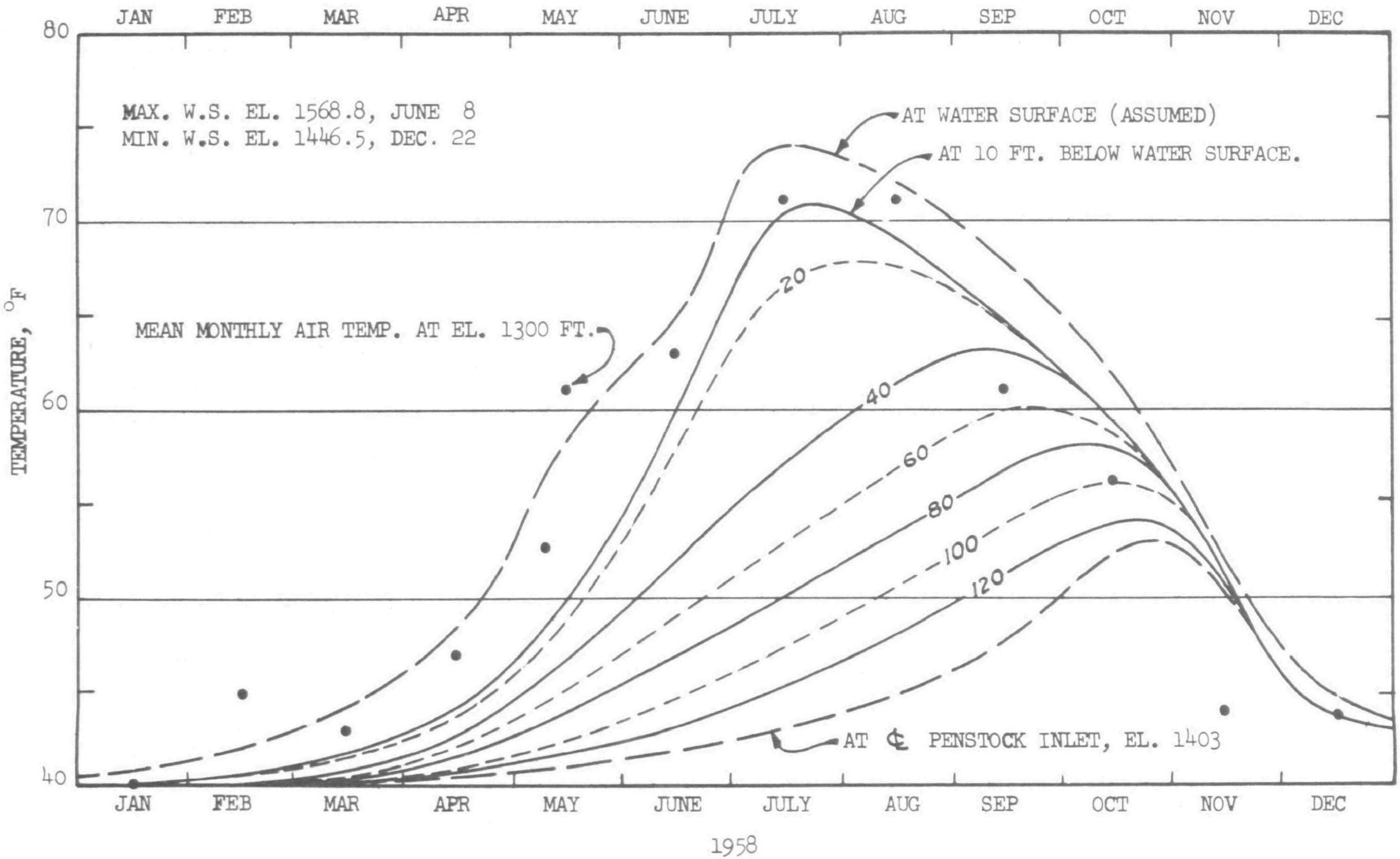


FIG. 3 TEMPERATURE VARIATION
DETROIT RESERVOIR, ORE.

1. During winter, there is little or no variation of temperature with depth and time. This is the rainy season when continuous and complete mixing takes place from repeated filling and emptying operations of the reservoir for flood control. Mixing also takes place by wave action and by the sinking of the surface water as it cools and increases in density.

2. The alternate warming and cooling of the reservoir surface is a daily occurrence, particularly during summer. Estimates of heat flux indicate that heat loss by outgoing radiation and by evaporation generally begins to exceed heat gain from solar radiation about two hours before sunset; the loss rate increases decidedly as night approaches and continues until about an hour after sunrise.

3. The temperature of the water below the sill of penstock inlet varies little with time. This suggests that relatively little of the discharge is drawn from below this level.

4. The temperature of the released water is assumed to equal that of the water in the reservoir at a level about 10 feet above the center line of penstock inlet.

5. Near the surface, the reservoir starts to warm in March. Summer withdrawal of cold water (in excess of inflow) and continued surface heating produce steep gradients of temperature. The maximum surface temperatures occur late in July or early in August.

6. Temperature stratification begins with the warming of the reservoir surface in early March and continues through the filling and evacuation periods.

7. By the end of August the cooling rate at the surface is fast enough to begin reversing the temperature-depth curve near the surface.

8. At the end of November or early in December the reservoir attains a near-isothermal condition and remains isothermal until March when surface warming begins again.

9. The average monthly temperature of the surface water is not observed, but it appears to be generally higher than that of the air.

10. It is believed that streamflow entering the reservoir sinks rapidly to a level where the existing water has the same temperature, particularly when the velocity is reduced to less than one foot a second.

Heat Storage Equation

The heat content of a reservoir changes as a result of the difference in the inflow and outflow of heat energy. The increase is chiefly due to:

1. Heat content of water entering the reservoir, and

2. Net heat gain from Solar and Sky radiation.

and the decrease in heat content results mostly from loss of heat:

1. In water leaving the reservoir,

2. By long-wave radiation, and

3. By evaporation.

In addition, a reservoir gains sensible heat by convection when its surface is colder and loses heat when the surface is warmer than the air.

The Heat-Storage Equation, suggested for computing the average reservoir temperature at end of a selected time interval, is expressed in the form:

Eq. (1) $S_2T_2 = S_1T_1 + I\,T_i - O\,T_o \pm C\,A\,H$

where S_2T_2 is the product of the volume of water in the reservoir and its average temperature at end of the selected time interval;

S_1T_1 is a similar product at the beginning of the time interval;

$I\,T_i$ is the product of the reservoir inflow and its temperature;

$O\,T_o$ is the product of the reservoir outflow and its temperature;

$C\,A\,H$ is the quantity of heat entering or leaving the reservoir surface, A being the area, C a dimensional constant; and

Eq. (2) $H = S_a - R_n - H_e \pm H_c$

with H representing the net rate of heat flow across the reservoir surface,

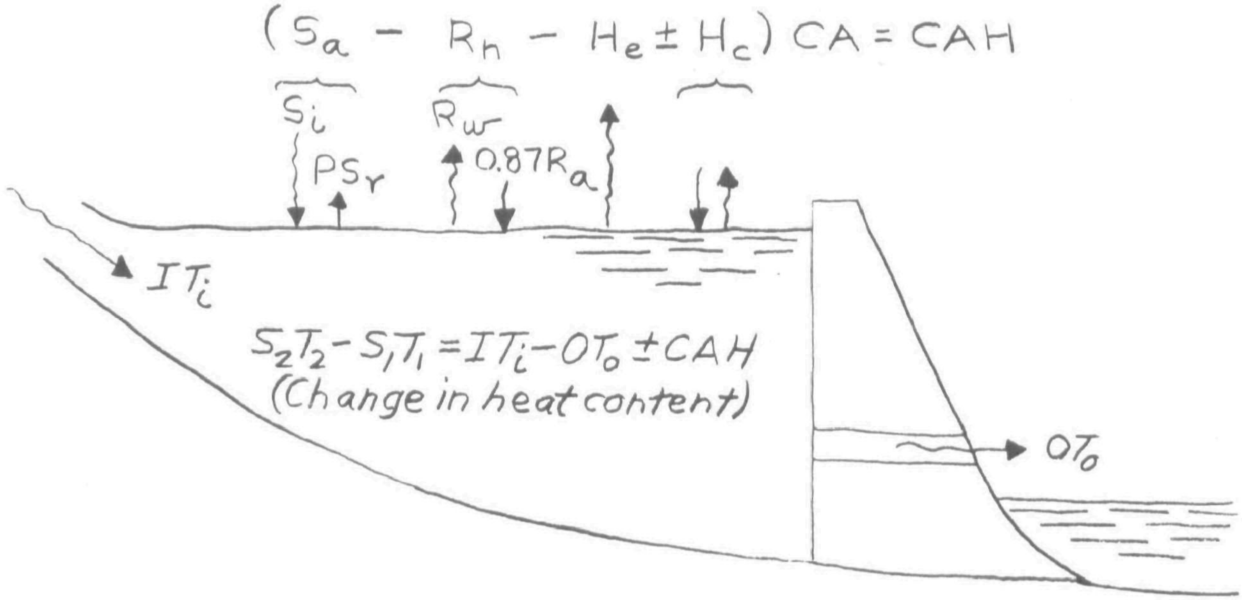
S_a the absorbed solar and sky radiation,

R_n the net loss of heat by long-wave radiation,

H_e the heat loss by evaporation, and

H_c the relatively small heat gain (or loss) by conduction.

The following figure illustrates the terms of Eqs. (1) and (2):



The net effect of the following heat factors is considered negligibly small and a reliable appraisal exceedingly difficult, if not impossible:

1. Ground heat,

2. Bank storage and its heat content,

3. Evaporation of residual ground and surface moisture as reservoir is drawn down,

4. Shading effect of canyon walls and trees,

5. Heating (or cooling) effect of the surrounding terrain by long-wave radiation and by reflected short-wave radiation reaching the reservoir surface,

6. Heating effect of possible chemical and biological changes and density currents in the reservoir.

Their introduction would only compound further the uncertainties involved in the evaluation of the terms of the heat-storage equation, with resultant decrease of confidence in the reliability of the method. Fortunately, the cooling effect of some items on the list is compensated by the heating effect of others. They are omitted from the heat-storage equation in this analysis.

Evaluation of Terms in Eq. (1)

Table 1 includes the working data, formulas, nomenclature, computations, and references to sources used as aids for evaluating the terms of Eq. (1). The computed and observed values of month-end average reservoir temperatures are shown on the last two lines in the table.

As noted in Figures 1, 2, and 3, during January and February, $T_1 = T_o = T_2 = T_i = T_a$, approximately. Therefore, these are the logical months in which computation may be started. Values of S_1, S_2, 0, and A are available from an actual reservoir regulation (or from an adopted rule curve for regulation.) Note that S_2 and T_2 at the end of a period equal S_1 and T_1 at the beginning of the succeeding period.

In this verification study, the outflow temperature T_o was taken from Figure 1 at a level 10 to 20 feet above the center of the penstock inlet. In a hypothetical study, T_o is generally specified or assumed for each period.

The average reservoir inflow temperature (T_i) for 1958 was available for the computation shown in Table 1. If T_i is not available, it may be obtained from a graph of $T_i = f\ (T_a)$, similar to that shown in Figure 4, constructed from observed river and air temperature data.

If H, the net rate of heat flow at the reservoir surface, is in gram-calories per square centimeter (langleys) per day, the total in 30 days over the entire water surface (A acres) is

Eq. (3) $30 \times 4.05 \times 10^7\ A\ H = 1.22 \times 10^9\ A\ H$ calories

And since 4.11×10^{10} calories will change the temperature of one cfs-month volume of water by 1 degree Fahrenheit, the monthly change in the heat content of the reservoir from surface heating,

Eq. (4) $C\ A\ H = 0.03\ A\ H$ cfs-month - ^oF.

The basic data together with the computed values of the components of the heat flow H across the reservoir surface are illustrated in Figure 8.

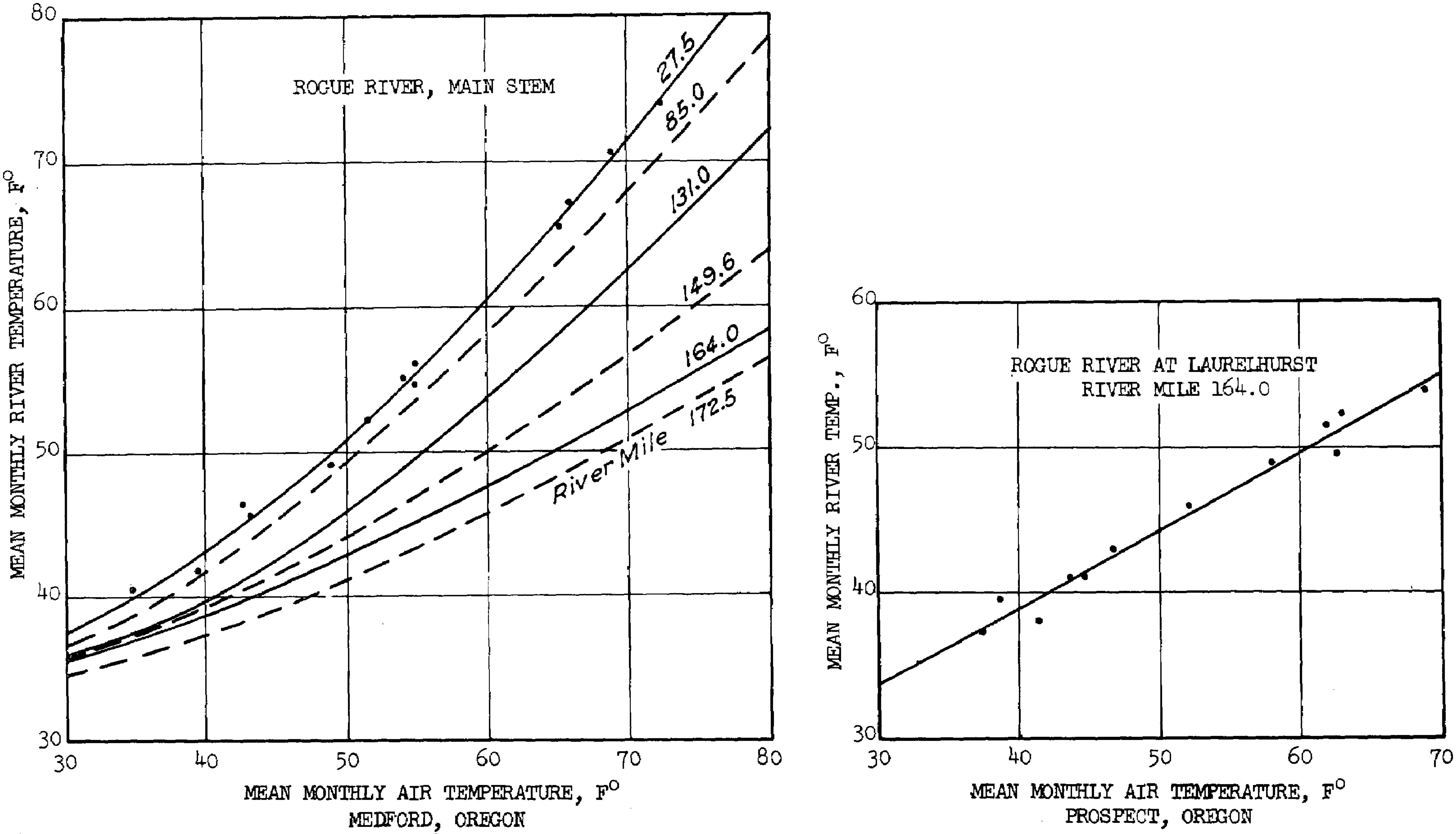


FIG. 4 RIVER TEMPERATURE VS. AIR TEMPERATURE

Evaluation of Terms in Eq. (2)

1. S_a, the absorbed solar and sky radiation, is determined from

Eq. (5) $S_a = S_i - P\, S_r$ 1/

in which S_i is the solar and sky radiation, incident on the reservoir surface. It is obtained from Figure 5, which is an adaptation of a nomograph by R. W. Hamon, L. L. Weiss and W. T. Wilson 2/.

S_r is the reflected amount under a cloudless sky. For a given latitude, the monthly values of S_r are nearly the same for each year. Values of S_r for Detroit Reservoir are found on line 13, Table 1.

P is the percentage of possible sunshine duration. In this study P was estimated from Figure 5, using cloud cover for a nearby Weather Bureau station.

2. R_n, the net long-wave radiation heat loss, is determined from

Eq. (6) $R_n = R_w - 0.87\, R_a = 1.1331\,(10^{-8})\,[(T_w + 460)^4 - 0.87\,(T_a + 460)^4]$

or

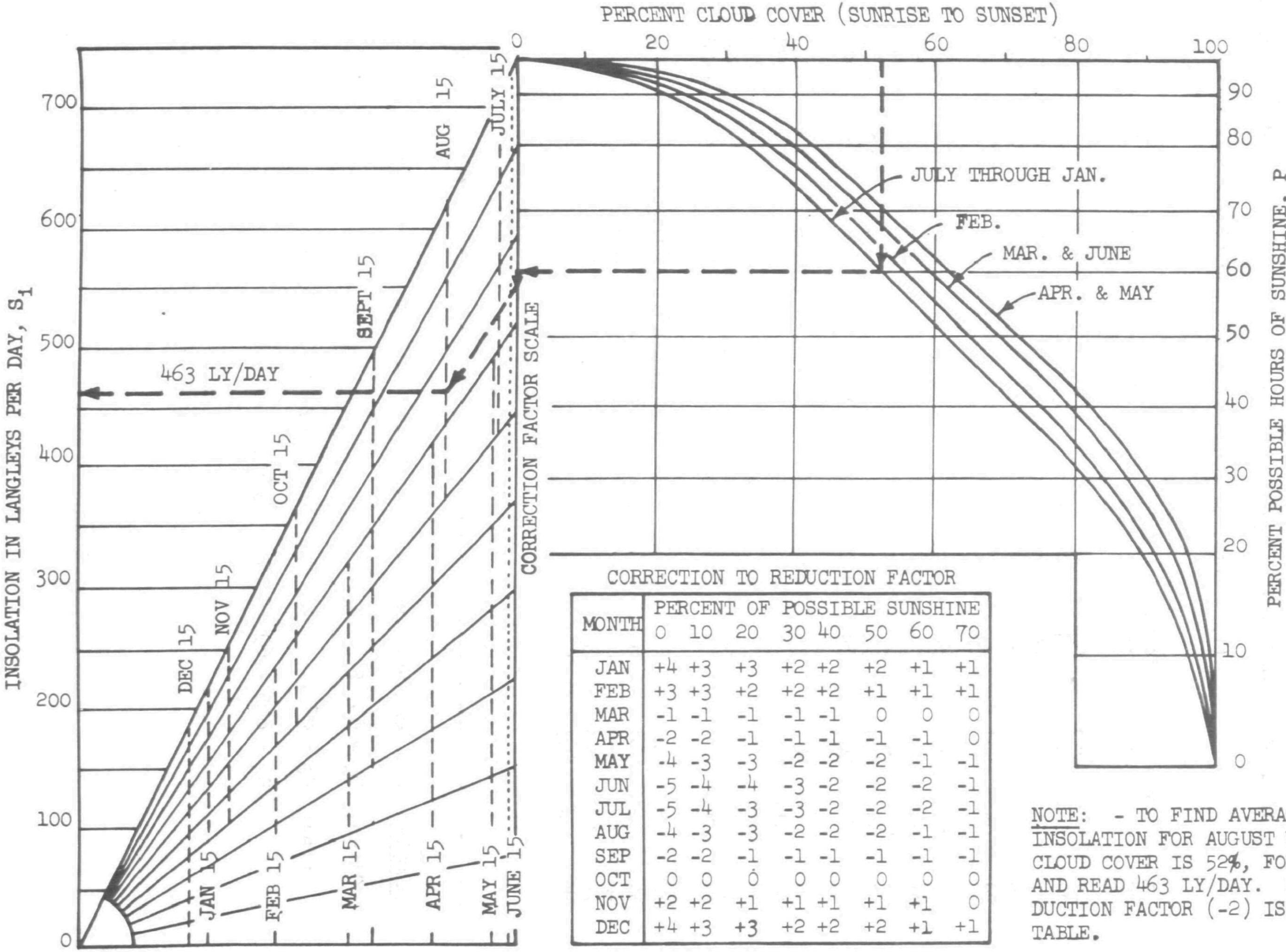
$R_n = 60 + 6.2\, T_w - 5.4\, T_a$ which is a close approximation for temperatures between 30 and 85°F. In Eq. (6) R_w and R_a are the "black body" 3/ radiations at water surface temperature T_w and air temperature T_a, respectively. Values of R and 0.87 R are found in Table 2, together with an example which shows the use of the table for estimating R_n. If not available, T_w and T_a must be estimated. In this study, T_a was observed at project headquarters; but T_w had to be appraised. (Throne 4/ suggests $T_w = 1.05\, T_a$. At Lake Hefner the observed monthly averages of T_w for the months of October through May were from 1 to 5°C. less than T_a, and for the months of June through September they were 1 to 2°C. more than T_a.)

