EPA-905/9-74-012

WATER POLLUTION INVESTIGATION: CUYAHOGA RIVER AND CLEVELAND AREA

ECO-LABS INC.

U.S. ENVIRONMENTAL PROTECTION AGENCY
REGION V ENFORCEMENT DIVISION
GREAT LAKES INITIATIVE CONTRACT PROGRAM

DECEMBER 1975

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WATER POLLUTION INVESTIGATION:

CUYAHOGA RIVER AND CLEVELAND AREA

by

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ECO-LABS, INC.
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This report has been developed under auspices of the Great Lakes Initiative Contract Program. The purpose of the Program is to obtain additional data regarding the present nature and trends in water quality, aquatic life, and waste loadings in areas of the Great Lakes with the worst water pollution problems. The data thus obtained is being used to assist in the development of waste discharge permits under provision of the Federal Water Pollution Control Act Amendments of 1972 and in meeting commitments under the Great Lakes Water Quality Agreement between the U.S. and Canada for accelerated effort to abate and control water pollution in the Great Lakes.

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ABSTRACT

A computer model is developed to rapidly simulate dissolved oxygen content in the Cuyahoga River under varying conditions of flow and biochemical oxygen demand. It is composed of three separate models: Model I is based upon Streeter-Phelps equations (Streeter and Phelps, 1925); Model II is a revised and expanded version of the Delaware Estuary finite difference model (Thomann, 1972); and Model III is a time-variant model. These models, which have been used to simulate present and projected dissolved oxygen levels for the entire length of the Cuyahoga River, show that the municipal and industrial treatment programs to be implemented by 1978 will result in improved dissolved oxygen conditions in the Cuyahoga River. However, run-off and benthic oxygen demand will still result in a severe oxygen sag in the navigation channel during summer low flows.

Programming is in FORTRAN IV (level G) language and is compatible with the IBM 360/70 system. The program requires 20 K storage. A flow chart and explanations for the model's routines are detailed in Appendix C.

This report was submitted in fulfillment of Contract Number 68-01-1568 by Eco-Labs, Inc. under the sponsorship of the Environmental Protection Agency.

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CONCLUSION

1) The steady state transition matrix provides direct information which is extremely useful in waste load allocation and to water quality management decision making. This matrix permits evaluation of questions such as:

a) What is the effect of specific upstream loadings on dissolved oxygen (DO) in the river;

b) What effect on DO may be expected from relocation of outfalls;

c) Which industrial outfalls contribute greatest to DO deficit at the location in the river where maximum sag occurs;

d) What increased treatment for a given industry would be necessary to raise DO to an acceptable level at a given location in the channel.

Such questions are not readily obtained from traditional Streeter-Phelps application and are not as easily interpreted as is the tabular format provided in the matrix.

2) Simulation of the dissolved oxygen content in the River shows that anticipated reduction in waste loads from municipal and industrial sources to be implemented by 1978 will result in improved oxygen levels in the Cuyahoga River. However, secondary sources such as non-point source run-off and benthic demand are indicated as significant enough to result in a severe oxygen sag in the navigation channel during summer low flows.

3) The results of the modeling effort indicate that the DO regime within the navigation channel is relatively insensitive to dispersion coefficients. Therefore, at critical low flow, application of Streeter-Phelps equations for the channel above mile point 2.0 will give a close approximation of the results of the finite difference model.

4) Simulation runs in which DO drops to zero may contain an unknown error factor. Transition in biochemical mechanisms responsible for CBOD oxidation occurs when DO drops near zero. Anaerobic oxidative mechanisms are largely unquantified and complex. Thus, interpretation of simulation of very low (1.0 ppm) DO should be made cautiously.

5) Existing dissolved oxygen water quality standards for the river (See Appendix A) will be met by anticipated treatment programs, however, such standards are not adequate to protect other than pollutant tolerant life forms.

6) Significant stratification occurs in the lower one mile of the navigation channel. Therefore, sampling at several depths is necessary to define water quality in this section of the river.

SECTION II

RECOMMENDATIONS

1. The system was shown to be especially sensitive to the deoxygenation coefficient value (K_1). Since no extensive study of deoxygenation coefficients within the navigation channel exists, it is recommended that such a study be conducted.

2. Tuning the model was complicated by lack of current and substantial data on the water quality in the Cuyahoga River It is recommended, therefore, that a detailed study of the physical, chemical, and biological systems of the River from the Akron STP to its mouth be undertaken.

3. To determine their various effects upon the model's output it is recommended that deoxygenation, reaeration, and nitrification rates within the various reaches of the Cuyahoga River be elucidated.

4. Model I and Model II should be expanded to include other conservative, as well as, non-conservative constituents.

5. Even with the municipal and industrial treatment programs scheduled for implementation by 1978, the lower Cuyahoga will have difficulty supporting anything but the most pollution-tolerant aquatic life forms. Accordingly, it is recommended that continued consideration be given to non-point source controls, additional point source controls and other means in order to minimize waste loads.

SECTION III

INTRODUCTION

When, in 1965, the Federal Government began to seriously enforce pollution control legislation the lower Cuyahoga River was in such a depleted state that its damage seemed irreparable. In the 1968 U.S. Dept. of Interior-Lake Erie Report the lower Cuyahoga was declared "a virtual waste lagoon". In the succeeding year the lower Cuyahoga caught fire and burned so violently that two bridges were nearly destroyed. Today, the lower Cuyahoga has lost all signs of visible plant and animal life.

This study was conducted to provide the USEPA with additional data regarding the present nature and trends in water quality, aquatic life, and waste loadings in the lower Cuyahoga River. The data developed in this report will:

*Assist the State of Ohio in monitoring for the implementation of the National Pollution Discharge Elimination System (NPDES);

*Assist the Federal Government in determining its needs in order to meet its commitment with Canada in an accelerated program to abate and control water pollution in the Great Lakes;

*Assist the Federal Government in determining its point of view on water quality in the Cuyahoga River;

*Assist in determining if present water quality standards are being violated and, if so, will these standards continue to be violated;

*Assist in estimating the nature and quantities of effluent to be discharged when permit requirements are imposed in the Cuyahoga River;

*Assist in determining what effect permit requirements will have on the water quality in the Cuyahoga River.

This study consisted of acquiring and analyzing water quality data and developing a mathematical simulation computer model.

A "Users Manual" and all information required to utilize the model are included.