1/ In view of the complexity and uncertainties involved in the appraisal of unobserved elements, one may be justified in ignoring the reflected solar radiation term in Eq. (5), but compensating for it by increasing the coefficient in Eq. (7) by about 10 percent. That is, $H_e + P\, S_r - 55\, E$ approximately.

2/ Monthly Weather Review, June 1954.

3/ $R = \sigma t^4 = 8.26\,(10^{-11})\; t^4$ ly/min. P. 38, compend. of Meteor., 1951. (t in °K).

4/ How to Predict Lake Cooling Action, by R. F. Throne, Sept., 1951, POWER.



CORRECTION TO REDUCTION FACTOR

MONTH	PERCENT OF POSSIBLE SUNSHINE 0	10	20	30	40	50	60	70
JAN	+4	+3	+3	+2	+2	+2	+1	+1
FEB	+3	+3	+2	+2	+2	+1	+1	+1
MAR	-1	-1	-1	-1	-1	0	0	0
APR	-2	-2	-1	-1	-1	-1	-1	0
MAY	-4	-3	-3	-2	-2	-2	-1	-1
JUN	-5	-4	-4	-3	-2	-2	-2	-1
JUL	-5	-4	-3	-3	-2	-2	-2	-1
AUG	-4	-3	-3	-2	-2	-2	-1	-1
SEP	-2	-2	-1	-1	-1	-1	-1	-1
OCT	0	0	0	0	0	0	0	0
NOV	+2	+2	+1	+1	+1	+1	+1	0
DEC	+4	+3	+3	+2	+2	+2	+1	+1

NOTE: - TO FIND AVERAGE DAILY INSOLATION FOR AUGUST WHEN AVE. CLOUD COVER IS 52%, FOLLOW ARROWS AND READ 463 LY/DAY. THE REDUCTION FACTOR (-2) IS TAKEN FROM TABLE.

FIG. 5 DIAGRAM FOR ESTIMATING INSOLATION IN LATITUDE 45° N.

TABLE 2. LONG WAVE RADIATION, $R = 1.1331 (10^{-8}) (T + 460)^4$, Ly/day

(Ly - Langleys = cals./cm^2 = 3.69 BTU/ft^2)

Temp. °F	Ly/day R	Ly/day 0.87 R	Temp. °F	Ly/day R	Ly/day 0.87 R	Temp. °F	Ly/day R	Ly/day 0.87 R	Temp. °F	Ly/day R	Ly/day 0.87 R
25	624	543	45	734	639	65	857	746	85	995	866
26	629	547	46	739	643	66	863	751	86	1003	873
27	634	552	46	745	648	67	870	757	87	1010	879
28	640	557	48	751	653	68	877	763	88	1017	885
29	645	561	49	757	659	69	883	768	89	1025	892
30	650	566	50	673	664	70	890	774	90	1032	898
31	655	570	51	769	669	71	897	780	91	1040	905
32	661	575	52	775	674	72	904	786	92	1047	911
33	666	579	53	781	679	73	910	791	93	1055	918
34	672	585	54	787	685	74	917	798	94	1063	925
35	677	589	55	793	690	75	924	804	95	1070	931
36	682	593	56	800	696	76	931	810	96	1078	938
37	688	599	57	806	701	77	938	816	97	1086	945
38	694	604	58	812	706	78	945	822	98	1094	952
39	699	608	59	818	712	79	952	828	99	1102	959
40	705	613	60	825	718	80	959	834			
41	710	618	61	831	723	81	966	840			
42	716	623	62	837	728	82	973	847			
43	722	628	63	844	734	83	981	853			
44	728	633	64	850	740	84	988	860			

__Example__: Net Long Wave Radiation Heat Loss, $R_n = R_w - 0.87 R_a$.

Given: $T_w = 60^\circ$ F; $T_a = 55^\circ$ F

Find: $R_w = 825$; $0.87 R_a = 690$ Ly/day from table.

$R_n = 825 - 690 = 135$ Ly/day

In Eq. (6) the coefficient 0.87 represents the monthly ratio of the atmospheric to "black-body" radiation at T_a. Actually, this ratio varies with local humidity and cloudiness 1/ (amount, height, type, and thickness), smoke and dust level of the air. West of the Cascade Range, it varies from about 0.82 in summer to 0.87 in winter--a relatively narrow range. The effectiveness of the incoming long-wave radiation is further reduced by the reflectivity (0.03) of water 2/. The reason for using the upper limit of these ratios is to compensate for taking 1.0 as the emissivity coefficient for water instead of 0.97, commonly used. This modification eliminates the effort required to evaluate the local humidity and cloudiness which are not ordinarily available. On this subject, E. R. Andersen 2/ concludes that:

"Empirical relationships between atmospheric radiation and local vapor pressure may be used if 10 percent accuracy is acceptable, provided the air mass is similar to that of the area where the original observations were recorded. For other areas, with no consideration of air masses involved, the accuracy of the relationships is more questionable . . . . To obtain more accurate methods of determining atmospheric radiation, in terms of more easily available parameters, it will be necessary to consider the total vapor content of the atmosphere as the moisture variable, rather than the local vapor pressure."

"Without taking into account the local moisture-temperature distribution with height, we should expect nothing better than a rough approximation of the downward atmospheric radiation in the absence of clouds," says J. G. Charney 3/.

3. H_e, the evaporation heat loss, takes place mostly during rainless periods when surface-water temperature is within 42-80°F. In this range, the reservoir loses approximately 1485 (varying from 1473 to 1499) calories of heat per inch depth of water evaporated from each square centimeter. Letting E be the evaporation in inches during a selected period of t days, the average daily rate of heat loss by evaporation H_e is 1485 (E/t). And for t = 30 days:

Eq. (7) $H_e = 49.5\ E$ ly/day

1/ U.S.G.S. Prof. Paper 270, Water Loss Investigation: Lake Hefner Studies, Base Data Report.

2/ pp. 90-99, U.S.G.S. Professional Paper 269, Water Loss Investigations: Lake Hefner Studies, 1954.

3/ Sec. IV, Handbook of Meteorology, 1st edition, 1945.

In this study, the monthly values of reservoir evaporation E are estimates, using as guides the pan evaporations observed at U. S. Weather Bureau stations in the vicinity, the number of rainy days, and the monthly values of lake or reservoir to pan evaporation ratios summarized on page 140 of U.S.G.S. Professional Paper 269, 1954.

Of course, such appraisal of E cannot be considered objective, but one cannot do otherwise when required data are not available for determining with confidence the regional constants and computing evaporation by the generally accepted Meyer formula, as Marciano and Harbeck 1/ did and derived:

Eq. (8) $E_1 = 0.0045\ U\ (e_w - e_a)$ cm/day

in which U is the wind speed in mph and $(e_w - e_a)$ is the vapor pressure difference, in millibars, between reservoir surface and air.

4. H_c, the conduction of sensible heat, which is relatively small in this case, was estimated from:

Eq. (9) $H_c = 0.89\ U\ (T_w - T_a)$ ly/day

derived from the Bowen ratio 2/

Eq. (10) $$\frac{H_c}{H_e} = B \frac{P\ (t_w - t_a)}{1000\ (e_w - e_a)}$$

by substituting $E_1/0.0045\ U$ for $(e_w - e_a)$ from Eq. (8), 0.61 for B[8], 1000 for the atmospheric pressure P, $(5/9)\ (T_w - T_a)$ for $(t_w - t_a)$, and 585 E_1 for H_e.

U and T_w in Eq. (9) are only appraisals, based on observed values at a meteorologic station in the vicinity of the reservoir. $T_w - T_a$ is the temperature difference in °F. between water surface and air, and $t_w - t_a$ in Eq. (10) is a similar difference in °C.

The working equation used as guide for estimating the monthly average flow of heat at the reservoir surface was:

$$H = S_i - Ps_r - (R_w - 0.87R_a) - 49.5E - 0.89U\ (T_w - T_a) \text{ by/day}$$

But $H = S_i - (60 + 6.2T_w - 5.4T_a) - 55E - 0.89U\ (T_w - T_a)$

1/ P. 67, U.S.G.S. Professional Paper 269, Water Loss Investigations, Lake Hefner Studies, 1954.
2/ P. 104, U.S.G.S. Professional Paper 269, Water Loss Investigations, Lake Hefner Studies, 1954.

was found to be a satisfactory approximation. The latter may be used when one cannot evaluate with confidence the reflected solar radiation and the emissivity of the air. Furthermore, the latter is also a more suitable form for a digital computer.

Application

Following the verification step described in this report, the heat-storage equation was applied for estimating the month-end average temperature of water in a proposed reservoir during a critical year of low runoff and above-normal summer-air temperature. A chart showing the temperature variation with depth and time, similar to Figure 1, was drawn in such a manner that the weighted average temperature at the end of each month equalled the computed month-end reservoir temperature. Of course, the assumed monthly average reservoir-surface temperatures and the adopted design temperatures of the outflow were also employed as guides in drawing the isotherms.

Future Work

As time permits, efforts will be made to simplify the procedure, to increase the reliability or confidence in the appraisal of unavailable but necessary factors, and shorten the unit time from 30 to 10 days or less. Exploratory statistical analysis is under way to find a relationship between the heat content of a layer of water in the reservoir and the pool elevation at the end of the month. Such a relationship, if satisfactory, will serve to distribute the computed month-end average temperature throughout the depth of the reservoir with more confidence.

Water surface temperature, which is not available, makes the task of evaluating long-wave, evaporation, and convection heat terms of Eq (2) very difficult. Plans are ready to instrument Lookout Point, Detroit and Fern Ridge Reservoirs for the purpose of assembling sufficient surface-water temperatures which can be studied in relation to the solar-radiation estimates or to air temperature and land pan evaporation, ordinarily observed at the project.

Conclusion

This is an office progress report on the analysis of Lookout Point and Detroit Reservoir water temperatures collected since 1954 by the Portland Office of the U. S. Corps of Engineers. The month-end average reservoir temperatures have been reproduced with acceptable reliability, using the heat-storage equation as a guide, and the procedure was applied in estimating the temperature pattern in several proposed reservoirs during critical years of low runoff and above-normal summer temperature.

The most difficult task is the numerical evaluation of the heat flow across the reservoir surface because of the uncertainties involved in the conversion of the ordinarily observed meteorologic elements at some Weather Bureau station to those over the reservoir. Considerable judgment and trial-error method must be exercised in the appraisal of the heat terms in Eq. (2). This task will continue to be difficult until the reservoir surface temperature, evaporation, distribution of the local humidity, wind and air temperature are indexed to a satisfactory degree of approximation to the ordinarily observed elements at a Weather Bureau station and the short-wave and long-wave radiation can be determined with confidence for cloudy sky conditions.

As noted in Figure 6, the relative magnitudes of the inflow and outflow have greater influence on the average temperature of the water in Detroit Reservoir than the heat flow across the reservoir surface. Near the surface, however, the change in water temperature is almost entirely due to heat exchange taking place at the water surface-air interface.

The recent emphasis on water quality demands continued effort to close the gaps in observational data and analysis leading to the simplest procedure possible for satisfactory estimates of reservoir and river temperatures.

Acknowledgment

The aid given by C. Pedersen, Chief, Water Control Section, in reviewing this paper, is gratefully acknowledged. The assistance of Orville Johnson (Hydr. Engr.) in collecting, processing, and charting the basic data is also appreciated. Reservoir temperature data are collected by project personnel under the supervision of Donald Heym and Donald Westrick, the Project Engineers for Lookout Point and Detroit Reservoirs.

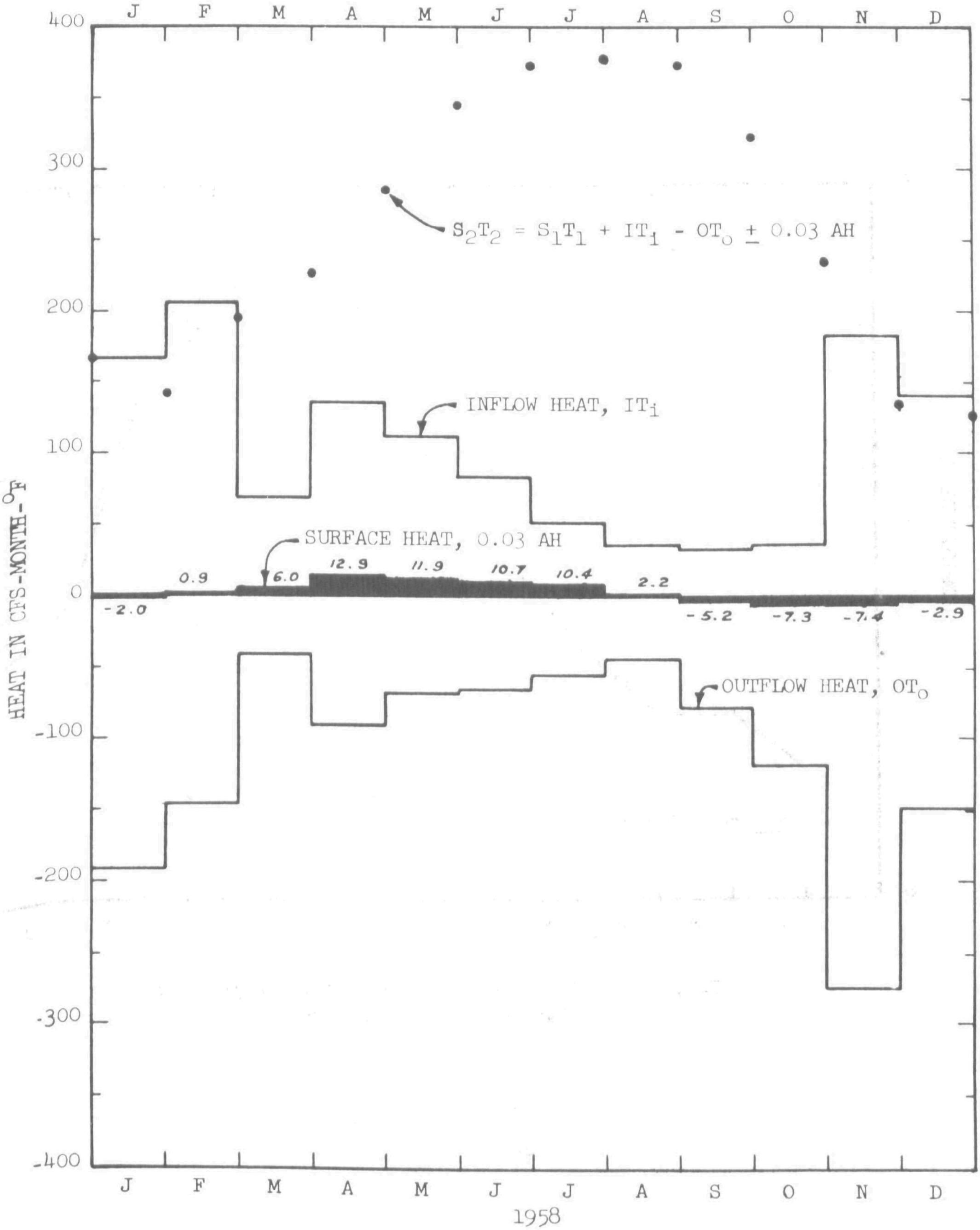


FIG. 6 RELATIVE MAGNITUDES OF HEAT TERMS IN EQ. (1)

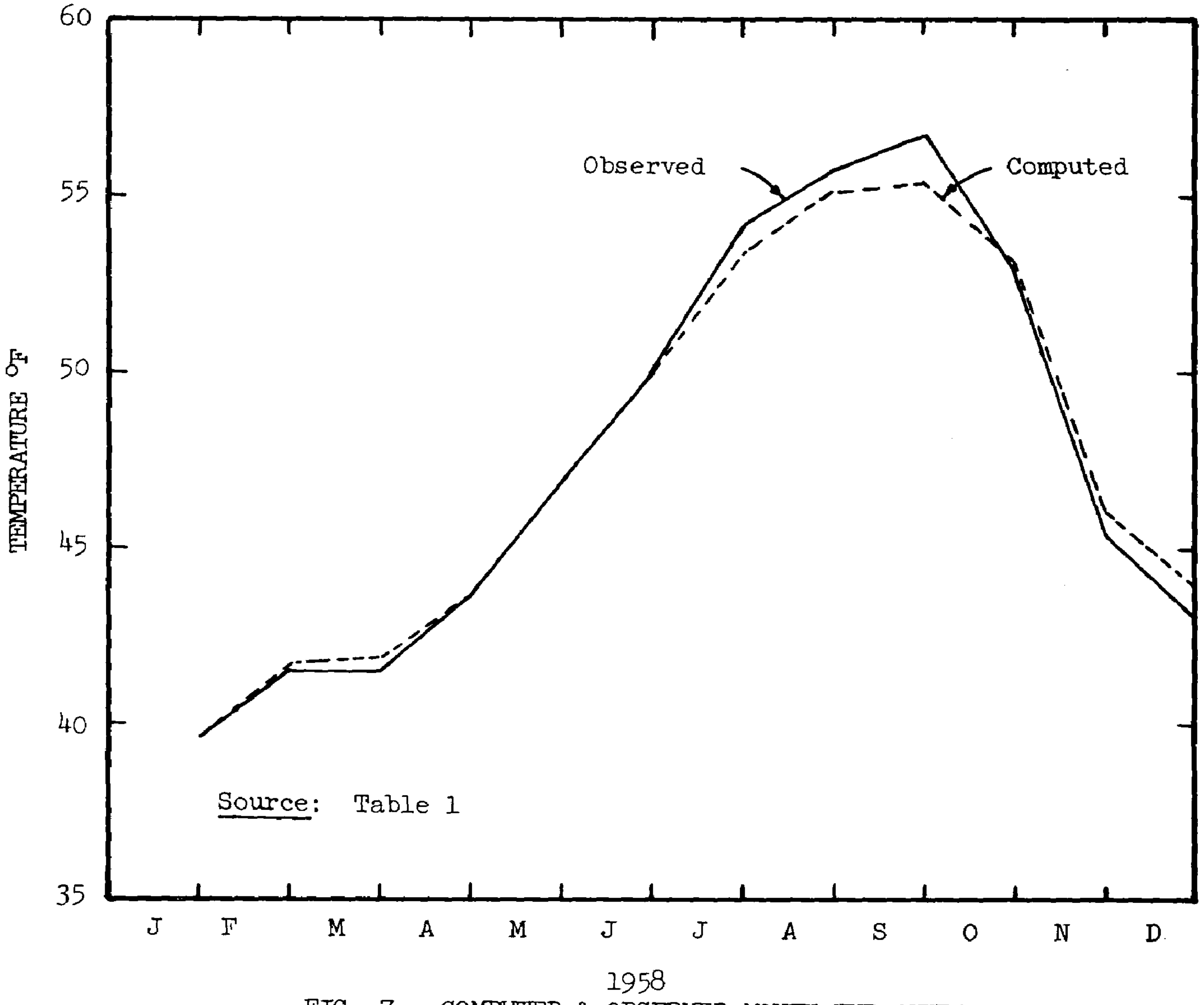
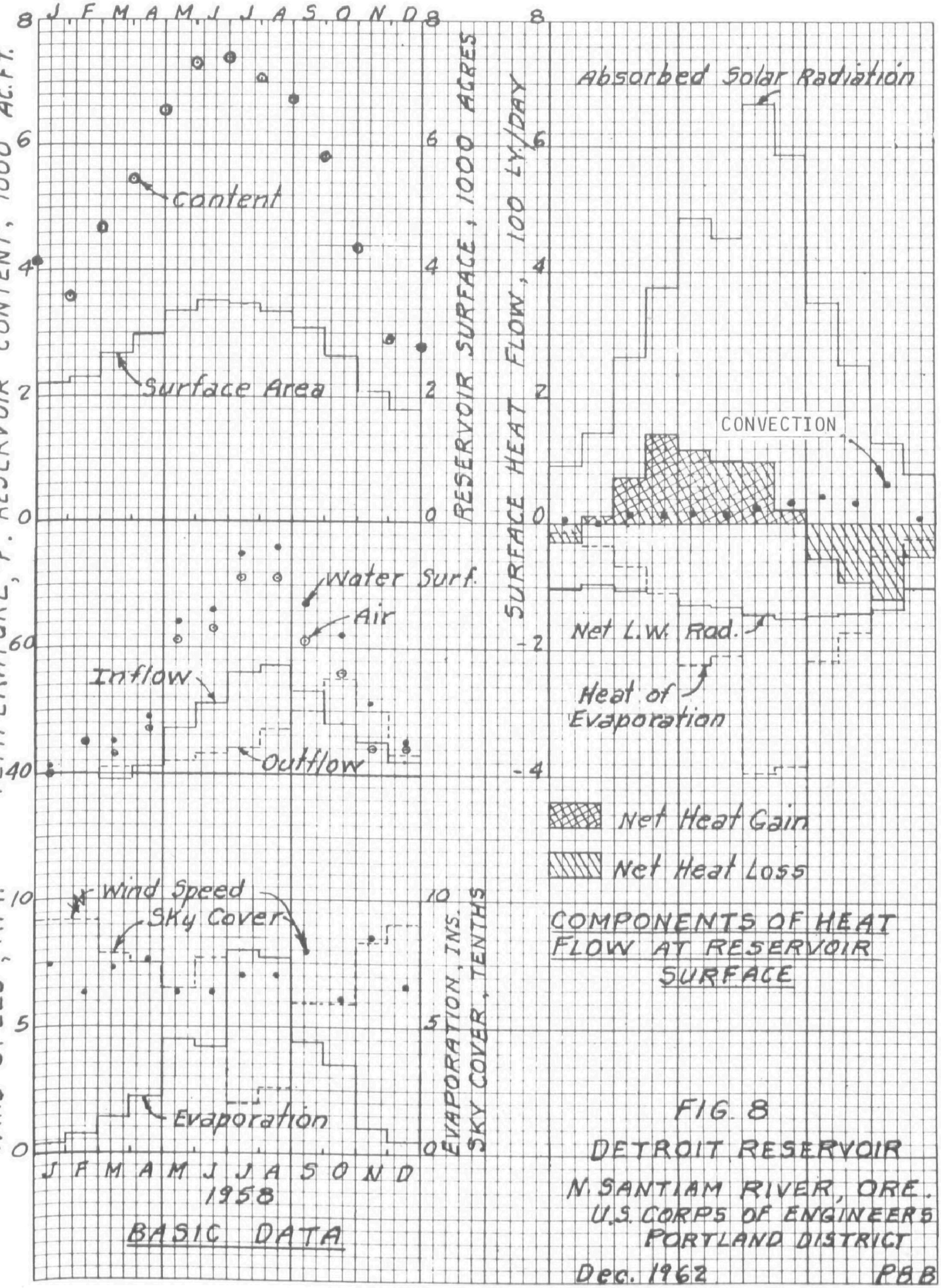


FIG. 7 COMPUTED & OBSERVED MONTH-END AVERAGE RESERVOIR TEMPERATURES


J F M A M J J A S O N D
TEMPERATURE, °F. RESERVOIR CONTENT, 1000 AC. FT.
RESERVOIR SURFACE, 1000 ACRES
SURFACE HEAT FLOW, 100 LY./DAY
Content
Surface Area
Absorbed Solar Radiation
CONVECTION
Water Surf.
Air
Inflow
Outflow
Net L.W. Rad.
Heat of Evaporation
Net Heat Gain
Net Heat Loss
WIND SPEED, MPH
EVAPORATION, INS.
SKY COVER, TENTHS
Wind Speed
Sky Cover
Evaporation
1958
BASIC DATA
COMPONENTS OF HEAT FLOW AT RESERVOIR SURFACE
FIG. 8
DETROIT RESERVOIR
N. SANTIAM RIVER, ORE.
U.S. CORPS OF ENGINEERS
PORTLAND DISTRICT
Dec. 1962
PBB

SOME OBSERVATIONS OF COLUMBIA RIVER AND RESERVOIR BEHAVIOR FROM HANFORD EXPERIENCE

R. T. Jaske*

Considerable interest in reservoir behavior has been generated as a result of the desire to extend the purposes of impoundments to include regulation of downstream water quality. Churchill 1/ on a previous occasion has stated, based on his 26 years' experience, "It can be concluded that water control structures may exert a profound influence during warmer months of the year on water temperature of both impounded and released waters. By understanding the forces that control these influences, advantage can be taken of the desirable effects, and the less desirable effects can be controlled or perhaps avoided." In our own experience with Lake Roosevelt and the Columbia River we have come to an identical conclusion, although from an entirely different set of circumstances.

Where Churchill and other investigators have dealt with large impoundments on streams of relatively low flow, the Columbia River system of dams, with the exception of Grand Coulee, is a system where daily through-put is a significant fraction of reservoir capacity. In some projects, such as Rocky Reach, Rock Island and Priest Rapids, this could involve as much as 30 percent or more of the available storage. As a result, despite heads ranging to 90 feet, we find little effective stratification. Rather, the stream has been slowed and subjected to increased exposure to solar radiation, heat transfer and bank flow effects with the net effect of a persistent increase in temperature over the natural conditions. Attempts to explain these effects have not fully yielded to rational explanation although Raphael 2/ has pointed a way evolved from earlier work by Anderson, et. al., at Lake Hefner and Lake Mead. Our measurements during 1962 and 1963 fail to confirm the values predicted in the reports, although the general method appears to have merit. Rather, it appears that Raphael's correlation requires the additional benefit of a broader meteorological data base and machine computation from an improved mathematical model.

*Principal Engineer, Facilities Engineering Section, Irradiation Processing Department, General Electric Company, Richland, Wash.

1/ Symposium on Streamflow Regulation for Quality Control held in Cincinnati, Ohio, April 3-5, 1963.

2/ The Effect of Wanapum and Priest Rapids Dams on the Temperature of the Columbia River, September, 1961.

The behavior of Lake Roosevelt more closely resembles the eastern situation with the exception that the relatively high through-out and low BOD demand of tributaries currently results in little or no effect on dissolved oxygen. Lake Roosevelt does, however, develop considerable stratification, as much as 7 degrees to 9 degrees C. during August and September. Temperature soundings show a characteristic slope of isotherms downward toward the 1030-foot discharge. Correlation of the data from various stations suggests a discontinuity rising approximately according to the one-third power of the distance from the outlets. Further measurements in the unusual year of 1963 indicate that as of October 25, the cooler inflow has failed to appear in the turbine discharge at the rate estimated by displacement of withdrawn water, the net result being that discharges from Grand Coulee have remained relatively constant through September and October. It might appear that, due to the difference in weather over the lake length and the sharp curvature of the old stream bed, the lake is filling by displacement from the north rather than the expected layer flow. The data will be published by the author at a later date.

Additional work by the Irradiation Processing Department in support of the river-cooling program will include attempts to derive a mathematical model with computation in the IBM 7090 machine at Hanford. At present, we are collecting the following data for the passive record:

1. Continuous monitoring of temperatures at Grand Coulee Dam at levels of -5 feet, -20 feet referred to surface at the penstock level approximately 230 feet deep.

2. Once-a-shift readings of Chief Joseph turbine discharge.

3. Hourly turbine discharge temperatures at Rocky Reach.

4. Continuous temperature monitoring at the Priest Rapids gage.

We expect to add a continuous recorder to a point downstream of Grand Coulee by the first of April, 1964. To the extent of available resources, we expect to continue temperature soundings of Lake Roosevelt, but these will remain somewhat fragmentary.

Downstream from the plant, the Hanford Laboratories conduct a research and development program which includes an investigation of the effects of reactor effluent on Columbia River water quality. The purpose of this study is to distinguish any net changes in river water characteristics due to plant operations from those which would occur naturally. The emphasis is on water temperature variations, but potential chemical effects are also being studied. The work is in addition to our routine and special studies of radioactivity in the river.

The various phases of this work include the following:

a. Continuous upstream and downstream monitoring at several points, plus repeated comparisons of parameter distribution in cross sections with the continuous point monitor data.

b. Dye studies to define diversion patterns from individual release points, as well as the labeling of water masses in order to follow time sequential changes of temperature.

c. Measurement of pertinent variables for a calculated heat budget, using portable meteorological instruments. The portability feature permits comparison measurements along the river with routine data from our Hanford meteorological station.

In summary, we believe that continued study of the thermal aspects of the Columbia River system should form an essential part of planning for ultimate optimum use of the river. Recent contacts by the Bureau of Reclamation regarding the potential construction of a third powerhouse at Grand Coulee indicates the desirability of assessing the economic benefits of thermal regulation, of identifying possible thermal effects of upstream impoundments, and the need for improving insight into the physical processes involved. It has been suggested that interested agencies sponsor a cooperative study of the Snake and Columbia River Basins over the next several years in order to strengthen the theory and provide a reasonable basis for incorporating appropriate regulating works in the proposed upstream storage projects.

The General Electric Company, under contract to the Atomic Energy Commission, currently expects to continue a program related primarily to operational aspects of the Hanford plant. We hope other agencies will avail themselves of the opportunity to broaden these studies to the extent that long-range planning can proceed on a factual basis without involving potential danger to resources such as fisheries because of inadequate investigation.

INSTRUMENTATION FOR WATER-TEMPERATURE STUDIES*

A. M. Moore**

Our knowledge of the thermal properties of lakes and streams has grown largely with the development of suitable temperature-measuring instruments and with demands imposed by present and predicted water use. Temperatures of water in lakes or streams depend upon many factors, a discussion of which is beyond the scope of this paper. Professor Sylvester has mentioned many of these factors in the excellent paper he presented earlier today.

Instrumentation for temperature determination depends on such things as the purpose of the investigation, required accuracy of data, number of additional parameters to be measured, and the depths (pressures) that instruments must withstand. Temperature data are needed for water-loss, thermal-load, water-quality, fish and wildlife, water-use, and sediment-transport investigations. Equipment presently in use ranges from the simple, direct-reading hand thermometers to infrared photography. Other agencies may be using instruments with which I am not completely familiar; my comments will, therefore, be limited largely to equipment used by the Geological Survey.

Temperature-Profile Recorder

The temperature-profile recorder was developed by the Navy Electronics Laboratory for use in the water-loss investigations conducted by the Geological Survey at Lake Hefner, Oklahoma. 1/ The temperature-sensing element for this instrument was a thermocouple which was connected to a length of electrical cable. The small current generated by the thermocouple was amplified by a storage battery and then routed to an Esterline-Angus event recorder, which also was used to record other data. The equipment was maintained in a boat for the temperature surveys and to conserve electrical power the Esterline-Angus recorder was clock-driven. The lake thermocouple equipment gave excellent results once the cables were covered to prevent electrical leakage and mechanical abrasion. The temperature-profile recorder gave more accurate data than the bathythermograph that had been used previously to obtain water-temperature data.

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

1/ Water-Loss Investigations: Lake Hefner Studies, U.S.G.S. Professional Paper 269, Harbeck and others, 1954.

Bathythermograph

In similar water-loss investigations for Lake Mead the bathythermograph was used to record water temperature. The temperature-profile recorder is more accurate, but would not function properly at the greater depths of Lake Mead. 1/

The bathythermograph provides a continuous record of temperature versus depth. A stylus, attached to a Bourdon (pressure) tube records the temperature on a smoked-glass slide. The slide is held in a frame attached to a pressure bellows and hence the frame and slide move relative to the arc of the stylus as the depth changes. Thus, pressure changes resulting from temperature changes cause the temperature stylus to move, while pressure changes resulting from changes in depth cause the frame and slide to move. Observed surface temperatures are used to calibrate the bathythermograph record.

Whitney Underwater Thermometer

The Whitney underwater thermometer utilizes a small thermister as the temperature-sensing element and a small dry-cell battery to supply power needs. The thermister is used as one arm of a Wheatstone bridge circuit. Depth of observation is measured by the length of line from the sensing element to the water surface. Temperature is read directly from the dial of an electrical meter which is calibrated for a range of 5°F. and is provided with multiple settings for temperature range.

The Whitney thermometer was used to obtain water-temperature profiles in the thermal-load investigations of Lake Colorado City, Texas. 2/ The instrument, though non-recording, is portable and therefore is preferable, for some purposes, to the bathythermograph or temperature-profile recorder.

Infrared Photography

Although the existence of infrared energy has been recognized since the 17th Century, the development of scientific instruments utilizing this energy was negligible prior to World War I. Some development of infrared photography occurred during and shortly after that War, but significant progress was hampered by lack of sensitive infrared detectors. Highly sensitive detectors were developed during World War II

1/ Water-Loss Investigations: Lake Mead Studies, U.S.G.S. Professional Paper 298, Harbeck, Kohler, Koberg, and others, 1958.

2/ The Effect of the Addition of Heat from a Powerplant on the Thermal Structure and Evaporation of Lake Colorado City, Texas, U.S.G.S. Professional Paper 272B, Harbeck, Koberg, and others, 1959.

and these have spurred widespread use of infrared equipment for many important purposes.

Infrared photography, as applied to bodies of water, utilizes aerial cameras, infrared detectors, and photographic film. Everything warmer than absolute zero (-273°C.) radiates infrared energy that can be optically focused. The infrared scanner consists of a plane mirror with rotational axis parallel to the line of flight of the airplane. The mirror scans along a line at right angles to the line of flight of the airplane. The infrared radiation picked up by the plane mirror is reflected to a parabolic mirror that then focuses the radiation on an infrared detector. The detector converts changes in radiation into an electrical signal that is amplified and then used to modulate the current passing through a glow tube. Light from the glow tube is scanned across the film in synchronization with the rotating scanner. The film itself is moved across the exposure station at a speed proportional to the speed-to-altitude ratio of the airplane. The airplanes are usually flown at altitudes ranging from 300 to 1,000 ft.

Normally the technique is limited to recording surface temperatures, but the Geological Survey has developed a modification in which sensing elements placed in the water transmit signals to the airplane as it passes overhead. In this way, accurate measurements of temperature of the water mass are made along with measurements of surface temperature.

Multiparameter Recorder

The multiparameter recorder can record simultaneously many water-quality parameters including temperature. Other parameters commonly recorded are dissolved oxygen content (DO), specific conductance, pH, oxidation-reduction potential (ORP), turbidity, chloride, radioactivity, and sunlight intensity. In water-quality investigations now being carried on in the Delaware River and estuary, temperature, DO, pH, specific conductance, and turbidity are recorded continuously on a single instrument. 1/ Four multiparameter recorders are now being installed on the Duwamish River in Washington, between Renton and Seattle, for a Geological Survey investigation of the effect on water quality of the discharge from a large new sewage treatment plant that is expected to double the usual low flow of the river below Renton. These four instruments will record the same five parameters included in the Delaware study and, in addition, solar radiation index (sunlight intensity). However, not all of the instruments will record all six parameters, but at two sites some parameters will be measured at more than one depth.

1/ Continuous Recording of Water Quality in the Delaware Estuary. McCartney and Bearner, U.S.G.S., A.W.W.A., October, 1962.

The U. S. Public Health Service is using instruments of this type in the Willamette River, Oregon, to record DO, pH, specific conductance, and temperature.

In these recorders, a thermocouple develops a small current having a voltage of 50 millivolts or less that is proportional to the water temperature. The electrical signal is amplified and fed to a strip-chart recorder or a paper-tape punch. In some instances, the signal is telemetered to a central location where receiving equipment provides a periodic print-out of the data and a recording on paper punch-tape.

Telethermometer

The telethermometer provides a convenient means of obtaining temperature profiles in streams, lakes, ponds, and reservoirs. As with the Whitney underwater thermometer, the temperature-sensing element is a thermister, and a very tiny one, as the probe in which it is housed is only 3/16-inch both in length and diameter. Power is supplied by two flashlight batteries housed in a small console. Depth of observation is measured by the length of line from the thermister to water surface. A dial on the console provides for registration of temperature directly, both in degrees Fahrenheit and degrees Celsius (Centigrade). The instrument used by the Oregon District does not provide for a recorder, but some models of the telethermometer do make such provision. Our instrument covers a range from 30° to 120°F. with only one dial setting, but more sensitive (multiple-setting) models are available. We have modified our telethermometer by constructing a small aluminum bar in which to house the probe and about one foot of the insulated electrical cable. This bar provides enough weight to position the probe for depth in ponded water; the bar can be taped to a wading rod or attached to a regular hanger bar and sounding weight for use in flowing water.

Thermograph

To obtain continuous records of stream temperature, the Geological Survey uses a thermograph attachment with the Stevens A-35 water-stage recorder. The pen trace of water temperature is continuous on the same strip chart on which is recorded the stage record. Some Federal and State agencies use recorders that provide a pen trace of temperature on a circular chart, usually geared to make one rotation in seven or eight days. Those recorders are not suited to our normal routine visits to basic network stations (streamflow and water quality) once every five to six weeks. Also, the computation of accurate records is more difficult from the circular charts than from the strip charts. Because of the difficulties involved in the use of circular charts and the advantage of obtaining both stage and temperature record on the same chart, we prefer the thermograph attachment to the water-stage recorder.

The thermograph attachment consists of a temperature probe connected by means of capillary tubing to a bellows mounted on the underside of the recorder. The temperature probe is placed at the stream end of a 1¼-inch galvanized inlet pipe and the position of this end of the pipe is so selected that it is always in moving water. The probe, capillary tubing, and bellows are filled with methyl alcohol. With increase in water temperature the alcohol expands and causes a piston-like movement of the bellows. This movement is transferred to the temperature pen through a torque arm, gear sector, wheel, shaft, and beaded cable. The temperature pen, which operates within the top three inches of the strip chart at a scale of 40°F. to the inch, is set one hour ahead of the stage pen to insure that the two pens will never interfere with each other.

Maximum-Minimum Thermometer

The maximum-minimum thermometer is a U-shaped thermometer so constructed that the mercury column on the left side of the U positions a small metal marker indicating minimum temperature, while maximum temperature is similarly indicated on the right side of the U. The temperatures so designated are those that occur between visits to the station. A small magnet is used to reset the metal markers on the mercury columns.

The Geological Survey has completed some preliminary experiments with these instruments and we believe they show promise as an inexpensive means of obtaining monthly maximum and minimum water temperatures.

Hand Thermometer

Hand thermometers used by the Geological Survey for spot observations of water temperature are red-liquid-filled and are graduated in intervals of 1° from 30° to 110°F. Initially, mercury-filled thermometers were used, but the red-liquid type are easier to read and almost as accurate although slower in responding to temperature change. These thermometers are also used to check the setting of thermographs. Hand thermometers that have been accurately tested and calibrated are used to check the setting of some of the more precise instruments such as the temperature-profile recorder, bathythermograph, and Whitney underwater thermometer.

Accuracy of Instruments

Whitney thermometers, temperature-profile recorders and bathythermographs are accurate to within about 0.2°F., but most of these instruments achieve that precision only if they are periodically checked against a standard milliameter or thermometer.

Thermograph attachments to water-stage recorders are, in themselves, accurate only to within about 2°F., but they are checked against hand thermometers and results can be considered accurate to within about 1°F.

Multiparameter recorders are considered accurate to within 1°F.

The telethermometer used by the Geological Survey in Oregon is guaranteed accurate within 1% of the range, or 0.9°F. for the 90° range, but accuracy is generally found to be within about 0.5°F.