SECTION IV

LITERATURE REVIEW

POLLUTION EFFECTS ON WATER QUALITY

Pollution of the Cuyahoga River is not a new concept. As far back as 1868 the Cleveland Plain Dealer newspaper referred to the red and iridescent scum from iron mills and petroleum refineries "dirtying" the water at the mouth of the river. This "dirtying" also occured 60 miles upstream at Akron which was then becoming famous as the world's capital for flour, cereal, and rubber.

Despite the concern for pollution in the river no comprehensive analytical survey describing water quality before 1947 was located. A 1947 study entitled, "Cuyahoga River Stream Survey", was found in the Ohio EPA files. It was the first complete study found which described various parameters in the river. It contained data, collected August 25 - 28, 1947 and October 14 - 16, 1947, which described temperature, pH, dissolved oxygen (DO), Biochemical Oxygen Demand (BOD_5), and oxygen balance at 121 locations in the river and in its tributaries. These locations extended from the river's source in Geauga County to its mouth at Lake Erie (See Figure 1).

In a study by Winslow, White, and Webber (1953), based on daily samples collected between March 1950 and February 1951, it was determined that there was a progressive downstream increase in pollution in the Cuyahoga River.

The Ohio Department of Health (1960), in a discussion of data pertaining to the origin and magnitude of pollution loads to the Cuyahoga River and their effects upon receiving streams, pointed out the degree of pollution reduction required to meet stream water quality objectives.

Northington (1964) studies the physical, chemical, and biological changes in the Cuyahoga River resulting from untreated and improperly treated discharges from combined sewer overflows, broken sewers, malfunctioning septic tanks, the Southerly Wastewater Treatment Plant and selected industries. He found that during the summer dissolved oxygen was zero (0) below Kent, Ravenna, Stow, Munroe Falls, and between Akron and the navigation channel and that in the warm season it seldom was greater than 2 mg/l

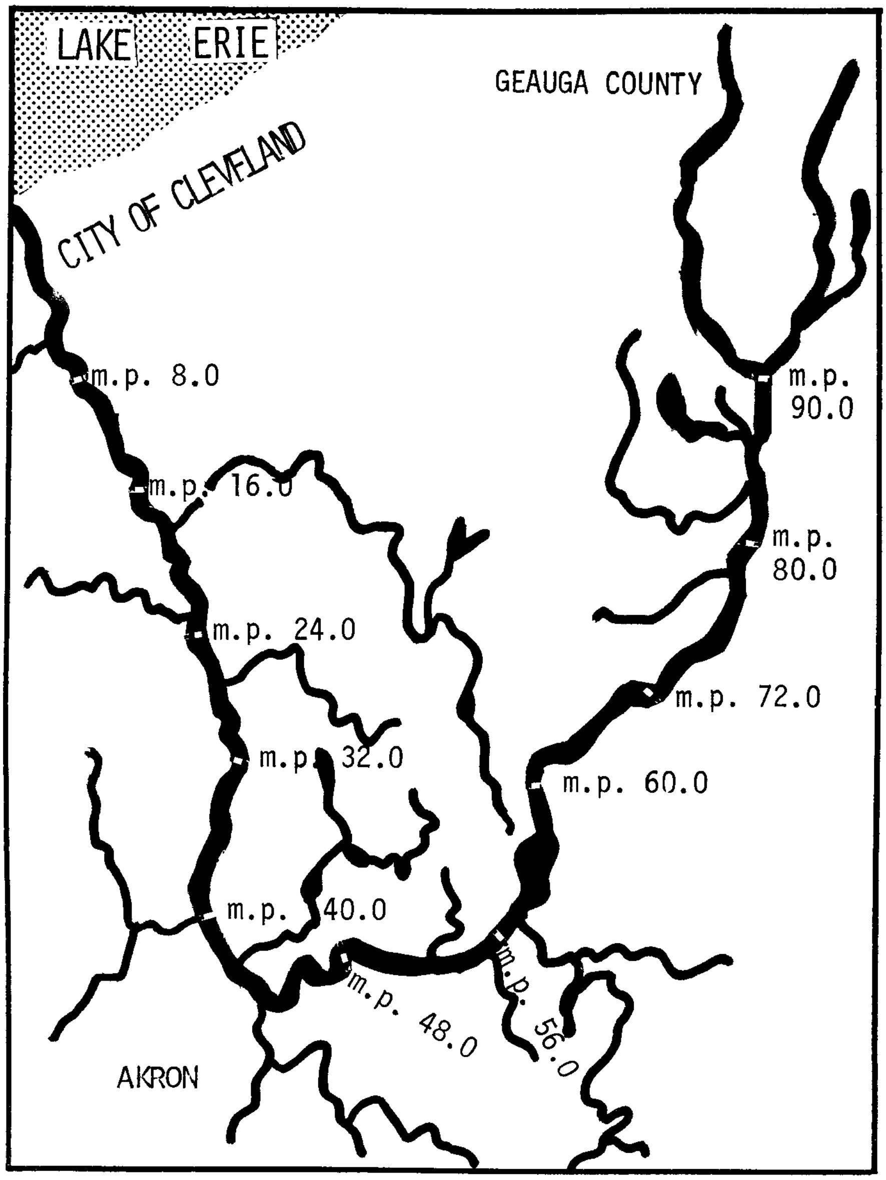

Figure 1. Cuyahoga River

Variations in specific conductance, temperature, and dissolved oxygen in the navigation channel (mouth to 5.1 miles upstream) were reported by Schroeder and Collier (1966). Data collected from monitors located .86, 1.2, 4.2, and 5.1 miles upstream indicated significant fluctuations in specific conductance at .86 and 1.2 miles. This resulted from the intrusion of the cooler, more dense Lake Erie water under the less dense Cuyahoga River water. Higher temperatures within and above the navigation channel were attributed to discharges from industrial and municipal sources.

The Stanley Engineering Co. (1966) detailed changes in the Cuyahoga River (January to November 1964) as it flowed from Lake Rockwell (m.p. 60.0) to Lake Erie. Waters above Lake Rockwell were generally good but the waters below Lake Rockwell experienced a variety of adverse changes as a result of municipal and industrial discharges.

Havens and Emerson (1968) reported industrial and municipal loads to the Cuyahoga River (from Lake Rockwell to the mouth) and its tributaries and identified the principal waste load inputs and their effect upon the quality of the river. The principal waste load inputs were residual wastes in the treated effluent from the Cleveland Southerly Wastewater Treatment Plant, industrial wastes originating in the Metropolitan Cleveland area (mainly from the steel and chemical industries), and organic and inorganic waste from tributary streams, combined sewer overflows, storm drains, and smaller municipal and industrial sources.

Individual municipal and industrial waste treatment needs for the Greater Cleveland - Akron Area discharging into the Cuyahoga River were identified in the U.S. Dept. of Interior - Lake Erie Report (1968). Akron (STP) and Cleveland Southerly (STP) were cited as the major municipal polluters; and Goodyear, B.F. Goodrich, Firestone, U.S. Steel, Republic Steel, and Jones and Laughlin Steel were cited as the major industrial polluters. Of these polluters Republic Steel, Jones & Laughlin Steel, and U. S. Steel ranked as the 2nd, 5th, and 15th (consecutively) largest producers of industrial waste being discharged into a tributary of Lake Erie. Cleveland ranked second and Akron ranked fifth among the ten largest sources of municipal waste discharged into Lake Erie.

A report designed to give a complete picture of the needs for and some possible solutions to the problems of wastewater management in the Cuyahgoa River Basin was published by the U.S. Army Corps of Engineers (1971). It noted that the restoration of the river could not be satisfactorily achieved without a significant reduction in the waste burden then being placed in the river. Data from the Havens & Emerson (1968) study was used as their data base for projecting municipal and industrial waste loads to the Cuyahoga from 1970 to 2020. This report identified the major polluters and recommended methods for improving water quality in the Cuyahoga River.

The U.S. Army Corps of Engineers' Wastewater Management Study (1973) characterized the volume of waste load being discharged into the Cuyahoga River from domestic sources, industrial processing and cooling operations, urban runoff, and rural runoff. These waste load values were reported for 1970 and were estimated for 1990 and 2020.

The enriching effects of industrial and municipal discharges were reported by the Great Lakes Water Quality Board (1973). The report studied areas in the Cuyahoga River which were not meeting Federal water quality requirements and pointed out that many Cleveland municipal and industrial pollution abatement projects were considerably behind schedule.

Dischargers located along Tinkers Creek, a tributary of the Cuyahoga, were described by Havens and Emerson (1974). Low flow, physical characteristics, benthic oxygen demand, and various chemical characteristics were included with reference to the municipal waste dischargers. Included among the municipal dischargers into Tinkers Creek were Bedford, Walton Hills, Bedford Hts., Solon, Twinsburg - Macedonia, and Hudson #5.

As part of a pollution source monitoring program the Ohio EPA (1974) compiled a list of principal municipal and industrial dischargers, their locations, and the status of their compliance in meeting pollution abatement schedules.

Garlauskas (1974) reported results of a study designed to be the first phase of a three phase project to comprehensively assess the environmental impact of pollution abatement programs in the Cleveland area. This first phase was an attempt to make a baseline study of the water quality and pollution load in the Greater Cleveland-Lake Erie shoreline area.

POLLUTION EFFECTS ON STREAM BIOLOGY

The literature search for information pertaining to the biological fauna in the Cuyahoga River revealed that, with the exception of coliform concentrations, very little biological data was available. The major thrust of the biological effort in the Cleveland area had instead been directed toward the near shore Lake Erie communities.

A 1967-68 study of the river (Havens and Emerson, 1968) touched lightly upon planktonic and algae of lava. While genera varied within the river, the upper reaches of the Cuyahoga were found to contain, in general, many more species than the navigation channel. The genus <u>Ossilatoris</u> was found to be ubiquitously distributed and was the only genus reported within the navigation channel. No study of any significance had been conducted on zooplankton.

The 1967-68 study by Havens and Emerson represented the only recent study of the benthic fauna in the Cuyahoga River. They reported that no benthic organisms were found within the navigation channel. Sludgeworms (Tubificids) were the first benthos encountered, making their first appearance above the navigation channel where Big Creek entered the Cuyahgoa (m.p. 7.4). These 'pollution tolerant' organisms were found to be ubiguitous components of the River's benthic community.

Proceeding further upstream midge larvae and pupae (Tendipedidae) and snails (genus Physa) joined the community. As with the phytoplankton and attached algae, the benthic community became richer and more varied as one proceeded upstream with mayflies appearing at and above Sagamore Creek (mile point 18.5).

No accurate record of the fish fauna of the Cuyahoga River was found. From general accounts of the history of this region it is probable that a varied fish assemblage was once present in the Cuyahoga drainage basin. However, by 1868, the Cleveland Daily Plain Dealer reported that the river had become filthy with refuse from oil refineries. Therefore, it is expected that the effects of this industrialization upon the fish community was disastrous.

Havens and Emerson (1970) and Cooke (1968) assembled lists of fish reported within the Cuyahoga River. They found that while fish diversity indices in the lower Cuyahoga River were near zero the diversity increased as the lower Cuyahoga opened into the harbor.

Both studies pointed out that the most distressed area within the general Cleveland region of Lake Erie was the lower 7 miles of the Cuyahoga River.

Sphaerotilus was reported to occur in some portions of the Cuyahoga River. Other than this genus and considerable information on coliforms, no studies of microorganisms were found. In the 1967 summer data total and fecal coliforms and fecal streptococci were discussed by Havens and Emerson (1968).

SECTION V

DESCRIPTION OF STUDY AREA (Figure 1).

The east and west branch of the Cuyahoga arise in farmland and woods in northern Ohio and flow relatively unpolluted to Lake Rockwell (m.p. 60.0). Here a varied biological population of fish, aquatic plants, and algae is found. Downstream of Lake Rockwell the river receives a significant waste load of silt from the Akron Water Plant (m.p. 59.6). Approximately three miles downstream of Lake Rockwell is the confluence with Breakneck Creek. The City of Ravenna Sewage Treatment Plant discharges waste containing significant BOD into Breakneck Creek. This discharge contributes to the low dissolved oxygen and high nutrient state of the water discharged from Breakneck Creek into the Cuyahoga River and is in part responsible for the scarcity of game fish in this section of the river.

From Breakneck Creek (m.p. 56.8) to Kent (m.p. 54.1) the water quality improves because the natural gradient of the river (descends 15 feet in 2.8 miles) provides good aeration in this area. At Kent the river receives waste from the Kent Sewage Treatment Plant.

From the Kent STP to the Munroe Falls Dam pool (m.p. 51.5) river flow is very slow. Water in the pool created by the dam is almost entirely depleted of dissolved oxygen as a result of the large surface area of the pool and the high concentrations of nutrients from the Kent STP. These nutrients encourage algae blooms which subsequently die and utilize dissolved oxygen. Rough fish such as goldfish, carp, and bullheads are found here.