Manufacturing practice reportedly permits inaccuracies in hand thermometers and maximum-minimum thermometers not to exceed one half of the smallest graduation interval. This means that hand thermometers used by the Geological Survey should be correct within 0.5°F. and maximum-minimum thermometers, within 1°F. We have checked our hand thermometers periodically and errors as great as 1°F. have been found only rarely.

Precautions in Use and Installation of Instruments

When a water-temperature station is to be established, whether it be recording or non-recording, care must be exercised to see that the temperature registered is representative for the cross section. For example, when we installed our first thermographs in Oregon, in 1949 and 1950, we assumed that if the thermometers or the temperature probes for thermographs were placed in moving water, the record would be representative. A series of near-surface measurements across the section indicated that this was so. In the summer of 1963, we used a telethermometer to obtain temperature profiles at 40 thermograph sites. Temperature at the inlet was found within 0.5°F. of average temperature for the cross section for 34 of the 40 sites, and within 1.0°F. for 39 of the 40 sites. At one site the difference was 1.6°F., but there the temperature profile had to be measured about 600 ft. upstream from the gage. For 35 of the 40 sites, the variation in temperature throughout the cross section was confined to a range of 1.3°; at the other five sites, temperatures in sluggish water at the banks were found to be about 2° higher than in the faster-moving water. However, water at these higher temperatures comprised a negligible part of the flow. Figure 1 shows the temperature-profile for Breitenbush River above Canyon Creek near Detroit, Oregon.

A temperature profile is particularly necessary where a tributary enters a short distance upstream from the proposed water-temperature station. In such an instance, the waters may not be thoroughly mixed as they pass the station. A site where incomplete mixing exists is unsuitable for the collection of water-temperature data.

The temperature probe for the thermograph should not rest on the stream bed. A few tests made in the summer of 1963 indicated that the stream bed, when exposed to direct sunlight, can be about 1°F. warmer

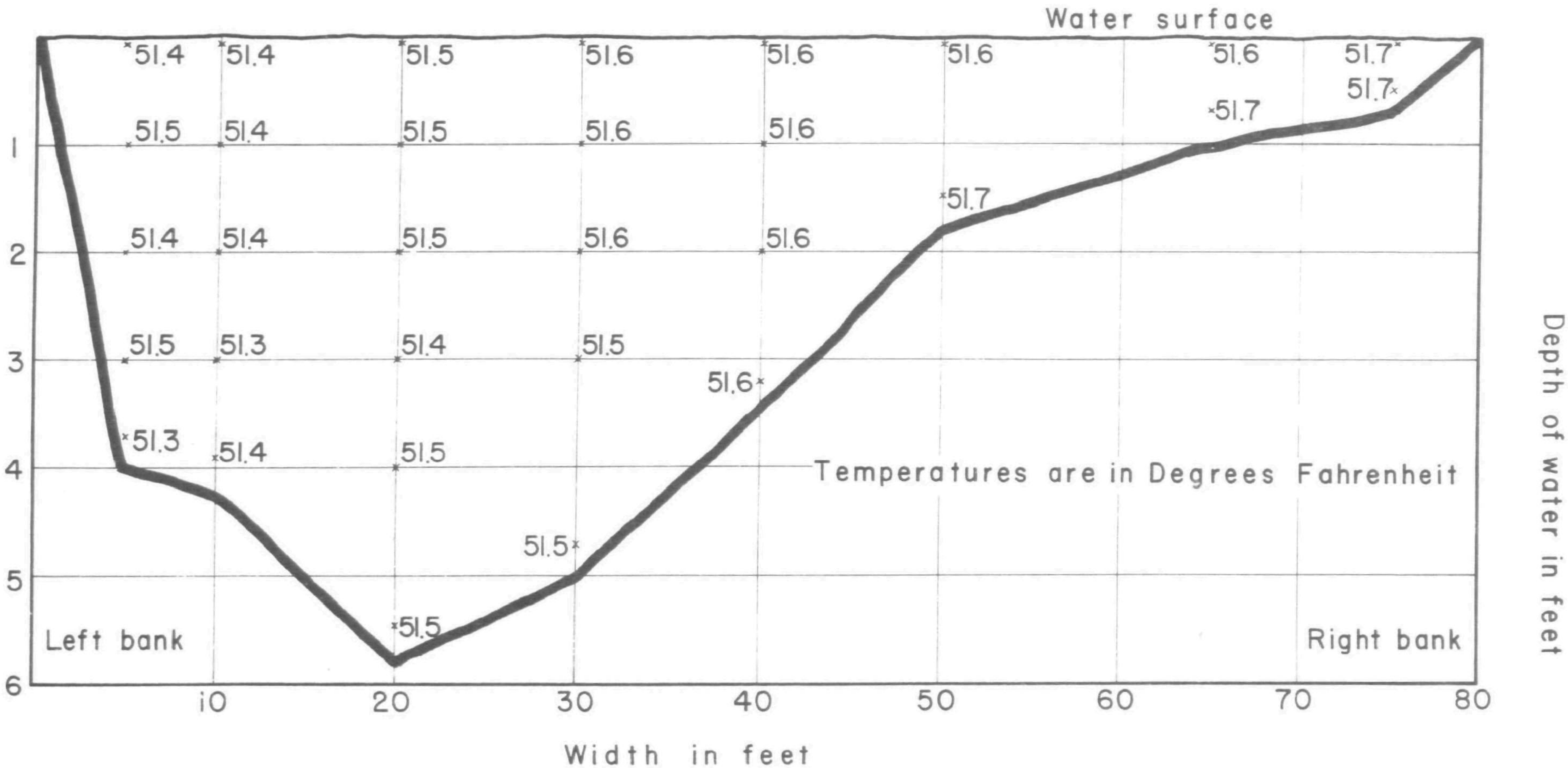

FIGURE I - TEMPERATURE PROFILE FOR BREITENBUSH RIVER ABOVE CANYON CREEK NEAR DETROIT ON JULY 16, 1963 than the water above it. As mentioned previously, Geological Survey installations are designed so that the stream end of the temperature inlet is above the stream bed.

Spot observations of water temperature with a hand thermometer should be made with the bulb end of the instrument immersed in moving water as the registration can change rapidly when the bulb is exposed to air. Because many streams have large diurnal fluctuations in temperature, the time of day should be noted along with the temperature. Minimum temperatures generally occur about 7 to 9 a.m. and maximum temperatures about 4 to 6 p.m. Figure 2 shows diurnal fluctuation of water temperature for selected streams at gaging stations in Oregon.

When maximum-minimum thermometers are serviced, the two readings should be made quickly because air temperature can reposition one of the metal markers indicating maximum or minimum water temperature. Another possibility for error is that the scale for minimum temperature increases in a downward direction and, so, is easily misread. Still another chance for error exists when the maximum-minimum thermometer is reset, because the mercury columns and markers must be set at the existing water temperature. When this has been accomplished, the thermometer must be quickly placed in position in the water before air temperature can affect the registration.

Conclusions

All instruments used for obtaining water temperature can, if used with proper precautions, yield results that are accurate to within at least 1°F. Also, all of these instruments have a place in the work to be done. Temperature-profile recorder, Whitney thermometers, bathythermographs, and infrared photography are adapted to precise measurements needed for water-loss and thermal-loading investigations. Continuous temperature records should be obtained for routine operational purposes and where good records are urgently and immediately needed. Also, at least one thermograph record should be obtained on each major stream for an indefinite period. Such records could serve as "primary" records with which "secondary", or intermittent, records could be correlated. The secondary records can be from thermographs operated for just a few years, or maximum-minimum thermometers operated for two or three summers. Where temperature records are not immediately needed, the secondary records can be in the form of spot observations made over a relatively long period. Multiparameter recorders are desirable where several water-quality characteristics must be measured. Infrared photography is particularly useful in locating sources of pollution in streams and in locating areas of groundwater inflow. The technique is also valuable in oceanographic work, where it helps define ocean currents and circulation patterns.

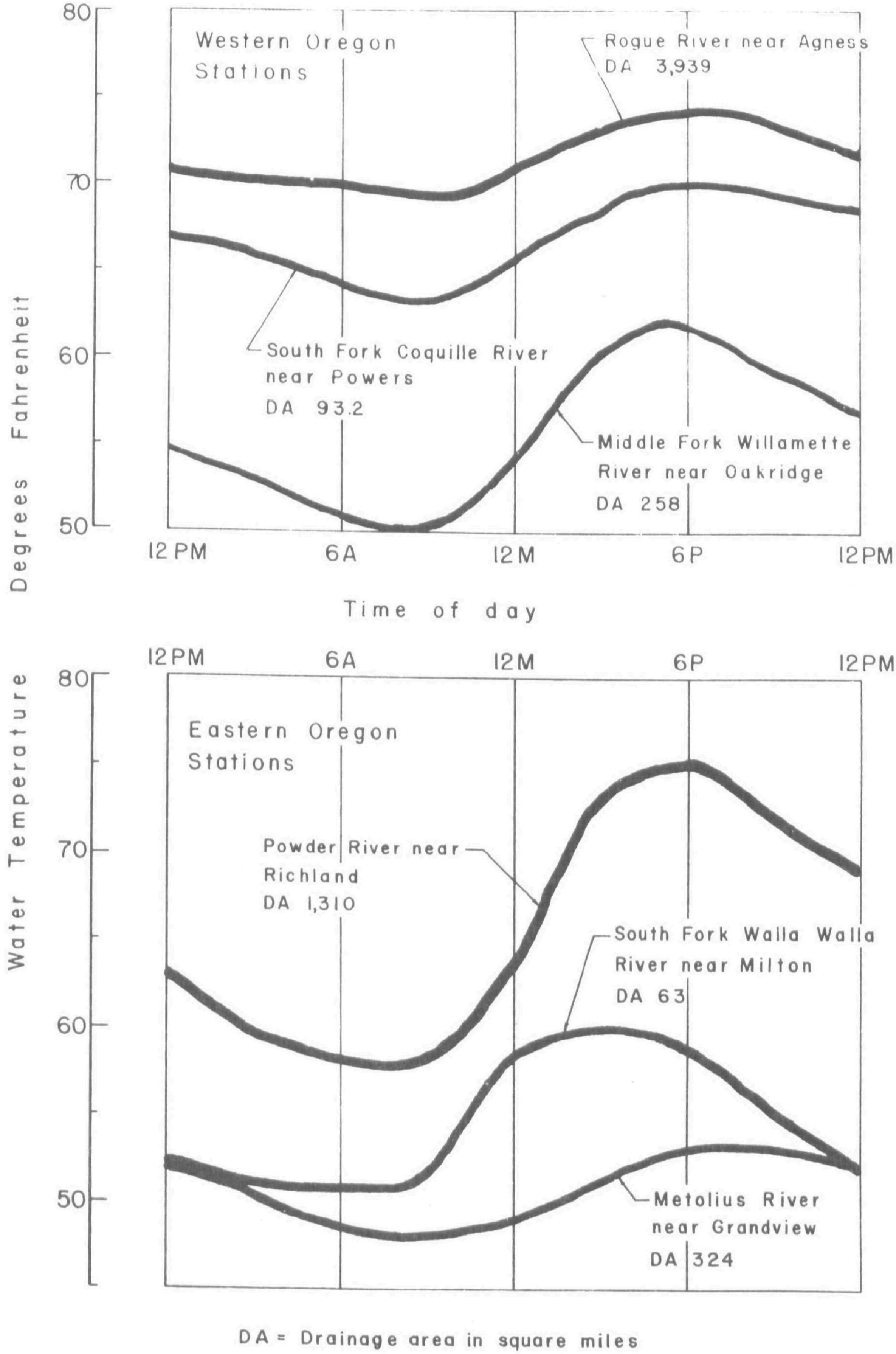

FIGURE 2 - TYPICAL DIURNAL FLUCTUATION OF WATER TEMPERATURES DURING SUMMER MONTHS

DISCUSSION

Q. Do you not use the Ryan thermograph?

A. No. We have written to them and have inquired of some of our offices who have used them. We are inclined to think that we probably will try them. They had some trouble over a year ago--the thermographs were not waterproof--but I think they have corrected most of that now and, if that is so, we are going to try them.

A. Fourteen of them are used in the Hungry Horse-Libby study with good results.

A. One of the advantages, of course, is that you don't have to build a house for these thermographs as we do with others. This is expensive. They could just be mounted in a pipe and this makes a very inexpensive installation. That is why we are thinking of trying them.

Q. Tell us again how many of these thermograph stations you have installed and approximately how long they have been in operation.

A. The first ones were installed in 1949 in cooperation with the Oregon State Fish Commission. Only one of these is operating now. Those installed for the Corps of Engineers have all been in continuous operation since 1949 and 1950. Up until this past summer we had obtained records at about 50 different sites with 33 thermographs which were constantly in operation. This past summer, in work for the Corps of Engineers, we installed 24 more. This was for their 308 Review Report for which these records were needed. We now have close to 80 thermograph records, 60 of which are in almost constant operation.

Q. Do you move these around from station to station?

A. Yes. Three or four were discontinued this year in the Alsea Basin.

SUMMARY OF CURRENT THEORIES AND STUDIES RELATING TO TEMPERATURE PREDICTION

Robert Zeller*

Outline

I. Introduction

A. Paper to be included in the Proceedings will:

1. Present several methods of temperature prediction

2. Discuss related studies involving these methods

3. Discuss research needs and present a general outline

for a comprehensive reservoir-stream temperature study.

B. This presentation will include:

1. Short description of the usual energy-budget approach

2. Outline of methods involving "heat-exchange coefficients"

a. Computation of "equilibrium temperature" by correlation with air temperatures.

b. Computation of natural stream temperature input and output functions.

3. A temperature prediction example using an exponential decay factor.

4. Discussion of research needs relative to the methods of temperature prediction presented.

II. Energy-Budget Approach

The energy budget attempts to equate the net exchange of heat between a body of water and its environment to a change in temperature.

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The exchange of heat involves: (notation from Schroepfer)

1. The difference between incident and reflected solar radiation ($+\Delta T_s$)

2. The difference between incident and reflected atmospheric radiation and the loss of heat by thermal radiation from the water surface (i.e., net exchange of long-wave radiation) ($-\Delta T_R$)

3. The loss of heat due to evaporative processes ($-\Delta T_E$)

4. The gain or loss of heat due to temperature difference at the air-water interface $\pm$ (ΔT_c)

5. The heat gain due to discharge, for example, of cooling water into the reach ($+\Delta T_A$)

These incremental temperatures, then, are added algebraically to the upstream temperature, T_A, to estimate the downstream interface temperature, T_B, as follows:

$$T_A + \Delta T_A + \Delta T_S - \Delta T_E \pm \Delta T_C - \Delta T_R = T_B$$

Other processes actually involved, but usually disregarded, are biochemical reactions and conduction of heat at the water-channel bottom interface.

Since computation of evaporation and thermal radiation exchange depend on the assumed downstream temperature, the equation cannot be solved directly. Formulae, such as the above, can be solved by successive trials assuming downstream temperatures, T_B.

This method is used equally well on streams in their natural, steady-state condition as on streams receiving large amounts of cooling water or cold, reservoir water.

III. Equilibrium Temperatures and Exponential Decay of Temperature Increments

This second approach is a two-fold operation:

A. First, the steady-state, or equilibrium, temperature of the water is estimated by any one of several methods.

B. Second, transient temperatures due to thermal additions are decayed exponentially downstream.

To elaborate just briefly:

A. Equilibrium temperatures can be estimated by:

1. Energy-budget equations, as just discussed.

2. Simple correlation with air temperature as Gameson, Hall & Preddy did on the Thames Estuary in 1957.

e.g.: The Thames Estuary data yielded the following relationship: Equil. Temp. = $\theta = 0.5 + 1.109\ T_a$

3. Estimation of the natural stream temperature according to its response to its thermal environment as expressed by Duttweiler's equations:

$$\text{Heat input} = T_\epsilon(t) = \frac{Q_n - 25}{\lambda} + \frac{B_1 T_{ad} + C_B T_a}{B_1 + C_B}\left(\frac{\lambda - \frac{1}{2}}{\lambda}\right)$$

$$\text{Water temp.} = T^*(x,t) = T_m + \sum_{n=1}^{\infty} T_{un} \sin(n\omega t + \phi_n - \alpha_n)$$

The first of these equations is plotted from a knowledge of climatological data. Short time intervals will yield points on a modified sine curve.

The second equation is merely a reflection of the first modified by an amplification factor (T_u/T_i) and phase lag (α).

B. Regardless of what form the equilibrium temperature takes, transients can be accounted for by computing the initial temperature increment and reducing it exponentially downstream. The exponential decay factor can be expressed as follows: $e^{-\frac{k}{v}x}$

Thus: $\Delta T_1 = \Delta T_o e^{-\frac{k}{v}x}$

Where: v = average velocity

x = dist. downstream

and: k has been evaluated by Major Duttweiler as $\frac{\lambda}{z}$

Where: z = avg. depth

and: $\lambda = C_1 + C_2 U_2 = 1.35 + 0.2\ U_2$

Where: U_2 = estimated wind speed in mph

An example of this procedure is worked out in the paper to be included in the Proceedings.

IV. Finally, I want to list some of the areas where continuing research is needed relative to the several methods of temperature prediction discussed in the paper included in the symposium Proceedings.

A. Energy-budget approach

1. Inexpensive instrumentation to replace the array of equipment currently needed to obtain accurate radiation and evaporation data.

   One possibility which has been around for some time now is the CRI. (These are, essentially, insulated evaporation pans instrumented to simulate a complete-miniature heat-budget unit. Several small units of this type were installed recently here in Oregon. Evaluation results should be available soon.)

2. Extensive correlation of all available meteorological data could eliminate the need for this instrumentation on many projects, if not most projects.

3. Methods should be developed to determine location and quantities of significant bank storage.

4. We still need some guidelines on the accuracy of computations required. This relates directly to the basic temperature criteria problem.

B. Equilibrium temperature correlations and exchange coefficients

1. Although usefulness of air-water temperature correlation seems controversial for this region, a reasonable correlation study would settle this question.

2. The values arrived at by Duttweiler for the constants used to estimate the exchange coefficient (λ) need verification.

Synopsis

The following paragraphs are intended to familiarize the reader with some of the currently-used methods for estimating stream temperatures as a function of their thermal environment and time. No attempt has been made here to evaluate the methods presented other than to point out major features of interest.

Also included is a presentation of some recent and proposed field studies involving one or more of the temperature prediction methods. Several of these studies are discussed in conjunction with the presentation of the method of prediction; others are discussed separately.

Finally, a partial tabulation of research needs relative to the methods of temperature prediction included in this paper has been attempted.

Summary of Current Theories and Studies Relating to Stream Temperature Prediction

Generally speaking, there are two currently-used methods of predicting stream temperatures. The first method applies an energy-budget approach to both streams in a steady-state thermal environment and to streams responding to significant discharges of industrial cooling water or impounded water.

The second method is a two-fold operation. First, the steady-state, or equilibrium, temperature of the stream is estimated by any one of several methods, including the energy budget. Second, transient temperatures due to thermal additions are imposed on the equilibrium temperature profile at the point of discharge and decayed exponentially downstream.

I. The Energy-Budget Approach

The energy budget attempts to equate the net exchange of heat between a body of water and its environment to changes in water temperature. Energy-exchange processes normally considered include:

1. The difference between incident and reflected solar radiation.

2. The difference between incident and reflected atmospheric radiation and the loss of heat by thermal radiation from the water surface (i.e., net exchange of long-wave radiation).

3. The loss of heat due to evaporative processes.

4. The gain or loss of heat due to temperature differences at the air-water interface.

5. The heat gain or loss due to advected water (e.g., heat gain due to cooling-water discharges).

Other processes actually involved, but usually disregarded, are biochemical reactions and conduction of heat at the water-channel bottom interface.

For detailed descriptions of theory and data relative to individual energy-budget parameters, the interested reader is referred to several references in the bibliography (1, 6, 7, 8, 17).

A. G. J. Schroepfer (1961) presented an energy-budget solution to temperature prediction for the Mississippi and Minnesota Rivers at Minneapolis-St. Paul, Minnesota (15).

Schroepfer set up the energy budget in the form of its effects on stream temperature by converting heat-exchange quantities to incremental temperatures. The resulting mathematical expression of the energy budget is as follows:

$$T_A + \Delta T_A + \Delta T_S - \Delta T_E - \Delta T_C - \Delta T_R = T_B$$

Where T_A = temperature of river at point A

ΔT_A = temperature increase due to thermal addition

ΔT_S = temperature increase due to solar radiation

ΔT_E = temperature decrease due to latent heat loss

ΔT_C = temperature decrease due to convective heat transfer

ΔT_R = temperature decrease due to thermal radiation exchange

T_B = temperature of river at point B

After substitution of measured and estimated quantities plus conversion units, Schroepfer's "working" relationship is:

$$T_A + \left[\frac{0.1855}{Q}\right] H_A + \left[\frac{0.00445A}{Q}\right]\left[H_s - (0.3253)(10 + W)(V_w - V_a) - (0.16)(5 + W)(T_w - T_a) - 1.1\ (T_w - T_a)\right] = T_B$$

Where: Q = river discharge; cfs

H_A = thermal additions (i.e., heat load); mega BTU/day

A = water surface area; 1000's sq. ft.

H_s = solar radiation; BTU/sq. ft./hr.

W = mean wind speed; mph

V_w = saturation water vapor pressure at the mean temperature of the water surface; mm. of Hg.

V_a = partial pressure of water vapor at the temperature and relative humidity of the surrounding air; mm of Hg.

T_w = mean water temperature; ^{o}F.

T_a = mean air temperature; ^{o}F.

In the above equation, Meyer's formula for evaporation was selected since the values for the empirical constants were developed in Minnesota:

$E = C\ (1 + 0.1W)\ (V_w - V_a)$ = evaporation rate; inches/month

C = empirical constant = 10 for deep rivers to 15 for shallow streams

W = wind speed; mph

V_w = saturation vapor pressure at the temperature of the water surface; inches of Hg

V_a = absolute vapor pressure at the temperature and relative humidity of surrounding air; inches of Hg.

Solar radiation was estimated from St. Cloud, Minnesota, radiation data after a correlation study using local percent sunshine records for comparison. No correction for reflected radiation was applied to the solar radiation data. Wind speeds and other meteorological data were all estimated from local records.

The above "working" equation is solved by successive approximations using assumed downstream temperatures. Ordinarily, convergence on the assumed temperature is rapid.

With this equation, Schroepfer computed temperature profiles of the Mississippi River from the Minneapolis waterworks intake downstream 43 miles to the Hastings Dam for the month of August. The results were checked against Minneapolis-St. Paul Sanitary District temperature data for the years 1950-59 obtained during routine river sampling operations (Figure 1). Agreement was generally good where the sampling data was adequate for comparison. Temperature profiles computed for the Minnesota River downstream of a large steam generating power plant provided similarly good agreement with measured temperatures (Figure 2).

A six-day, diurnal plot of the Mississippi River temperature a short distance downstream from a steam generating power plant in St. Paul was computed for August 25-31, 1959. Measured temperatures at the downstream station again provided good agreement with the computed profile (Figure 3).

AVERAGE MISSISSIPPI RIVER TEMPERATURE PROFILES
August 1950-1959

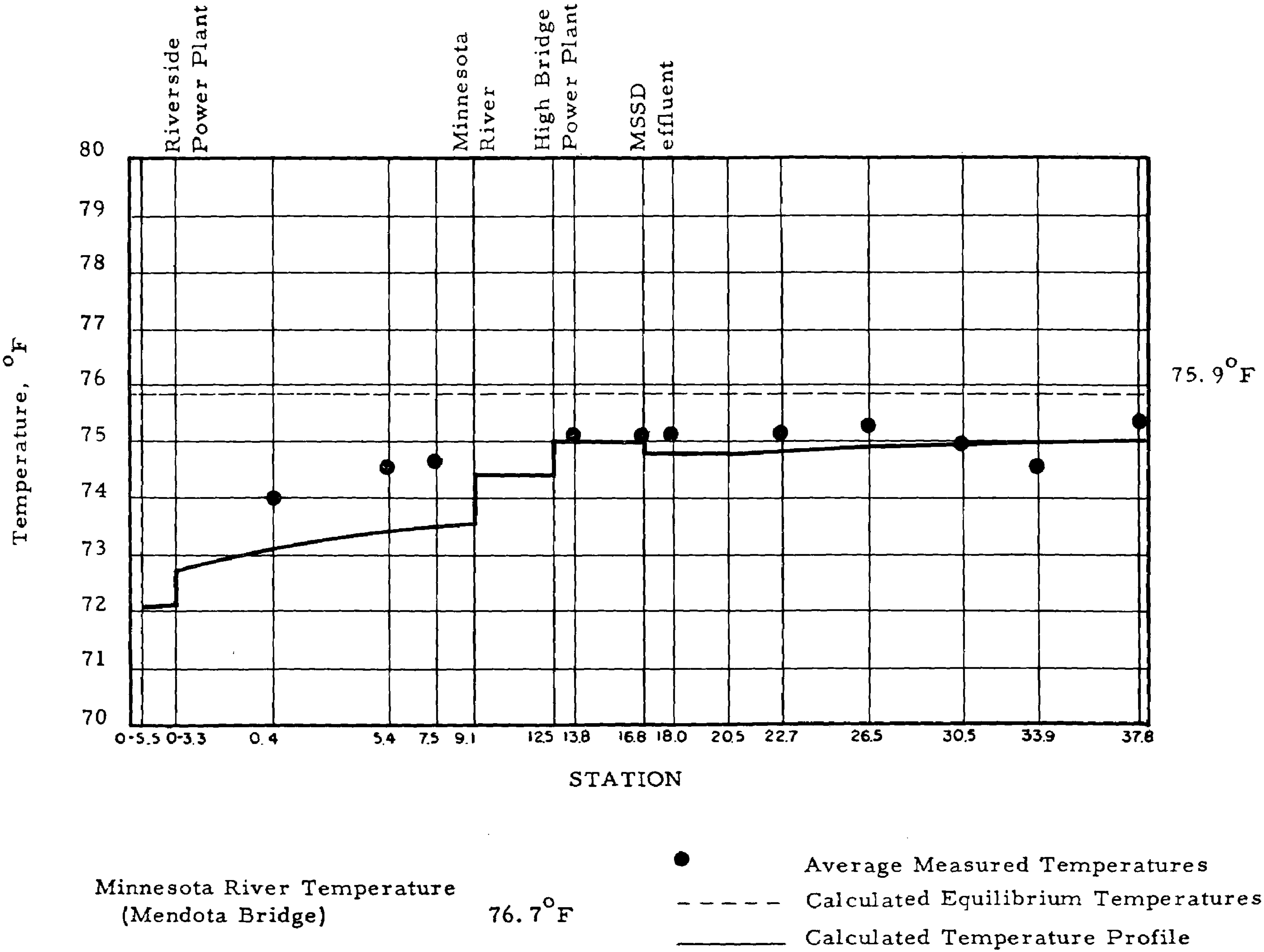
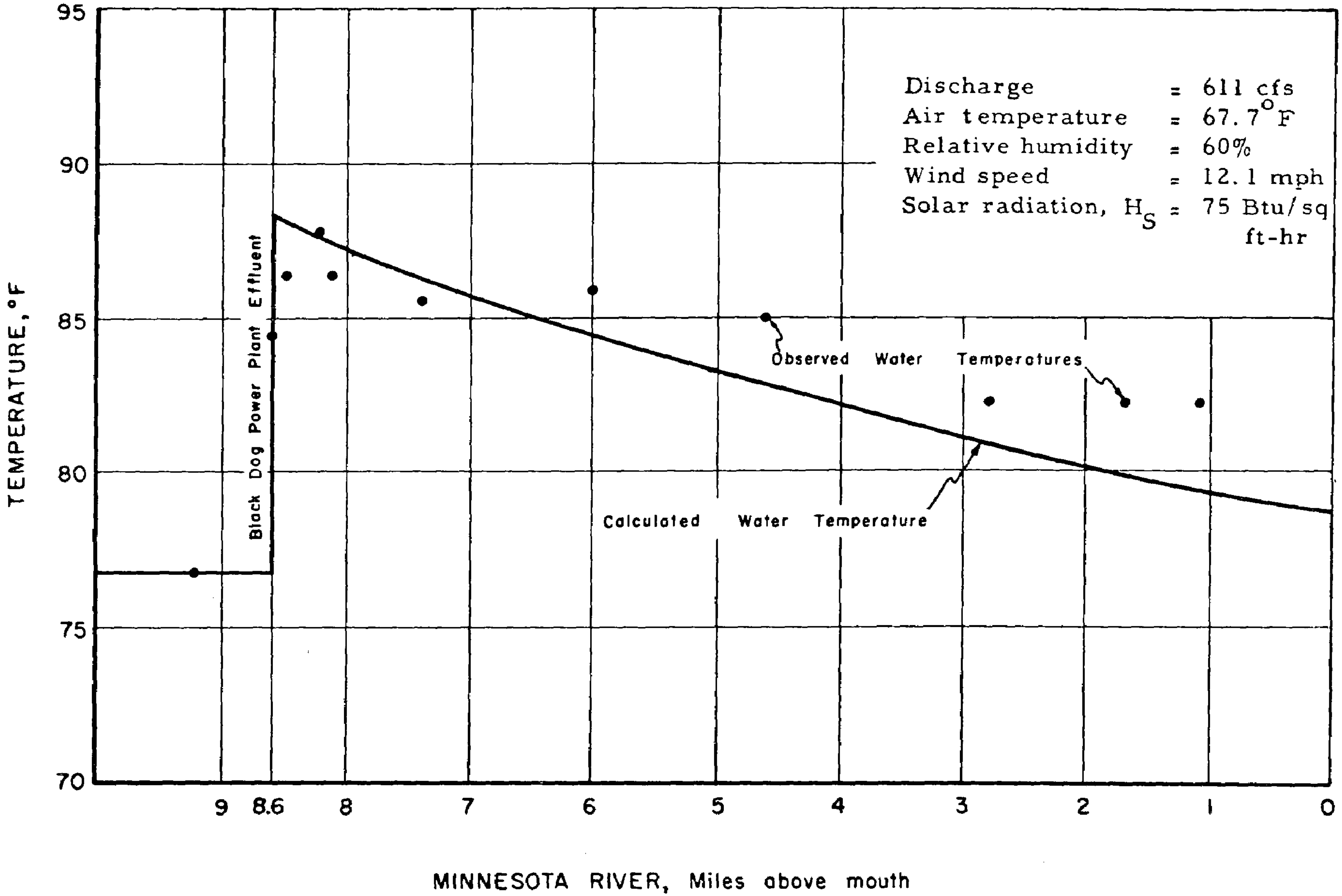
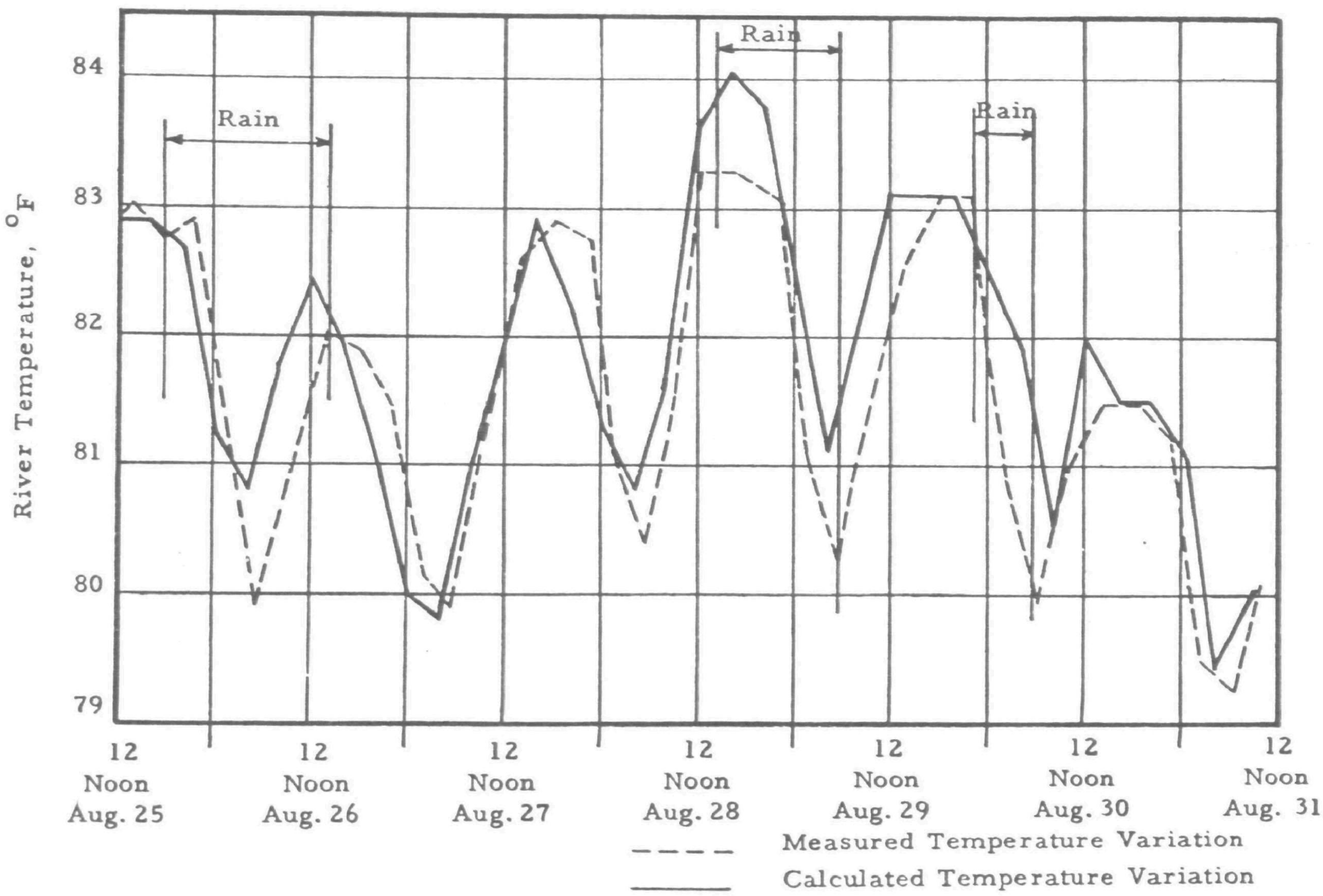


Figure 1



MEASURED AND CALCULATED TEMPERATURE PROFILES
Minnesota River, August 21, 1958

Figure 2



COMPARISON BETWEEN CALCULATED AND OBSERVED WATER TEMPERATURES, MISSISSIPPI RIVER STATION M 13.4
August 25-31, 1959

Figure 3

Finally, the derived energy-budget equation was used to predict 1980 temperature profiles of the Mississippi and Minnesota Rivers based on estimated steam generation thermal additions and values for meteorological conditions.

B. Jerome M. Raphael (1962) presented an energy-budget formulation applicable to lakes, reservoirs, and stream increments of isotropic temperature structure (12).

Raphael's method applies a numerical integration of a time rate of temperature change function as follows:

$$\text{Time rate of temperature change} = \frac{dt_w}{d\theta} = \frac{Q_t A + m_i (t_i - t_w)}{m_w}$$

Where: θ = time

m_w = total mass of the lake

t_w = mean temperature of the lake

m_i = inflow water mass

t_i = inflow water temperature

A = lake surface area

Q_t = total surface heat transfer per unit of time.

Substitution of volumes for mass and simplification for solution over given increments of time resulted in the following working equation:

$$V_l t_w = \frac{Q_t A \theta}{62.5} + V_i (t_i - t_w)$$

Where: V_l = volume of the lake

V_i = inflow volume

t_w = average lake temperature over the increment of time, θ

Solution of this equation requires evaluation of the gross heat transfer parameter, Q_t, as follows:

$$Q_t = Q_i - Q_b - Q_h - Q_e + Q_v; \text{ BTU/sq.ft./hr.}$$

Where: $Q_i = (1\text{-}0.0071\ C^2)\ (Q_s - Q_r)$ = net short-wave insolation and Q_s = incident solar radiation (measured)

Q_r = reflected solar radiation (measured or estimated)

C = average cloud cover in tenths of sky covered

Q_b = effective back (long-wave) radiation

$= 0.970 \sigma (T_w^4 - \beta T_a^4)$

σ = Stefan-Boltzmann constant = 1.71×10^{-7}

β = function of atmospheric vapor pressure

$= Q_a / \sigma T_a^4$; where Q_a = atmospheric radiation

T_w = water surface temperature; °F.

T_a = air temperature; °F.

Q_e = evaporation energy = $12U (e_w - e_a)$

U = average wind speed in knots

e_w = saturation water vapor pressure at the temperature of the water surface; in. of Hg.

e_a = absolute vapor pressure of water in the air; in. of Hg.

Q_h = conducted heat = $0.00407 \, UP (t_a - t_w)$

P = atmospheric pressure; in. of Hg.

t_a = air temperature; °F.

t_w = water surface temperature; °F.

For application to stream temperature prediction, Raphael's working equation assumes the outflow temperature of a reach to be the inflow temperature of the adjacent downstream reach.

In his presentation of the method, Raphael includes examples of its application to temperatures in a small, re-regulating reservoir for a period of one week and to a major western river, estimating daily temperatures for July through September.

C. The 1960-61 Advanced Seminar of the Johns Hopkins University, Department of Sanitary Engineering and Water Resources, submitted a study report on heat exchange processes in flowing streams (8). This report includes discussion of the energy budget, turbulent diffusion theory, and exponential decay of temperature with time.

Following a detailed examination of the individual heat exchange processes, the Advanced Seminar expressed the total "heat budget" for a selected stream as follows:

$$S \left[Q_s - Q_r - Q_a - Q_{ar} - Q_{bs} - Q_e - Q_h - Q_w \right] + Q_{vi} - Q_{vo} + (Q_{vi}{}^1 - Q_{vo}{}^1) = Q_{v}$$

Where: S = surface area

Q_s = incident solar radiation (measured)

Q_r = reflected solar radiation (measured or estimated)

Q_a = atmospheric radiation (measured)

Q_{ar} = reflected atmospheric radiation $\approx 0.03\ Q_a$

Q_{bs} = back radiation from water = $e'\sigma T^4 = 0.97\sigma T^4$

e.g.: $Q_{bs} = 25 + \frac{t}{2}$; cal./cm.^{2}/hr.

Where: $10^oC. < t < 40^oC.$

t = water surface temperature

Q_e = evaporation energy = $EL\rho_e$

E = volume of water evaporated per unit time

L = latent heat of vaporization

ρ_e = density of water evaporated

Q_h = conduction loss at air-water interface

$$= -C_p A \left(\frac{dt}{dz} + \gamma\right)$$

Where: C_p = specific heat of air at constant pressure

A = vertical component of eddy conductivity

$$\frac{dt}{dz} = \text{temperature gradient of air}$$

γ = adiabatic lapse rate

However, using Bowen's ratio, R, $Q_h = RQ_e$

$$\text{Where:} \quad R = C_B \left[\frac{T_o - T_a}{e_o - e_a}\right] \frac{P}{1000}$$

C_B = 0.61 (varies from 0.58 - 0.66)

T_o = water surface temperature; °C.

T_a = air temperature; °C.

e_o = saturation water vapor pressure at water surface temperature; mb

e_a = water vapor pressure of the air; mb

P = atmospheric pressure; mb

Q_w = loss of sensible heat by evaporation of water at constant temperature

$$= (\rho_e E) \ C \ (T_e - T_b)$$

C = specific heat of water at temperature of evaporation

T_e = evaporation temperature; °C.

T_b = arbitrary base temperatures; °C.