Approximately 10 miles downstream of Kent the Cuyahoga River receives thermal loading from the Ohio Edison generating plant. This loading causes a temperature rise of about 6-8 degrees centigrade in the summer months. However, 5-6 degrees of this heat is dissipated in the pool created by the 80 foot Ohio Edison Company Dam and the fall of the water over this dam. Low dissolved oxygen resulting from the heat input and thermal stratification is found here during periods of low flow.

Between the Ohio Edison plant (m.p. 44.0) and the Akron Metropolitan

Area (m.p. 43.5) the Cuyahoga recovers to a relatively unpolluted stream (coliform bacteria is low, several species of desirable game fish are prevalent, and dissolved oxygen is high). The Little Cuyahoga River and the Cuyahoga River flowing through Akron receive gross pollution from industrial and municipal dischargers. The significant dischargers are: Goodyear Tire and Rubber (m.p. 42.4), Firestone Tire and Rubber (m.p. 42.4), B.F. Goodrich (m.p. 41.0), and the Akron Sewage Treatment Plant (m.p. 37.2). These complexes, along with various small landfill operations and industries, pollute the Cuyahoga with solids, chloride, ammonia, phosphate, temperature, COD, oil, organics, BOD, and silt to such an extent that the river does not recover from this point to its mouth.

From Akron (m.p. 43.5) to Furnace Run (m.p. 33.1) the river is generally septic, dark grey, and odorous in the marginal bank zones. Sludge beds appear frequently but are washed out by intermittent high flows, and dark and light waste rubber particles are in abundance. Except for the navigation channel, this reach supports the lowest population of aquatic life.

Downstream of Furnace Run to the head of the pool behind the Ohio Canal Diversion Dam (m.p. 21.1) the river recovers significantly with BOD, COD, and coliform bacteria decreasing as DO is increasing. Below the dam flow is reduced as water is diverted to the Ohio Canal to be used by industry. Here the DO decreases to almost zero as a result of the high oxygen demand of the wastes.

The next major degrading impact on the Cuyahoga River is the discharge from Tinkers Creek (m.p. 17.2). This tributary receives the effluent from several small treatment plants including Bedford and Bedford Heights.

From the confluence of Tinkers Creek the water quality in the river improves slightly until it receives the discharge from Cleveland's Southerly Wastewater Treatment Plant (m.p. 11.0). Downstream of Southerly the river again becomes grossly polluted. Dissolved oxygen is reduced and BOD, COD, solids, ammonia, nitrate, phosphate, and bacterial counts are increased.

Below Southerly the water quality is further reduced, as it flows through the navigation channel, by discharges from Lamson and Session (m.p. 7.3), Harshaw Chemical (m.p. 7.0), and the Ford Motor Company Plant (m.p. 7.3). Also the pollution in this area is complicated by decreased water velocity which results from the dredging of this channel.

The dredging operations are conducted by the Corps of Engineers. The present controlling depths for dredging in the Cuyahoga are:

27 feet in the Cuyahoga River channel between piers to the Central Transportation Bridge (Lake Erie to m.p. 1.0)

23 feet in the Cuyahoga River (m.p. 1.0 to approximately m.p. 6.0)

23 feet in the Old River (enters main channel at m.p. 0.3) to the Sand Corporation dock (m.p. 0.4 - Old River)

21 feet in the remainder of the Old River

18 feet in the turning basin in the Cuyahoga River (m.p. 5.2)

This dredging of the lower reach has made it the deepest section of the river. It has also made it the most sluggish section with the lowest currents. These low currents make it impossible for adequate movement of waste discharged into the channel. For this reason, this portion of the river is polluted to such a degree that it has been classified as the third dirtiest river in the United States by the U.S. Dept. of Interior (Lake Erie Report, 1968).

SECTION VI

STUDY OF LAKE INTRUSION

Five sampling stations were established in the lower navigation channel of the Cuyahoga River from mile point 0.0 to mile point 1.0. Here intrusion effects were considered most significant. Stations were located at intervals of approximately 0.2 miles as shown in Figure 2. Station 3 was located in the Old River Channel. The sampling program was designed to collect data to be utilized in the development of the finite-difference time-variant estuary model for the lower one mile of the river and to establish water quality parameters for this section. Samples for each station were collected at the surface and at 8 meters. All data collected during the eight week program are listed in Appendix B.

Data collected on September 12, 1973 were typical and will be used to show the various water quality parameters determined within the sample area and how they varied as a result of Lake Erie intrusion. Figure 3 shows levels of conductance and temperature found at the various sampling stations on September 12, 1973 at both the surface and 8 meters depths. Surface conductance values ranged from a high of 950 micromhos at Station 6 to a low of 210 micromhos at Station 1. Data at 8 meters showed the conductance to be lower when compared to values found in the surface waters. This indicated stratification within the water column. At Station 1, however, the conductance values were very similar at both the surface and 8 meters indicating that at mile point 0.0 water of a uniform nature was being measured. Temperature showed the same general pattern as conductance in that it decreased from mile point 1.0 to mile point 0.0 and was lower at 8 meters than at the surface. The exception again was at Station 1 where the temperature was identical. This is an indication of complete mixing throughout the water column at mile point 0.0.

Figure 4 graphically presents data collected at the surface and 8 meters depths on September 12, 1973 for chloride and dissolved oxygen. In comparing the concentrations at Station 6 (m.p. 1.0) and Station 1 (m.p. 0.0) respectively, the following observations are made: chloride at the surface decreased from 122/mg/ to 89 mg/l while at 8 meters it decreased from 118 mg/l to 76 mg/l, dissolved oxygen flucuated at the 8 meters depth from 1.0 mg/l to 6.5 mg/l. The surface dissolved oxygen values followed the same general trend although the measured values were lower.