Q_{vi} = primary advected heat input (i.e., inflow heat)

Q_{vo} = primary advected heat output (i.e., outflow heat)

$Q_{vi}^1 - Q_{vo}^1$ = heat exchange by eddy diffusion

Q_θ = change in heat storage

Rearranging the above equation:

$$SQ_n = SQ_{bs} - S(1 + R) \ Q_e - SQ_w + (Q_{vi} - Q_{vo}) + (Q_{vi}^1 - Q_{vo}^1) = Q_\theta$$

Q_n = net radiation input

and: reach length $= \Delta x$

average discharge in the reach = q

average velocity in the reach $= \bar{v} = \frac{\Delta x}{\Delta t}$

Then: $q(T_o - T_b)\, C_p + SQ_n - SQ_{bs} - S(1 + R)\, Q_e - SQ_w +$

$$(Q_{vi}{}^1 - Q_{vo}{}^1) = (q - E)\,(T_1 - T_o)\ C\rho$$

Where: T_o = average entering water temperature; °C.

T_b = arbitrary base temperature; °C.

C = specific heat capacity

ρ = average water density; gm/cc

T_1 = average leaving water temperature; °C.

Substituting for: Q_{bs}; Q_e; Q_w; and $Q_h + Q_e = (1 + R)\, EL\rho$

Then: $q^C\rho(T_o - T_1) + EC\rho(T_1 - T_b) + (Q_{vi}{}^1 - Q_{vo}{}^1)$

$$= S\,[\,Q_{bs} + (1 + R)\ Q_e + Q_w - Q_s\,]$$

$$= S\,[\,(25 + \frac{T_{o1}}{2}) + (1 + R)\, EL\rho + EC\rho\ (T_{o1} - T_b) - Q_s\,]$$

Where: $T_{o1} = \frac{To + T_1}{2}$

This "working equation," as with previous energy-budget formulations, is solved by trial and error for the downstream-face temperature, T_1.

Now, if heat in the form of cooling water is uniformly discharged into the reach at the upstream face with no significant gain in overall discharge, q, then:

$$(q-q_c)\,(T_o{}^1 - T_b)\, C\rho + q_c C\rho(T_c - T_b) + SQ^1{}_n - SQ^1{}_{bs} - S(1 + R^1)$$

$$Q^1{}_e - SQ^1{}_w + (Q^1{}_{vi}{}^1 - Q^1{}_{vo}{}^1) = (q - E^1)\,(T_1{}^1 - T_b)\ C\rho$$

Where: q_c = cooling-water discharge

T_c = temperature of cooling water; °C.

Primes indicate new heated condition.

Rearranging and letting: $T_b = To$ & $T_{o1} = \dfrac{T_o + T_1}{2}$

Then:

$$q_c C\rho[(To^1 - To) - (T_1{}^1 - T_1)] + q_c C\rho(T_c - To^1)$$
$$+ C\rho[E^1 (T_1{}^1 - T_b) - E (T_1 - T_b)]$$
$$= S\left[\frac{(To^1 - To) + (T_1{}^1 - T_1)}{4}\right] + S\rho[1 + RL^1E^1\rho - (1 + R)LE]$$
$$+ SC\rho\left[E^1 \frac{(To^1 - To) + (T_1{}^1 - To)}{2} - E\frac{T_1 - To}{2}\right]$$

By trial and error, this equation will approximate the new downstream temperature, assuming a discharge of q_c at temperature T_c into it.

Note that solar radiation quantities are independent of water temperature. Hence, solar radiation data is not needed for solution of the modified stream temperature. Evaporation data and original temperatures are needed, however.

In conjunction with their discussion of stream temperature prediction relative to heated discharges, the Advanced Seminar pointed out the necessity for examining in-stream temperature equalization by temperature diffusion. For example, if cooling water (or reservoir water) is discharged at a point in a stream, there will be a finite, predictable distance downstream in which significant vertical and/or horizontal stratification exists. Until a point is reached where no stratification of temperature exists, temperature equalization by turbulent diffusion must be investigated because of its effects on heat exchange at the air-water interface. No attempt will be made in this paper to investigate this problem further. The interested reader is referred to the Advanced Seminar and related papers on this subject.

To test their evaluation of the energy-budget processes and study the relationship of the energy budget to turbulent mixing mechanisms, the Advanced Seminar analyzed data from an eastern river temperature study conducted in August, 1960.

Data collected in the study included the following:

1. Location of temperature transects relative to a heated discharge outfall as follows:

Transect	Distance from Outfall (ft.)
3	(upstream)
4	50
6	500
7	1,000
9	3,000
10	5,000
11	7,000

2. Soundings at each temperature sample point

3. Temperature profiles spaced approximately 100 ft. apart at each transect. (Stream width averaged greater than 1,000 ft.)

4. Relative humidity along each transect

5. Time intervals of study at each transect (necessary for temperature correction calculations to follow a specific body of water downstream)

6. Weather description at each transect

7. Automatic stream temperature recorder data in area of the heat outfall

8. Radiation data from nearest weather station

9. Wind velocity data

10. Heated water discharge and temperature

11. River discharge estimates for the specified date.

Seven transects were studied in all--one upstream of the heat outfall and six downstream. Total reach distance was about 1½ miles.

Field data were analyzed as follows:

1. Advected heat = $Q_v = K \sum a_1 V_1 \Delta T_1$; cal/hr.

   Where: a_1 = subsection areas of uniform width

   V_1 = average velocity at subsection

ΔT_1 = temperature excess over the natural water temperature; °C.

$K = 0.565 \times 10^8$

2. Radiation

The water surface area was divided into areas of equal temperature where diffusion of the heated discharge was incomplete. Generally, this involved a warm wedge, natural temperature wedge, and gradient area.

Net solar radiation input was computed from direct and diffuse solar radiation given at the weather station, assuming the reflected radiation at 0.048 cal./cm^2/min.

Net atmospheric radiation = 0.97 x 1.25 x solar radiation

Long-wave radiation emitted = $0.97 \sigma T^4$

3. Heat lost from evaporative processes was computed from the difference between the advected heat and net radiation input. (i.e., heat loss from evaporative processes = $Q_{vi} + Q_n - Q_{vo}$)

Finally, temperature excesses over natural temperature were computed from turbulent mixing theory (Hinze, J. O.; 1959; Turbulence; McGraw Hill; New York) and compared with the field data.

The conclusions drawn from this application of the energy budget and turbulent mixing theory are particularly interesting:

1. The reduction in cross-section temperature downstream of the heated discharge to a point where the temperature gradient vanishes was more a result of turbulent mixing than heat loss to the atmosphere. (Note that this reach was over a thousand feet wide.)

2. Turbulent mixing theory described actual conditions reasonably well.

3. The energy-budget needs for accurate instrumentation were emphasized.

4. Variation in evaporation rates and Bowen ratios between natural and "heat-loaded" conditions was significant.

D. There have been other presentations of the energy budget; however, the above methods are fairly representative of those currently used in application to stream temperature prediction.

Following are several recent and current studies involving energy-budget applications to stream temperature predictions:

Biblio. Ref.	Location: Stream	Location: Reservoir	Location: State	Author	Sponsoring Agency	Study Completion Date
10	Rogue R.	Lost Creek	Oregon	W. Bruce McAlister	Bureau of Sport Fish. & Wildlife	1961
2	Clearwater River	Bruces Eddy Dam	Idaho	Wayne V. Burt	Walla Walla District, Corps of Engineers	1960
13, 14	Columbia River	Wells, Rocky Reach, Wanapum, and Priest Rapids Dams	Wash.	J. M. Raphael	P.U.D. #2, Grant Co., Washington	1961-1962

In addition, the Oregon State Water Resources Board is currently applying energy-budget analyses to a cooperative study of stream temperature prediction and control in the Umpqua River Basin, Oregon. The Oregon State Water Resources Board is also applying the energy-budget method to data collected in August, 1963, on the Coast Fork Willamette River, Oregon, during a cooperative field study.

II. Equilibrium Temperatures and Exponential Decay of Transient Temperatures

A. M. LeBosquet, Jr., (1946) introduced a relationship for determining heat loss rates from streams receiving cooling-water discharges (9). The heat loss coefficient, K, would be found from examination of actual excess-temperature decay rates expressed as follows:

$$-\frac{df}{dT} = \frac{KA_sF}{L}$$

Where: K = heat loss in BTU/sq.ft./hr./°F. of excess temperature of water over air

F = excess temperature of water over air at distance (D) miles; °F.

A_s = surface area; sq. ft.

L = weight of water; lb.

After substitution of stream physical characteristics, integration, and simplification, the derived relationship for K is:

$$K = \frac{Q \operatorname{Log}_{10} \frac{Fa}{F}}{0.0102\ WD}$$

Where: Q = average discharge; cfs

Fa = initial excess temperature of water over air; °F.

W = average stream width; ft.

D = reach distance; miles

LeBosquet points out in his presentation that the decay of excess temperature with time is exponential. This phenomenon is readily seen from a rearrangement of the derived formula for K:

$$F = Fa \exp\left\{\frac{2.3\ (0.0102)\ WK}{Q}\ D\right\}$$

The range of values for K given by LeBosquet for rapid, shallow streams and slow, sluggish streams was 18 to 6 BTU/sq. ft./hr./°F.

B. Gameson, Hall, and Preddy (1957) presented a method for predicting temperature effects on the Thames Estuary due to steam-electric generation cooling water discharges (5). Their conclusions were based on the following study outline:

1. Measurements of water temperatures in the estuary over the years 1949-54.
2. Estimation of "unheated" water temperatures for the same years.
3. Estimation of the rate of heat entry to the estuary.
4. Calculation of the rate of loss of "excess" temperatures.
5. Prediction of the temperature distribution for unit inputs of heat at points throughout the estuary.

Elaboration of their study follows:

1. The estuary temperature measurements were taken weekly at a midstream depth of six feet and at fifteen regularly-spaced stations over a reach of fifty miles.
2. The "unheated" water temperatures were estimated by regression analyses of a comparison between long-term records of water and air temperatures dating back to the first half of the eighteenth century. This was done for three stations. The resulting correlations for the three stations studied were extrapolated to estimate "unheated" temperature curves for the entire fifty-mile reach.
3. The estimated rates of heat entry are summarized as follows:

a.	Steam-electric power plants (7)	228×10^9 BTU/day
b.	Industrial outfalls (gas works, paper mills, sugar refineries)	19×10^9
c.	Sewage outfalls	27×10^9
d.	Advected fresh water	20×10^9
e.	Biochemical activity	12×10^9
	TOTAL	306×10^9 BTU/day

4. The temperature change rate for a given heat loss was expressed as follows:

$$\frac{d\theta}{dt} = -\frac{f}{z}\theta$$

Where: θ = initial temperature increment

f = an exchange coefficient or rate constant with time^{-1} dimensions

z = average stream depth

t = time

Equating the heat-loss rate to rate of heat entry yielded an average value for the exchange coefficient, f, as follows:

$$\delta Q = \text{heat loss rate} = -(yz\delta x)\rho\sigma \frac{d\theta}{dt}$$

$$= -yz\delta x\rho\sigma\left(-\frac{f\theta}{z}\right)$$

$$= \rho\sigma y\theta \; f\delta x$$

and: $Q = \rho\sigma\bar{f}\int y\theta \; dx$ = total rate of loss of excess heat

Where: y = stream width

δx = reach increment

ρ = water density

σ = specific heat of water

The total rate of heat loss, Q, can be equated to the known rate of heat entry, assuming steady conditions, yielding a value for the average exchange coefficient, $\bar{f}$. For the Thames Estuary, $\bar{f}$ = 4.0 cm/hr. over a selected period.

5. Exchange coefficients, obtained in the above manner, were then used in conjunction with a derived temperature discharge distribution method to approximate observed temperature profiles.

C. Gameson, Gibbs, and Barrett (1959) published the results of a temperature survey and study of the River Lea near London (4).

For a total of 129 hours, water temperatures were measured about once every hour at five stations below a steam-electric generation plant and once every three hours at one station upstream.

Air temperatures were measured at each station. Solar radiation temperatures (mercury-in-glass thermometer with a blackened bulb placed in an evacuated outer glass bulb) and wind velocities were measured at a single station.

The stream temperature data showed strong diurnal variations of up to 8°C. near the power plant outfall. Decreasing diurnal variations and lower mean temperatures downstream indicated definite cooling effects.

Because of the strong diurnal temperature variations, it was possible to calculate channel volumes and flow times from flow records and the peak-to-peak time intervals on the temperature profiles.

Equilibrium (or unheated) water temperatures were estimated in the same fashion as for the Thames Estuary study. Using the same data as for the Thames Estuary, the equilibrium water temperature was estimated as follows:

$$\theta = 0.5 + 1.109\ T_a$$

Where: θ = equilibrium water temperature; °C.

T_a = air temperature; °C.

Again, the exchange coefficient was calculated from the time rate of temperature change function with the following results:

Over-all average; f = 2.6 cm/hr.

Range of f = 1.66 - 3.83 obtained by averaging all four reaches over four days

Range of f = 2.10 - 2.88 obtained by averaging all four days for each reach.

One conclusion of this study, later contradicted by others, was that the exchange coefficient was apparently unrelated to wind speed.

D. C. J. Velz and J. J. Gannon (1959) presented a comprehensive paper on stream temperatures; temperature effects on water quality; magnitude and sources of heat loads; and temperature prediction (16).

Velz and Gannon derived a relationship for the long-term equilibrium (unheated) stream temperature from meteorological data as follows:

$$(1.8 + 0.16W)\ E + 0.00722\ H_vC\ (1 + 0.1W)\ V_E$$

$$= (1.8 + 0.16W)\ T_a + 0.00722\ H_vC\ (1 + 0.1W)\ V_a + H_s$$

Where: W = wind speed average measured at 25 ft. above the water surface or surrounding land area; mph

E = equilibrium water temperature (unknown); °F.

H_v = latent heat of vaporization at the assumed water temperature; BTU/lb.

C = constant = 14 for flowing streams of moderate depth and velocity

V_E = equilibrium temperature vapor pressure (unknown); in. of Hg.

T_a = average air temperature; ^oF.

V_a = average absolute water vapor pressure of the air at 25 ft. above the water surface; in. of Hg.

H_s = solar radiation heat gain (measured); BTU/sq.ft.

The above energy-budget relationship is solved by successive approximation, assuming values for the equilibrium temperature. In the derivation of this relationship, Meyer's evaporation formula was used to estimate evaporation.

Velz and Gannon then derived a relationship between water temperature and the water surface area required for cooling, as follows:

$$A = -224{,}640 \sum_{T_1}^{T_2} \frac{\Delta T_w}{\alpha(V_w - V_E) + \beta(T_w - E)} = \text{sq.ft./cfs of streamflow}$$

Where: $\alpha = 0.00722\ H_v C\ (1 + 0.1W)$

$\beta = 1.8 + 0.16W$

The total increment of temperature between the initial heated condition and desired downstream temperature is divided into equal increments (ΔT_w) with T_w and V_w as the mean temperature and mean saturation vapor pressure in each increment. Note here, however, that E represents a "long-term" equilibrium temperature and is not specific for short-time periods. Hence, long-term weather data averages are used in this computation.

According to Velz and Gannon, the above solution for required cooling area will yield stream temperature profiles as follows: "Knowing the cumulative surface area along the course of the stream for the particular runoff from channel cross sectioning, the river temperature profile for that runoff can be constructed."

E. David W. Duttweiler (1963) completed a mathematical model of stream temperature (3). His derivation began by equating the heat gained in an incremental reach of stream to the time change in enthalpy of the water in the reach as follows:

$$\underbrace{c\rho q \; (T - T_b)dt}_{①} + \underbrace{((Q_n - Q_{bs} - Q_e - Q_w - Q_h - Q_hb)\; wdxdt)}_{②}$$

$$\underbrace{- c\rho(q - q_e) \; (T + \frac{\partial T}{\partial x} dx - T_b)\; dt}_{③} = \underbrace{c\rho\, adx \frac{\partial T}{\partial t} dt}_{④}$$

Where: ① = heat entering the reach

② = net heat exchange in the reach

Q_n = net radiation input

Q_{bs} = thermal radiation from the water surface

Q_e = evaporation heat loss due to latent heat of evaporation

Q_w = loss of sensible heat by evaporation of water at constant temperature

Q_h = conduction loss at air-water interface

Q_{hb} = conduction loss through stream bed

③ = heat leaving the reach

④ = increment in enthalpy in time, dt, for the volume, adx

c = specific heat of water; gcal/gm/^oC.

ρ = density of water; gm/cm^3

q = discharge

T = entering water temperature

T_b = arbitrary base temperature

dx = reach increment

dt = time increment

w = stream width

a = cross-sectional area

q_e = rate of evaporation; cm^3/hr.

After substitution of expressions for the energy-budget terms; disregarding bank loss; letting wdx = surface area; q_e = Ewdx; q = av (where v = velocity); L = constant; assuming $q \gg q_e$; rearranging and simplifying, Duttweiler arrived at:

$$\frac{c\rho a}{w}\frac{\partial T}{\partial t} + \frac{c\rho av}{\omega}\frac{\partial T}{\partial x} = Q_n - 25 + \frac{(A + BU_2)}{24}(\beta_1 T_{ad} + C_B T_a)\ L\rho$$

$$-\left\{\tfrac{1}{2} + \frac{(A + BU_2)}{24}\ L\rho(C_B + \beta_1)\right\}\ T$$

The general expression for evaporation used in the above equation was as follows:

$$E = \frac{(A + BU_2)\ (e_w - e_a)}{24}\ ,\ \text{and}\ e_w - e_a = \beta_1\ (T - T_{ad})$$

where β_1 = incremental slope of the vapor-pressure curve.

Note that the above-derived equation is now a space-time expression for the rate of temperature change in the reach. In this equation, Duttweiler made the following substitutions:

$$\mu = Q_n - 25 + (\beta_1 T_{ad} + C_B T_a)\ \frac{(A + BU_2)}{24}\ L\rho;\ \text{gcal./cm}^2\text{/hr.}$$

$$\lambda = \tfrac{1}{2} + (\beta_1 + C_B)\ \frac{(A + BU_2)}{24}\ L\rho;\ \text{gcal./cm}^2\text{/hr./}^\circ\text{C.}$$

Thus: $$\frac{c\rho a}{w}\frac{\partial T}{\partial t} + \frac{c\rho av}{w}\frac{\partial T}{\partial x} = \mu - \lambda T$$

and: $$\frac{c\rho a}{\lambda w}\frac{\partial T}{\partial t} + \frac{c\rho av}{\lambda w}\frac{\partial T}{\partial x} = \frac{\mu}{\lambda} - T$$

Now, let: $\bar{z}$ = mean depth = $\frac{a}{w}$

and: $k = \frac{w\lambda}{c\rho a} = \frac{\lambda}{c\rho \bar{z}}$

and: $T_\epsilon(t) = \frac{\mu}{\lambda}$

Then: $$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial x} = k\left\{T_\epsilon(t) - T(x,t)\right\}$$

Now, let: $v = \frac{dx}{dt}$

Then, by Euler's expansion: $$\frac{\partial T}{\partial t} + \frac{\partial T}{\partial x}\frac{dx}{dt} = \frac{dT}{dt} = k\left\{T_\epsilon(t) - T(t)\right\}$$

According to Duttweiler, then, "the time rate of temperature increase is proportional to the deficit between the actual temperature and some equilibrium temperature." Here, the actual temperature, $T(t)$, can be described as a reaction, or output, of the stream to the thermal input, $T_\epsilon(t)$. The output temperature, in this case, will approach but never equal the input temperature.

As seen in earlier discussions, the idea of a proportionality constant or exchange coefficient, k, is not new. The input function concept of the equilibrium temperature, however, is believed to be original.