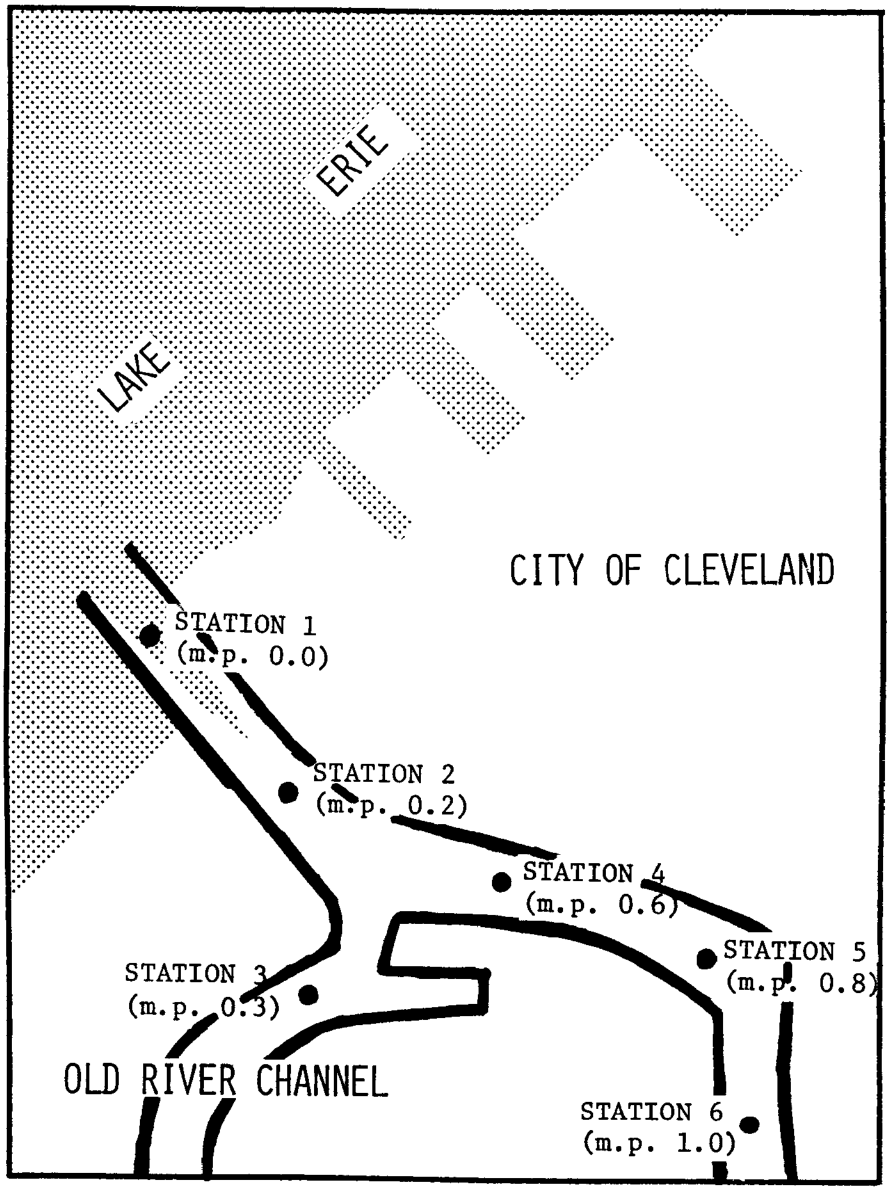

Figure 2. Sampling stations in navigation channel and Old River Channel.

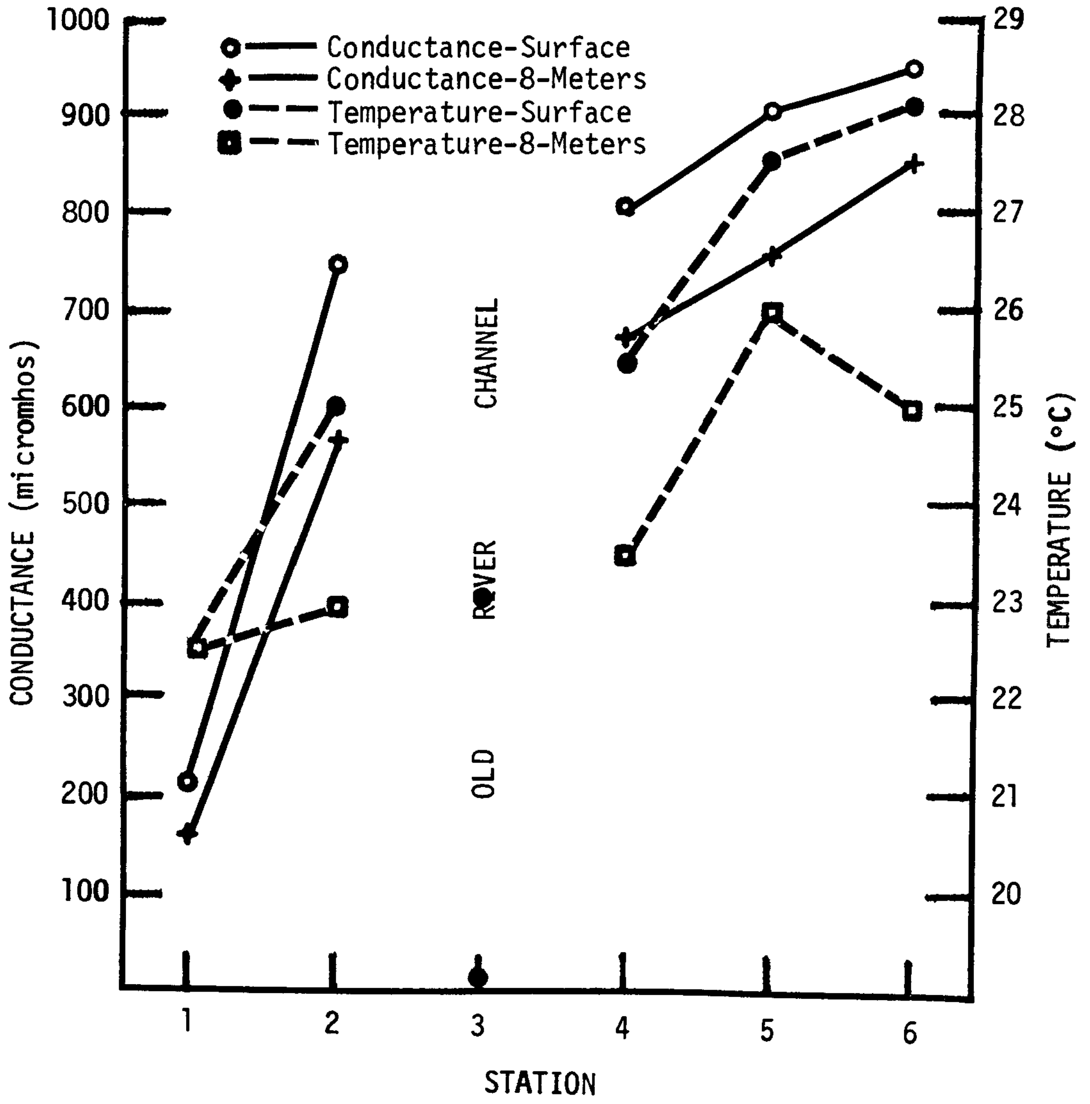

Figure 3. Level of conductance and temperature found at sampling stations on 9/12/73.

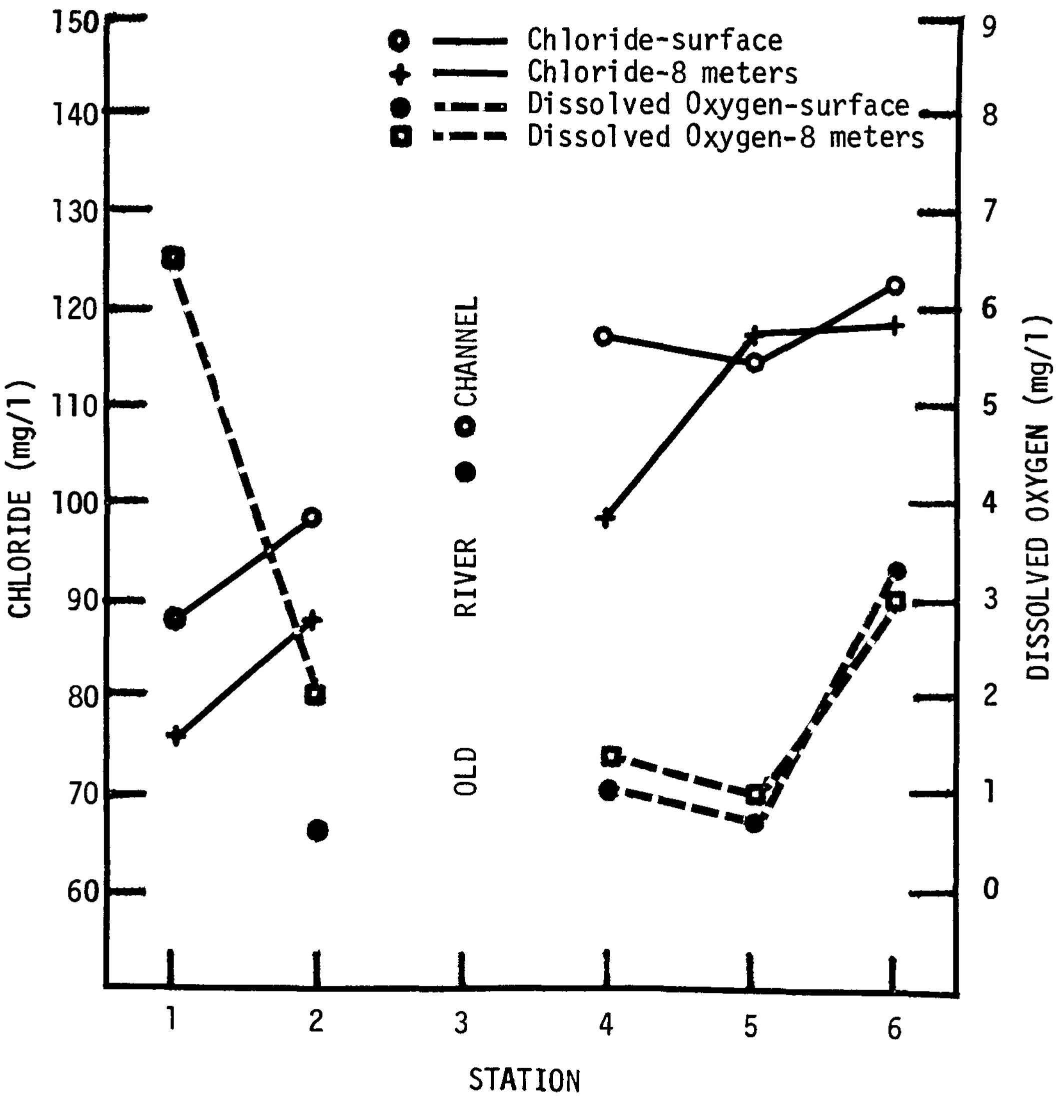

Figure 4. Graphic presentation of chloride and dissolved oxygen data collected on 9/12/73.

BOD_5 values measured on September 12, 1973 are presented in Figure 5. Concentrations of BOD_5 in the surface waters ranged from 9.0 mg/l to 14.0 mg/l, being highest at Station 4 and lowest at Station 1. At 8 meters BOD_5 values varied from a low of 7.0 mg/l at Station 2 to a high of 13.0 mg/l at station 1 and 4. In general, the values at 8 meters were lower than the values observed in surface waters at the same stations. The most notable exception being Station 1 where, at 8 meters, the BOD_5 values were higher than those of the surface waters.

Organic nitrogen and ammonia nitrogen observed on September 12, 1973 at the various stations at the surface and at 8 meters are shown graphically on Figure 6. In the surface waters ammonia nitrogen ranged from a high of 4.7 mg/l at Station 6 to a low of 2.35 mg/l at Station 4. Organic nitrogen values were less than the ammonia values. The highest surface concentration of organic nitrogen (1.68 mg/l) was found at Station 2. At 8 meters organic nitrogen ranged from 5.82 mg/l to 0.0 mg/l and ammonia nitrogen ranged from near 0.11 mg/l at Station 5 to a high of 8.06 mg/l at Station 2. The organic nitrogen values of the latter were lower.

The data shows that for the conservative element chloride and the water quality parameters of conductivity and temperature there is a pattern of increasing values from mile point 0.0 (Station 1) to mile point 1.0 (Station 6). This indicates, as one would expect, that as one travels upstream in the Cuyahoga River the effect of Lake Erie on water quality parameters decreases. Comparison of this data at the surface and at the 8 meters depth indicates almost complete mixing of the Cuyahoga River water with Lake Erie water at Station 1 (mile point 0.0), whereas, intrusion under the river water (stratification) at all stations upstream of this point is observed. Other water quality parameters such as organic nitrogen, ammonia nitrogen, and BOD_5 did not show trends as definite; however, it can be said that, generally, for any given parameter values were lower at 8 meters than in the surface waters. Factors contributing to the variations observed were probably such things as the occurrence of biological transformations and the discharge of wastes into the river near and/or between the sample locations.

Figure 7 shows weekly variations in temperature at Station 4 (surface and 8 meters). Both curves have the same general shape with the values at the surface being higher in each case. At the surface temperatures ranged from a high of 29°C during the fourth week to a low of 19°C during the sixth week. Values at the 8 meters depth varied from 25°C during the fourth week to 16.5°C during the seventh week.