Duttweiler solves the above time-rate change of temperature relationship and arrives at the following expression for the temperature of a stream as a function of its "equilibrium" temperature:

$$T(x,t) = e^{-kt}\int e^{kt} k T_\epsilon(t)dt + e^{-kt} f(t-\int\frac{dx}{v})$$

He then represented the equilibrium temperature, $T_\epsilon(t)$ by a Fourier series with a period of $\frac{2\pi}{\omega}$ hours, where $\omega = \frac{\pi}{12}$ as follows:

$$T_\epsilon(t) = Tm + \sum_{n=1}^{\infty} (a_n \cos. n\omega t + b_n \sin. n\omega t)$$

or alternatively:

$$T_\epsilon(t) = Tm + \sum_{n=1}^{\infty} T_{in} \sin (n\omega t + \phi_n)$$

Where: T_m = time average temperature

$$T_{in} = \sqrt{a_n^2 + b_n^2}$$

$$\phi_n = \arctan.\frac{a_n}{b_n}$$

Substituting these expressions for $T_\epsilon(t)$ into the equation for the actual temperature, $T(x,t)$, yielded:

$$T(x,t) = Tm + \sum_{n=1}^{\infty}\left\{\bar{a}_n \cos. (n\omega t - \alpha_n) + \bar{b}_n \text{sih}. (n\omega t - \alpha_n\right\}$$
$$+ e^{-kt} f(t - \int\frac{dx}{v})$$

Where: $$\bar{a}_n = \frac{a_n}{\sqrt{1 + (\frac{n\omega}{k})^2}}$$

$$\bar{b}_n = \frac{b_n}{\sqrt{1 + (\frac{n\omega}{k})^2}}$$

$$\alpha_n = \arctan. \frac{n\omega}{k}, \quad o < \alpha_n < \frac{\pi}{2}$$

or alternatively:

$$T(x,t) = Tm + \sum_{n=1}^{\infty} Tun \sin.(n\omega t + \phi_n - \alpha_n) + e^{-kt} f(t - \int \frac{dx}{v})$$

$$\text{Where:} \quad Tun = \frac{T_{in}}{\sqrt{1 + (\frac{n\omega}{k})^2}} = \sqrt{\bar{a}_n^{\,2} + \bar{b}_n^{\,2}}$$

The input function, $T_\epsilon (t)$, is modified by an amplification factor, Tun/Tin, a phase lag, α_n, and a "transient," fe^{-kt}.

These equations for $T_\epsilon (t)$ and $T(x,t)$, then, can be pictured, in a simple case, as two sine curves with amplitudes of T_i and T_u, respectively. The maximum actual temperature, T_u, is somewhat smaller than the equilibrium temperature, T_i, and occurs somewhat later, according to the phase lag, α. Both the amplification factor, Tun/Tin, and phase lag, α, are functions of the frequency.

Duttweiler also points out that for steady-state conditions, the transient, fe^{-kt}, will disappear and can be disregarded. As will be seen later, however, this is not true of streams in the area of significant heat advections.

Also noted is the fact that for stream reaches of constant depth, $k\bar{z} = \frac{\lambda}{c\rho}$; cm/hr. This expression is equivalent to the exchange coefficients noted previously (e.g.: Gameson, Hall, and Preddy). Finally, $\lambda = k\bar{z}$ if $c\rho$ is taken as 1.00. Hence, λ is equivalent to the exchange coefficient and can be evaluated as follows:

$$\lambda = \frac{A}{24} (\beta_1 + C_B) \; L\rho + \tfrac{1}{2} + \frac{B}{24} \; (\beta_1 + C_B) \; L\rho U_2 = C_1 + C_2U_2$$

Where: A and B are constants in the evaporation equation

β_1 = slope of vapor pressure curve

C_B = 0.58 - 0.66 (from Bowen's ratio data)

L = latent heat of vaporization

ρ = water density

U_2 = wind speed 2 meters above water surface

After substitution of estimated values for the above constants, Duttweiler determined probable values of C_1 and C_2 as 1.35 and 0.239 respectively. Hence: $\lambda = 1.35 + 0.239\ U_2$.

However, comparison with the studies of Gameson, Hall, and Preddy and of Gameson, Gibbs, and Barrett led Duttweiler to reexamine the value of C_2. The results of his reexamination have placed the value of C_2 between 0.179 and 0.239 as a current estimate.

Examination of the previously derived simplification constant, μ, resulted in the following expression:

$$\mu = Q_n - 25 + (\beta_1 T_{ad} + 0.61\ T_a)\ (0.505 + 0.1009\ U_2)$$

$$= Q_n - 25 + \frac{\beta_1 T_{ad} + C_B T_a}{\beta_1 + C_B}\ (\lambda - \tfrac{1}{2}) = \text{net radiation heat load} + \text{heat load from non-radioactive sources}$$

Duttweiler describes μ as "the hourly rate of heating per unit surface area independent of water temperature."

Then, since $T_\epsilon(t) = \frac{\mu}{\lambda}$:

$$T_\epsilon(t) = \frac{Q_n - 25}{\lambda} + \frac{\beta_1 T_{ad} + C_B T_a}{\beta_1 + C_B}\ \left(\frac{\lambda - \tfrac{1}{2}}{\lambda}\right)$$

Finally, assuming steady conditions, the water temperature at any fixed point in the reach, x*, is:

$$T(x^*,t) = T_m + \sum_{n=1}^{\infty} T_{un}\ \sin.\ (n\omega t + \phi_n - \alpha_n)$$

Hence, with adequate climatological data plus a set of discharge-depth-velocity curves, a space-time solution for the natural water temperature is now available. This, of course, is only a one-dimensional model, a restriction which should fit most streams quite well.

Duttweiler then modified his expression for natural water temperature to show the effects of a heat source at x - 0 such that the stream temperature will be uniformly increased by an increment $T_r(t)$, at x = 0. The resulting equation shows an exponential decay characteristic of the temperature increment as follows:

$$T(x,t) = Tm + \sum_{n=1}^{\infty} Tun\ sin.(n\omega t + \phi_n - \alpha_n) + Tr(t)e^{-\frac{k}{v}x}$$

If the heat source temperature itself follows a periodic function, for example:

$$Tr(t) = \bar{T}r + \sum_{n=1}^{\infty} (a_{rn}cos.n\omega t + \bar{b}_{rn}sin.\ n\omega t)$$

Then: $$T(x,t) = Tm + \sum_{n=1}^{\infty} \left\{ \bar{a}_n cos(n\omega t - \alpha_n) + \bar{b}_n sin.(n\omega t - \alpha_n) \right\}$$

$$+ \bar{T}_r e^{-\frac{k}{v}x} + e^{-\frac{k}{v}x} \sum_{n=1}^{\infty} (a_{rn}cos.\ n\omega t + b_{rn}sin.\ n\omega t)$$

Duttweiler solved a hypothetical problem using this relationship to illustrate the characteristics of an artificially-heated stream.

A second modification of the basic one-dimensional case involved expression of downstream water temperatures assuming a constant initial temperature at x = 0. (e.g., releases from the hypolimnion of a reservoir which constitute the entire stream discharge). The resulting equation assumed T_s as the temperature of the discharged water:

$$T(x,t) = Tm + \sum_{n=1}^{\infty} Tun\ sin.\ (n\omega t + \phi_n - \alpha_n)$$

$$-\sum_{n=1}^{\infty} T_{un}e^{-\frac{k}{v}x} sin.\ \left[n\omega (t - \frac{x}{v}) + \phi_n - \alpha_n \right] + (T_s - T_m)e^{-\frac{k}{v}x}$$

Again, a hypothetical problem was worked out to show characteristics of the model.

The temperature model was subjected to testing under controlled laboratory conditions to verify the basic concept of the input function and establish the validity of the exchange coefficient parameters. With these results, Duttweiler used the model to predict 19 hourly temperatures in a small stream and 13 monthly temperatures for Lake Hefner, using data from the Lake Hefner water-loss studies (17). Agreement of the model with measured temperatures was reasonably good. The following table lists estimated temperatures and observed temperatures (energy storage per gram $\cong$ °C.) for Lake Hefner:

Month	Estimated Temp.(°C)	Observed Temp.(°C)	Month	Estimated Temp.(°C)	Observed Temp.(°C)
Aug. '50	26.92	25.56	Mar. '61	7.59	7.88
Sept.	23.77	22.96	April	12.67	12.16
Oct.	19.66	20.08	May	20.01	19.15
Nov.	11.06	12.37	June	23.82	23.25
Dec.	6.55	6.02	July	26.50	26.77
Jan. '51	2.28	4.37	August	26.92	27.50
Feb.	2.08	5.80			

Theoretically, thermograph data would not be needed to estimate stream temperatures in the situations described above. However, with current records of climatological data falling considerably short of the standards required for accurate estimation with the model, thermograph installations are a desirable accessory to the computations. Initial conditions, at any rate, must be known or estimated.

F. The characteristic of exponential decay with time of temperature increments can be put to good use in estimating stream temperatures as a function of regulated releases from storage reservoirs.

The exchange coefficient, as developed by David Duttweiler, was used to predict temperatures of a reach of the South Umpqua River, Oregon, as a function of regulated releases from the proposed Tiller Dam. This example, worked out by Duttweiler, is attached along with appropriate comments on the method by the writer.

III. Research Needs

The following are a few thoughts regarding research needs of current temperature prediction theories:

A. Inexpensive instrumentation for obtaining net short-wave and net long-wave radiation data. The currently accepted method includes erect and inverted pyrheliometers to measure incident and reflected solar radiation plus Gier & Dunkle flat plate radiometers to measure incident, total radiation. Even then, expensive as this instrumentation is, the thermal radiation from the water surface must be estimated from measurements of the water surface temperature.

The Cummings Radiation Integrator (6, 17) has been suggested as a substitute for the pyrheliometers and radiometer; however, the CRI needs extensive evaluation for the Pacific Northwest region before its usefulness can be accepted for this area.

Even with adequate instrumentation, these measurements may have to be made for individual projects because of the scarcity of applicable data from nearby weather bureau stations. Extensive correlation of all available meteorological data at this time may or may not eliminate the need for complete instrumentation on each project. Some correlation studies have already been completed, but much more needs to be done.

B. Extensive water-loss investigations of the type conducted on Lakes Hefner and Mead are needed in the Pacific Northwest to evaluate existing evaporation equations and/or formulate new ones. Again, some work has already been done by the United States Geological Survey which is currently involved in mass-transfer studies on McKay Reservoir near Pendleton, Oregon. However, additional studies are needed at other regional reservoirs and on the streams themselves.

C. Studies relative to the location and yield of bank storage sources both on reservoirs and streams are needed. This item is usually ignored, presumably on the basis of its magnitude and temperature differences. However, until some method is found to determine these values, ignoring bank storage may lead to erroneous results.

D. Conduction losses across the water-channel bottom interface need evaluation. Again, this parameter is usually ignored.

E. The net thermal exchange due to biochemical reactions could conceivably be of some importance where algal counts are high or pollution is excessive, but is generally disregarded.

F. A detailed evaluation of the accuracy required of energy-budget computations is needed. Is it necessary, for example, to predict temperatures more specific than the mean temperature for the critical month? How important are diurnal variations in these temperature predictions? Answers to questions such as these will have a direct bearing on the complexity of energy-budget instrumentation and computations. Actually, considerable literature exists on portions of this problem. An extensive library research could conceivably yield enough data, if properly organized, to provide reasonable guidelines for accuracy objectives.

G. The constants used for estimation of the exchange coefficient, λ, need verification (3). This exchange coefficient is a function of several meteorological variables and is not necessarily constant. The error involved in assuming a constant value for λ (and the rate constant, $k = \frac{\lambda}{z}$) needs evaluation.

H. Simultaneous studies are needed of reservoirs and streams as a unit. Of necessity, most studies to date have had to be limited to either a reservoir or reach of a stream. To the writer's knowledge, there have been no fully-instrumented, long-term studies of temperature phenomena in a reservoir and its downstream reach as a unit.

Such a study would begin with the selection of a reservoir and stream physiographically and hydrographically comparable to other reservoir-stream units in the same region.

A complete evaluation of the water budget on the selected reservoir stream unit would be essential. To date, an accurate water budget is still required to check evaporation estimates and other computations.

Instrumentation should be selected to provide the basis for complete parameter evaluation. In this respect, complete meteorological stations are needed both on the reservoir and somewhere along the reach of stream to be studied. Differences in elevation, ground cover, wind velocities, and location relative to major geographical relief are all important and difficult to evaluate when extrapolating meteorological data. If evaluation of prediction methods is the objective of the study, extrapolation of climatological data from distant weather stations is not acceptable. There is too much latitude for "fudging the data to fit the answers" when estimation of radiation or evaporation is involved. In addition to pyrheliometers, radiometers, wet-dry bulb recorders, anemometers, and recording rain gages, Cummings Radiation Integrators are recommended at each meteorological station. If CRI installations are not practicable, evaporation pans would suffice.

If continuous stage recorders are not already in operation at all significant points on the selected reservoir-stream unit, they should be installed where needed.

Thermographs are needed just downstream of the dam, at the critical reach, and at one or more intermediate points. Additional thermographs are needed at the reservoir to record significant advected flows such as major tributaries and at turbine penstocks.

In addition to the full-time instrumentation described above, reservoir temperature surveys would be needed at least once every month, preferably once every two weeks. These surveys would include full temperature profiles down the centerline of the reservoir channel, plus sufficient cross-section temperatures to complete an accurate description of thermal stratification.

The reservoir temperature profiles would be planimetered and a mass diagram of heat quantities assimilated to aid in water-budget computations.

In addition to the routine sampling described above, attempts should be made to locate and measure velocity currents in the reservoir. Again, this data would simplify water-budget computations.

Finally, several discharge-depth-velocity surveys should be run during the course of the study. A fluorescent dye would be used as a tracer for flow-time determinations.

The total duration of the study would be at least one full year. It would be preferable, though not necessary, to include two summers during the study period.

A study following the general pattern outlined above would yield "working data" for any of the methods described in this paper.

Notes on Stream Temperature Prediction Assuming a Constant Temperature Source

The following notes pertain specifically to prediction of stream temperatures at a given point and time based on the exponential-decay-of-transient-temperatures method developed by Duttweiler. The prediction necessarily assumes that the entire source of flow is fixed at a short-time constant temperature (i.e., constant for the period of time under consideration). The temperature of the South Umpqua River, for example, can be predicted at any time for which the temperature of the discharge at the proposed Tiller Damsite is estimated. Attached is an example of the application of this method to the South Umpqua River, Oregon.

A. Data Collection Requirements

1. Flow data at the damsite, estimated reach of critical water temperatures (critical point), and above each major tributary. Also, the major tributaries at their mouths. This data must eventually be predicted for the period under consideration.

2. Stage-discharge-velocity relationships at the damsite, critical point, and above each major tributary.

It would also be desirable to get velocity data at enough intermediate points to assure satisfactory flow-time estimation. Flow times are critical.

The stage-discharge relationship is essential for parameter estimation in the prediction computations. It would be advisable to take cross sections and current meter sections concurrently with flow-time, dye studies.

If possible, at least two surveys, at different flows, should be made to increase the confidence in the stage-discharge, velocity data obtained.

3. Thermograph records at the damsite and critical point.

Minimal requirements would be continuous-strip records of water temperatures for a period of time analogous to the period under consideration. This will usually mean at least several days of records.

It would be better to obtain at least one full year of records to help understand the general characteristics of the stream relative to its thermal environment.

Of some value, also, would be graphs at several intermediate points in the reach.

Note that records must be obtained at the mouth of intermediate, major tributaries.

4. Wind velocity records at the damsite and critical point for analogous periods of several years.

This requirement may be difficult to fill in the usual situation. The temperature prediction can be completed without this data, using a conservative estimate for wind velocity.

If anemometers are available in addition to nearby weather stations, the survey anemometers should be read at both two meters and eight meters above the water surface. The two-meter data is preferable for computations. The eight-meter data would be used for correlation with the weather station data.

B. Data Analysis and Temperature Prediction

1. Basic Methodology

The method developed by Duttweiler assumes that any artificial deviation from a steady-state temperature will decay exponentially with distance downstream. In application, this means that with an artificially-imposed, uniform-temperature discharge, there will be a variable, but predictable initial deviation from the hourly temperatures of a steady-state thermograph at the damsite. These deviations will then decay on an exponential curve until, at some point downstream, the stream temperature will again exhibit the natural, steady-state diurnal variations.

Thus it is, for computation, both the damsite and critical point thermograph records are needed. The damsite data will yield the algebraic value of the deviation at that point. The residual deviation (after decay) will then be applied to the critical point thermograph data to yield the predicted temperature curve.

Mathematically, the method is stated as follows:

$$T^*(x,t) = T(x,t) + \left[Ts(t) - T(0,0) \right] e^{-\frac{k}{v}x}$$

(Predicted temp.) = (steady-state temp.) + (temp. deviation) (exponential factor)

Where: $T^*(x,t)$ = predicted temperature at time "t" and mile "x" taken from the damsite time of "0" and mile "0".

$T(x,t)$ = steady-state temperature at time "t" and mile "x".

$Ts(t)$ = reservoir discharge temperature, noted at $Ts(t)$, but assumed constant over entire period.

$T(0,t-\frac{x}{v})$ = steady-state temperature at damsite. The time will be "$\frac{x}{v}$" hours less than that used at mile "x" with "v" being the estimated stream velocity.

e = Naperian base

$k = \frac{\lambda}{\bar{z}}$ (assumed constant for the reach)

Where: $\lambda = C_1 + C_2U_2$ = exchange coeff.; cm./hr.

$C_1 = 1.35$

$C_2 = 0.18 - 0.24$

U_2 = wind velocity in mph

$\bar{z}$ = average stream depth; cm.

v = estimated average stream velocity; mph.

x = miles from damsite to critical point.

2. Application

Note that this method can be applied easily only to the situation where the entire flow of the stream is discharged from a constant temperature reservoir during the period under consideration.

Note also that the method assumes a temperature for the reservoir discharge. If needed, the reservoir temperatures would have to be evaluated by a separate study. Logically, the solution could be worked backwards to determine a reservoir temperature-discharge relationship to satisfy the stream temperature requirements.

For the situation where it is desired to reproduce existing thermograph records, more sophisticated data collection is required as follows:

a. Total solar and atmospheric radiation, using a Gier & Dunkle flat-plate radiometer.

b. Slope of vapor pressure curve within range of water temperatures concerned.

c. Relative humidity to obtain dewpoint.

d. Air temperatures.

e. Remaining climatological data is computed or assumed.

This data would be used to estimate, mathematically, the natural temperature curves. These computed curves would then take the place of thermograph records.

Temperature Predictions for the South Umpqua River from Tiller to Winston Assuming Constant Temperature Releases from the Reservoir at the Proposed Tiller Dam

Data available for the computations included thermograph records at Tiller and Winston plus discharge data for March 30 through April 5, 1961, at several applicable stations and sufficient stream characteristics to estimate depth of flow and flow times.

From these data, the following quantities were calculated:

$Q_{avg.}$ = 3,600 cfs

Difference in water surface elevations from Tiller to Winston = 541 ft.

River miles from Tiller to Winston = 55.5

Average channel slope = 1.85×10^{-3} ft./ft.

Average channel width = 165 ft.

Average depth of flow = 4.9 ft. = 151 cm.

Average velocity = 3 mph (Kutter's n = 0.04)

The water temperature, as measured by the thermographs, was assumed to be in a steady-state condition. Hence, the transient, fe^{-kt}, was assumed negligible.

The difference between steady-state temperatures and the temperatures modified by reservoir releases was designated as θ. That is, θ = temperature increment under natural temperature.

The following derivation for the modified temperature relationship at Winston ensued:

Let: the temperature increment at $x = o$ be $\theta(o)$

and: the temperature at $x = 55.5$ be $\theta(55.5)$

Then: $\theta(55.5) = \theta(o)e^{-\frac{k}{v}55.5}$

Now, assume that the temperature of the regulated release, $T_s(t)$, from Tiller Reservoir is equal to the steady-state temperature, $T(o)$, at Tiller plus the temperature increment, $\theta(o)$.

[i.e.: $T(o) + \theta(o) = T_s(t)$]

The flow time from Tiller to Winston for Q = 3,600 cfs is 55.5 miles/3 mph = 18.5 hr. or approximately 18 hr. Then, the temperature increment, $\theta(o)$ at $t = t_o$ will decay exponentially to $\theta(55.5)$ at $t_o + 18$.

Hence: $\theta(55.5, t) = \theta(o, t - 18)e^{-\frac{k}{v}55.5}$

Then, the predicted water temperature at Winston will be:

$$T^*(55.5, t) = T(55.5, t) + \theta(55.5, t)$$
$$= T(55.5, t) + \theta(o, t - 18)e^{-\frac{k}{v}55.5}$$
$$= T(55.5, t) + [T_s(t) - T(o, t - 18)]e^{-\frac{k}{v}55.5}$$

Where: $T(55.5, t)$ = steady-state temperature at Winston.