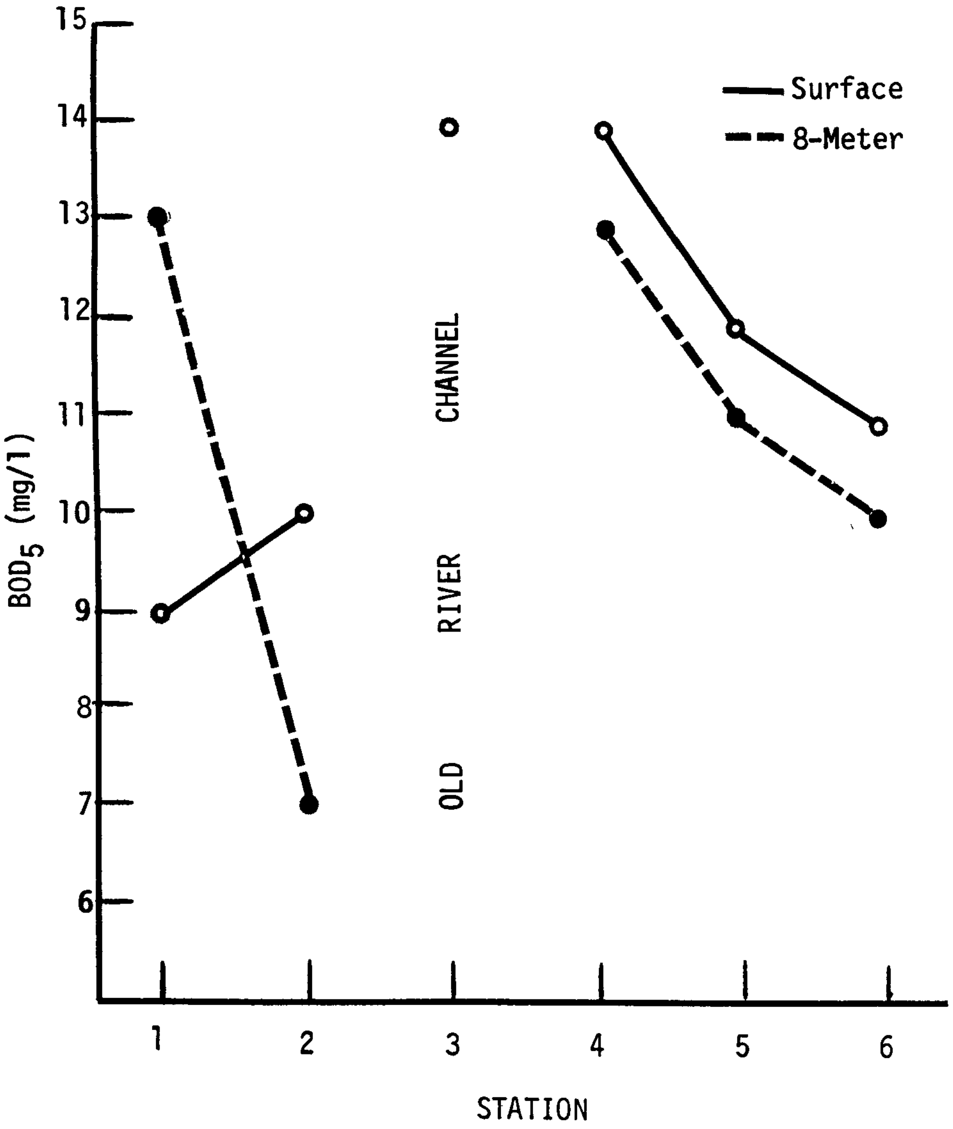

Figure 5. BOD_5 values measured at stations on 9/12/73.

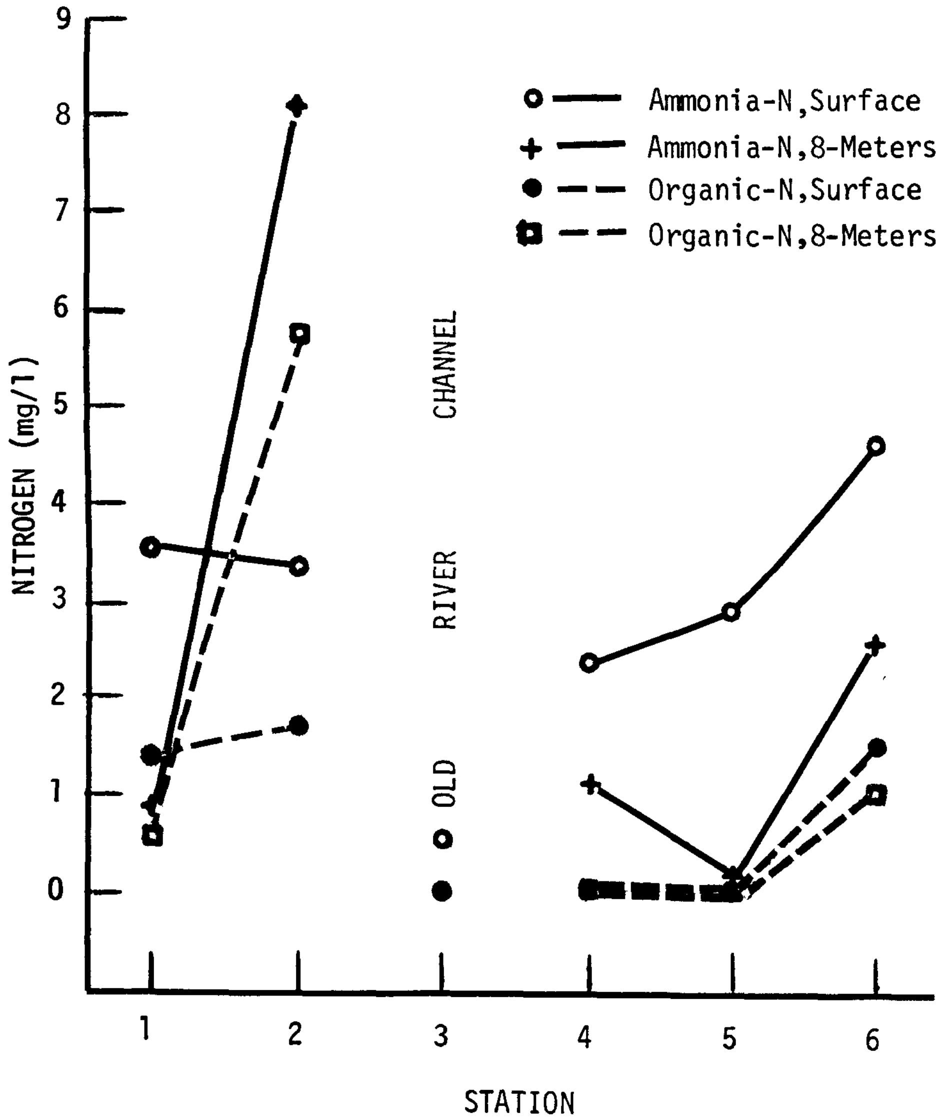

Figure 6. Organic and ammonia nitrogen values measured at stations on 9/12/73.