To apply the method, it is necessary to assume a hypothetical temperature for the reservoir release at Tiller. Let $T_s(t) = 40^oF$. for the period under consideration, 00 to 24 hours on March 30, 1961.

Finally, some value(s) must be estimated for the exchange coefficient, λ. For expediency, the decay factor, $e^{-\frac{k}{v}55.5}$, will be computed at the same time.

$$\lambda = C_1 + C_2U_2 = 1.35 + C_2U_2$$

Where: C_2 varies from 0.18 to 0.24 (assume $C_2 = 0.20$)

U_2 = wind speed at 2 meters above the water surface

$$\lambda = 1.35 + 0.2\ U_2; \text{ also, } k = \frac{\lambda}{\bar{z}} = \frac{\lambda}{151}$$

Although the usual prediction would involve the critical condition of low, or negligible, wind speed, a wide range of wind speeds will be assigned here to show the effect on λ.

U_2 (mph)	λ cm/hr.	k (1/hr.)	L/k (hr.)	$\bar{v}/k = 3/k$ (mi.)	$k/\bar{v} = k/3$ (1/mi.)	$e^{-\frac{k}{v}55.5}$
0	1.35	0.00894	112	336	0.00298	0.848
3	1.95	0.0129	77.5	232.5	0.00430	0.788
5	2.35	0.0155	64.5	193.5	0.00517	0.751
8	2.95	0.0195	51.3	153.9	0.00650	0.698
10	3.35	0.0222	45.0	135.0	0.00740	0.663
15	4.35	0.0288	34.7	104.1	0.00960	0.587
20	5.35	0.0354	28.2	84.6	0.0118	0.520

Computations for three wind speeds (0, 8, and 20 mph) are shown on the following pages. These computations and the accompanying graphs indicate probable temperatures at Winston for the conditions assumed.

To test the hypothesis that estimation of an average velocity, $\bar{v}$, is a critical factor in temperature computations, the estimates will be recalculated for an average velocity of 2.0 mph.

Q = 3,600 cfs

$\bar{v}$ = 2.0 mph = 2.94 cfs

w = 165 ft.

A = 3,600/2.94 = 1,220 sq. ft.

$\bar{z}$ = 1,220/165 = 7.4 ft. = 228 cm.

Table 1
Temperature Prediction Computations
So. Umpqua River--Tiller to Winston

March 30-31, 1961 - $\bar{v}$ = 3.0 mph

(1) t	(2) T(o,t) (Thermograph records)	(3) T(55.5,t) (Thermograph records)	(4) $\theta(o,t-18)$	(5) $\theta e^{-\frac{k}{\bar{v}}x}$ (λ=2.95)	(6) T*(55.5,t) (3)+(5)	(7) $\theta e^{-\frac{k}{\bar{v}}x}$ (λ=1.35)	(8) T*(55.5,t) (3)+(7)	(9) $\theta e^{-\frac{k}{\bar{v}}x}$ (λ=5.35)	(10) T*(55.5,t) (3)+(9)
March 30, 1961									
00	43.00	47.50							
01	42.25	47.25							
02	41.75	46.50							
03	41.50	46.25							
04	41.25	46.00							
05	41.00	45.50							
06	40.50	45.00							
07	40.25	44.75							
08	40.00	45.00							
09	40.00	46.00							
10	41.25	47.25							
11	42.25	48.75							
12	43.25	50.00							
13	44.75	51.00							
14	46.00	51.50							
15	46.50	51.75							
16	47.00	52.00							
17	47.00	52.25							
18	47.00	52.25	-3.00	-2.09	50.16	-2.54	49.71	-1.56	50.69
19	46.75	51.50	-2.25	-1.57	49.93	-1.90	49.60	-1.18	50.32
20	46.25	50.25	-1.75	-1.22	49.03	-1.49	48.66	-0.91	49.34
21	45.75	49.25	-1.50	-1.05	48.20	-1.27	47.98	-0.78	48.47
22	45.50	48.25	-1.25	-0.87	47.38	-1.06	47.19	-0.65	47.60
23	45.25	47.50	-1.00	-0.70	46.80	-0.85	46.65	-0.52	46.98
24	45.00	47.00	-0.50	-0.35	46.65	-0.42	46.58	-0.26	46.74
March 31, 1961									
01	44.75	46.75	-0.25	-0.17	46.58	-0.21	46.54	-0.13	46.62
02	44.25	46.25	0	0	46.25	0	46.25	0	46.25
03		46.00	0	0	46.00	0	46.00	0	46.25
04		45.50	-1.25	-0.87	44.63	-1.06	44.46	-0.65	44.85
05		45.25	-2.25	-1.57	43.68	-1.91	43.34	-1.17	44.08
06		44.75	-3.25	-2.27	42.48	-2.76	41.49	-1.69	43.06
07		44.50	-4.75	-3.32	41.18	-4.03	40.47	-2.47	42.03
08		44.50	-6.00	-4.19	40.31	-5.09	39.41	-3.12	41.38
09		46.00	-6.50	-4.54	41.46	-5.50	40.50	-3.38	42.62
10		47.75	-7.00	-4.89	42.86	-5.93	41.82	-3.64	44.11
11		49.50	-7.00	-4.89	44.61	-5.93	43.57	-3.64	45.86
12		51.00	-7.00	-4.89	46.11	-5.93	45.07	-3.64	47.36
13		52.25	-6.75	-4.71	47.54	-5.73	46.52	-3.51	48.74
14		53.00	-6.25	-4.36	48.64	-5.30	47.70	-3.30	49.70
15		54.00	-5.25	-3.67	50.33	-4.45	49.55	-2.73	51.27
16		55.00	-5.50	-3.84	51.16	-4.66	50.34	-2.86	52.14
17		55.00	-5.25	-3.67	51.33	-4.45	50.55	-2.73	52.27
18		54.75	-5.00	-3.50	51.25				
19		53.50	-4.75	-3.32	50.18				
20		52.25	-4.25	-2.97	49.28				

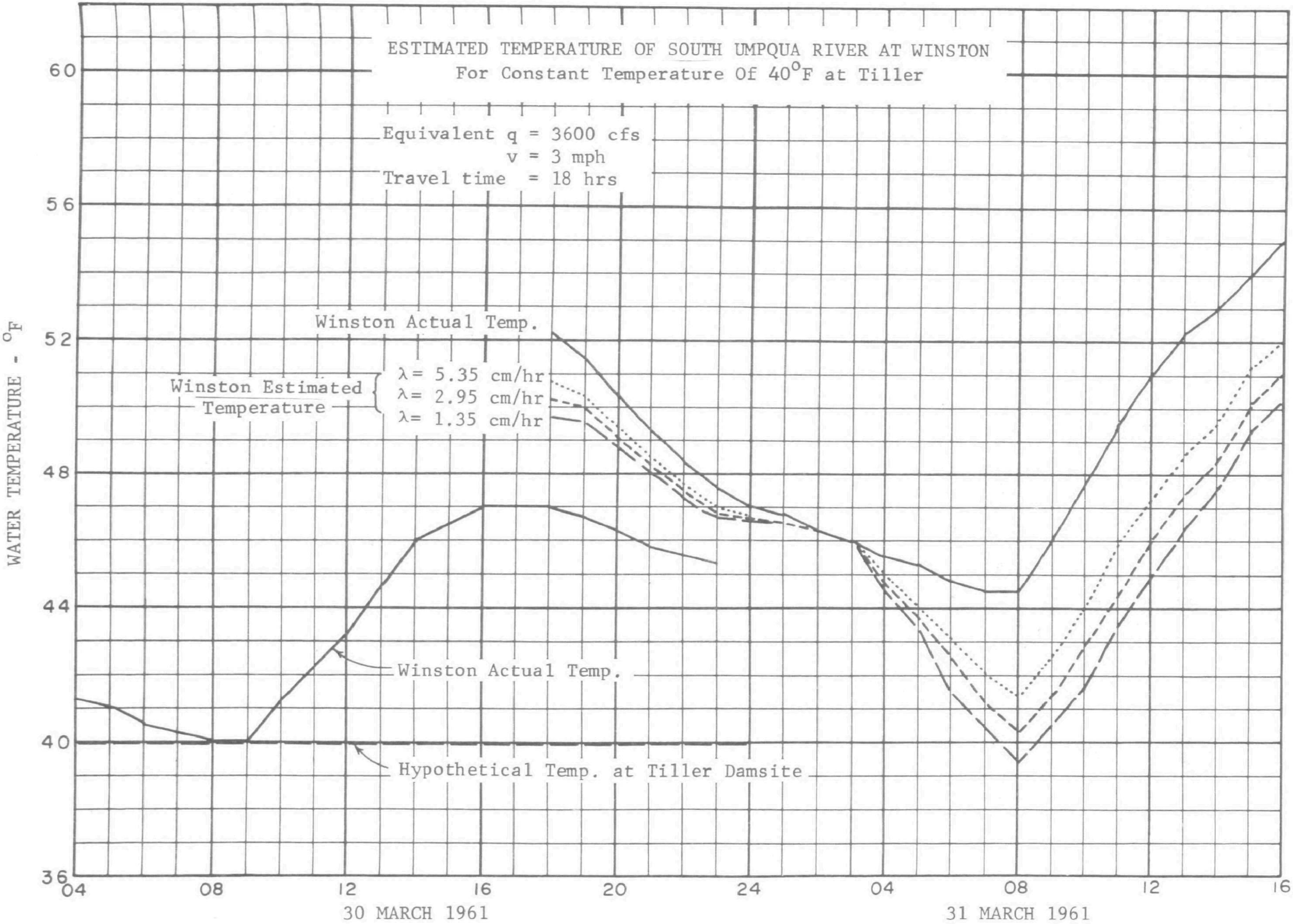

ESTIMATED TEMPERATURE OF SOUTH UMPQUA RIVER AT WINSTON
For Constant Temperature Of 40°F at Tiller
Equivalent q = 3600 cfs
v = 3 mph
Travel time = 18 hrs
Winston Actual Temp.
Winston Estimated Temperature
λ= 5.35 cm/hr
λ= 2.95 cm/hr
λ= 1.35 cm/hr
Winston Actual Temp.
Hypothetical Temp. at Tiller Damsite
WATER TEMPERATURE - °F
60
56
52
48
44
40
36
04
08
12
16
20
24
04
08
12
16
30 MARCH 1961
31 MARCH 1961

Figure 4

U_2 (mph)	λ (cm/hr.)	k (1/hr.)	k/v (1/mi.)	$e^{-\frac{k}{v} 55.5}$
0	1.35	0.00592	0.00296	0.849
8	2.95	0.0129	0.00645	0.70
20	5.35	0.0234	0.0117	0.523

Note at this point that the change in average velocity has had no effect on the exponential decay factor, $e^{-\frac{k}{v} 55.5}$. An examination of the units involved indicates this to be logical.

The modified computations for the temperature at Winston are shown on the following page. These temperatures for 04 to 1600 hrs., March 31, 1961, are plotted on the accompanying graph.

A comparison of Winston temperature predictions for average velocities of 2.0 and 3.0 mph does, indeed, show considerable variation. Diurnal variation of the steady-state temperature is important here.

Table 2
Temperature Prediction Computations
So. Umpqua River--Tiller to Winston

March 30-31, 1961 -- $\bar{v}$ = 2.0 mph

(1) t	(2) T(o,t)	(3) T(55.5,t)	(4) θ(o,t-18)	(5) $\theta e^{-\frac{kx}{v}}$ (λ=2.95)	(6) T*(55.5,t) (3)+(5)	(7) $\theta e^{-\frac{kx}{v}}$ (λ=1.35)	(8) T*(55.5,t) (3)+(7)	(9) $\theta e^{-\frac{kx}{v}}$ (λ=5.35)	(10) T*(55.5,t) (3)+(9)
	(Thermograph records)								
March 30									
00	43.00								
01	42.25								
02	41.75								
03	41.50								
04	41.25								
05	41.00								
06	40.50								
07	40.25								
08	40.00								
09	40.00								
10	41.25								
11	42.25								
12	43.25								
13	44.75								
March 31									
01									
02									
03									
04		45.50	-3.00	-2.10	43.40	-2.54	42.96	-1.57	43.93
05		45.25	-2.25	-1.57	43.68	-1.90	43.35	-1.18	44.07
06		44.75	-1.75	-1.22	43.53	-1.49	43.26	-0.92	43.77
07		44.50	-1.50	-1.05	43.45	-1.27	43.23	-0.79	43.71
08		44.50	-1.25	-0.87	43.63	-1.06	43.44	-0.65	43.85
09		46.00	-1.00	-0.70	45.30	-0.85	45.15	-0.52	45.48
10		47.75	-0.50	-0.35	47.40	-0.42	47.33	-0.26	47.49
11		49.50	-0.25	-0.18	49.32	-0.21	49.29	-0.13	49.37
12		51.00	0	0	51.00	0	51.00	0	51.00
13		52.25	0	0	52.25	0	52.25	0	52.25
14		53.00	-1.25	-0.87	52.13	-1.06	51.94	-0.65	52.35
15		54.00	-2.25	-1.57	52.43	-1.91	52.09	-1.18	52.82
16		55.00	-3.25	-2.28	52.72	-2.76	52.24	-1.70	53.30
17		55.00	-4.75	-3.32	51.68	-4.03	50.97	-2.48	52.52

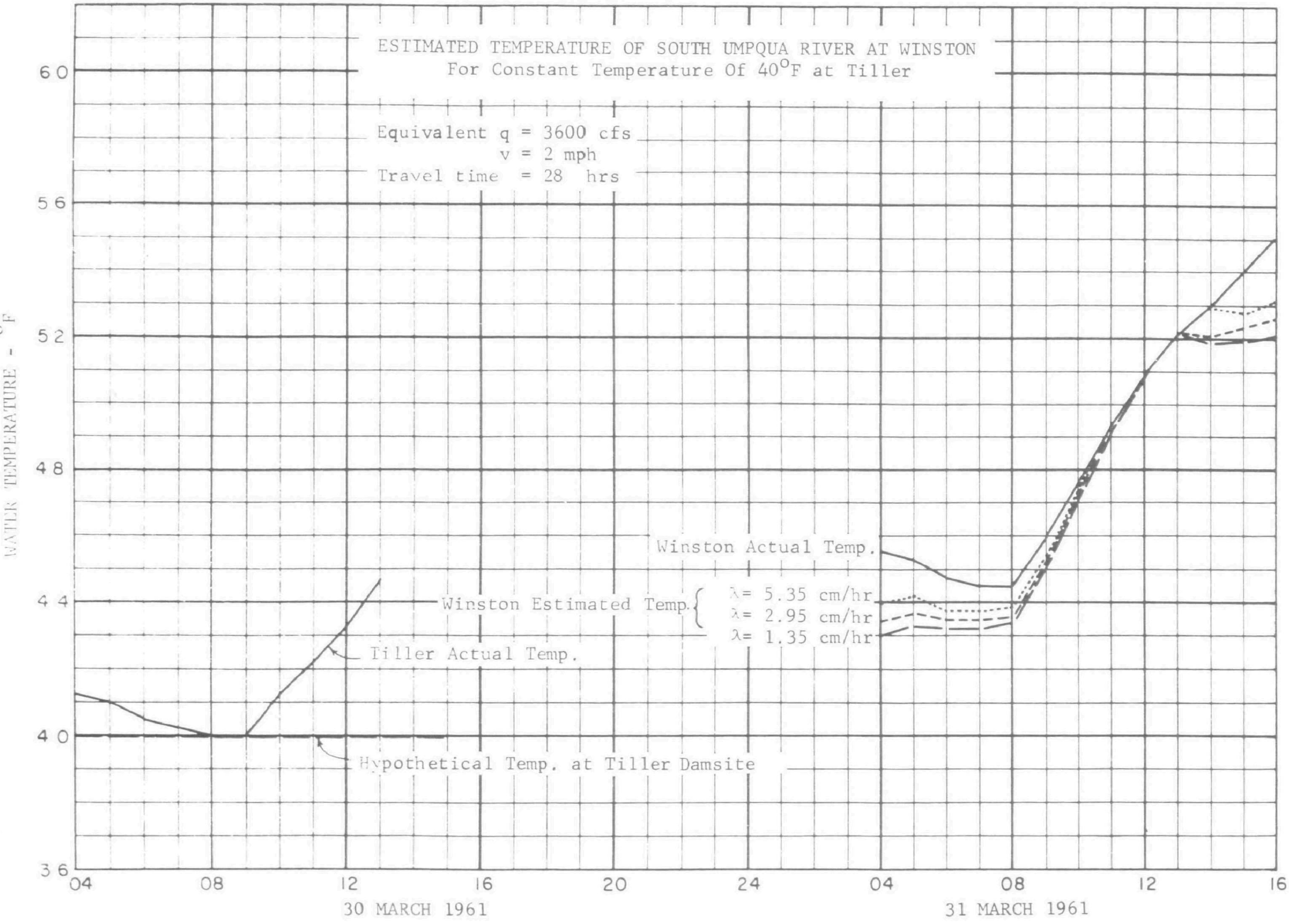

ESTIMATED TEMPERATURE OF SOUTH UMPQUA RIVER AT WINSTON
For Constant Temperature Of 40°F at Tiller
Equivalent q = 3600 cfs
v = 2 mph
Travel time = 28 hrs
WATER TEMPERATURE - °F
60
56
52
48
44
40
36
Winston Actual Temp.
Winston Estimated Temp.
λ= 5.35 cm/hr
λ= 2.95 cm/hr
λ= 1.35 cm/hr
Tiller Actual Temp.
Hypothetical Temp. at Tiller Damsite
04
08
12
16
20
24
04
08
12
16
30 MARCH 1961
31 MARCH 1961

Figure 5

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ATTENDANCE AT THE TWELFTH SYMPOSIUM

November 7, 1963

Donald F. Amend	Oregon State University	Corvallis
Aven M. Andersen	State Shellfish Laboratory	Brinnon
N. H. Anderson	Oregon State University	Corvallis
R. L. Angstrom	Oregon Fish Commission	Portland
Robert Averett	University of Washington	Seattle
Robert J. Ayers	Oregon Fish Commission	Portland
Richard Bakkala	Bur. Commercial Fisheries	Seattle
William J. Beck	PHS Shellfish San. Lab.	Gig Harbor
Paul F. Berg	Sport Fisheries & Wildlife	Boise
Richard Berg	Oregon State University	Corvallis
Harold Berkson	U. S. Public Health Service	Portland
Donald E. Bevan	University of Washington	Seattle
Russell O. Blosser	Oregon State University	Corvallis
B. R. Bohn	Oregon Fish Commission	Clackamas
C. E. Bond	Oregon State University	Corvallis
Peter B. Boyer	Corps of Engineers	Portland
Lt. George Brown	541st M.I. Det.	Forte Meade, Md.
R. L. Brown	State Water Resources Bd.	Salem
Fred J. Burgess	Oregon State University	Corvallis
Melvin H. Burke	U.S. Forest Service	Portland
Roger E. Burrows	Sport Fisheries & Wildlife	Longview
Wayne V. Burt	Oregon State University	Corvallis
Richard J. Callaway	U.S. Public Health Service	Portland
Dale A. Carlson	University of Washington	Seattle
George G. Chadwick	Oregon State University	Corvallis
W. N. Christianson	Ore. State Game Commission	Salem
Robert F. Clawson	Calif. Dept. of Water Resources	Sacramento
Wm. D. Clothier	Ore. Fish Commission	Portland
A. G. Coche	Oregon State University	Corvallis
Chas. W. Coddington	Oregon State University	Corvallis
Gerald B. Collin	Bur. Commercial Fisheries	Seattle
John F. Conrad	Oregon Fish Commission	Clackamas
A. C. Cooper	International Pacific Salmon Fisheries Commission	New Westminster, B.C., Canada
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Wm. H. Delay	State Water Resources Bd.	Salem

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Peter Doudoroff	Oregon State University	Corvallis
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John E. Edinger	The Johns Hopkins University	Baltimore
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