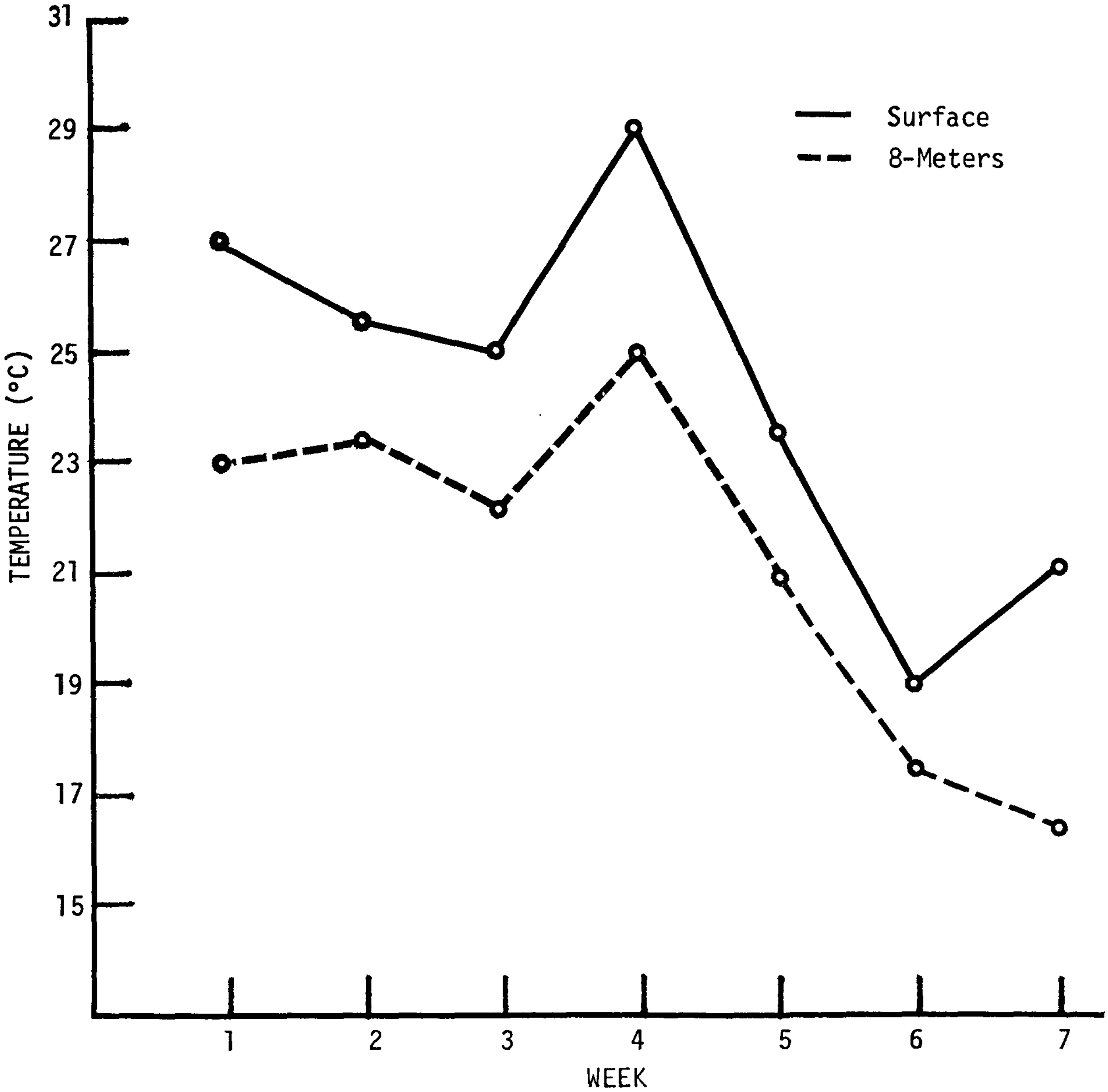

Figure 7. Weekly variations in temperature at Station 4.

Conductance values observed at the surface and 8 meters at Station 4 during the study period are presented in Figure 8. Again the curves follow the same general pattern with the values at 8 meters being lower in each case when compared with surface values. 950 micromhos, the highest surface value, was observed during the fourth week while a value of 800 micromhos was found for the second, fifth and sixth weeks. The highest value found at 8 meters was 840 micromhos during the third week.

Dissolved oxygen in the surface waters at Station 4 varied from a high of 3.4 mg/l during week six to a low of 1.0 mg/l during weeks two and seven (Figure 9). Waters at the 8 meters depth contained higher concentrations of dissolved oxygen than did surface waters on all sampling dates. Values at this level ranged from a low of 1.3 mg/l during the second week to a high of 6.4 mg/l during the sixth week.

Figure 10 presents weekly variations in the chloride found at the surface and 8 meters at Station 4. In the surface waters values ranged from a high of 117 mg/l during the second week to a low of 63 mg/l during the sixth week. At 8 meters the changes were not as pronounced but generally increased and decreased as surface waters concentrations increased or decreased. The highest concentration found was 103 mg/l during the seventh week and the lowest was 55 mg/l found during the sixth week.

An analysis of data collected at Station 4 on a weekly basis showed significant variations, with time, in water quality in both surface waters and at the 8 meters depth.

Generally, concentrations of materials found at 8 meters were lower than those found in the surface waters. This again indicated that, at this depth, Lake Erie water had intruded below the river water. A surface sample, therefore, would not represent water quality throughout the water column at this location. The dissolved oxygen values observed at Station 6 support this assumption of Lake water intrusion as concentrations of this parameter were higher (with the exception of one) at the 8 meter depth than in surface water on all dates measurements were made.

It can therefore be concluded that significant stratification occurs in the lower one mile of the navigation channel. Sampling at several depths is thus necessary to define water quality in this section of the river.

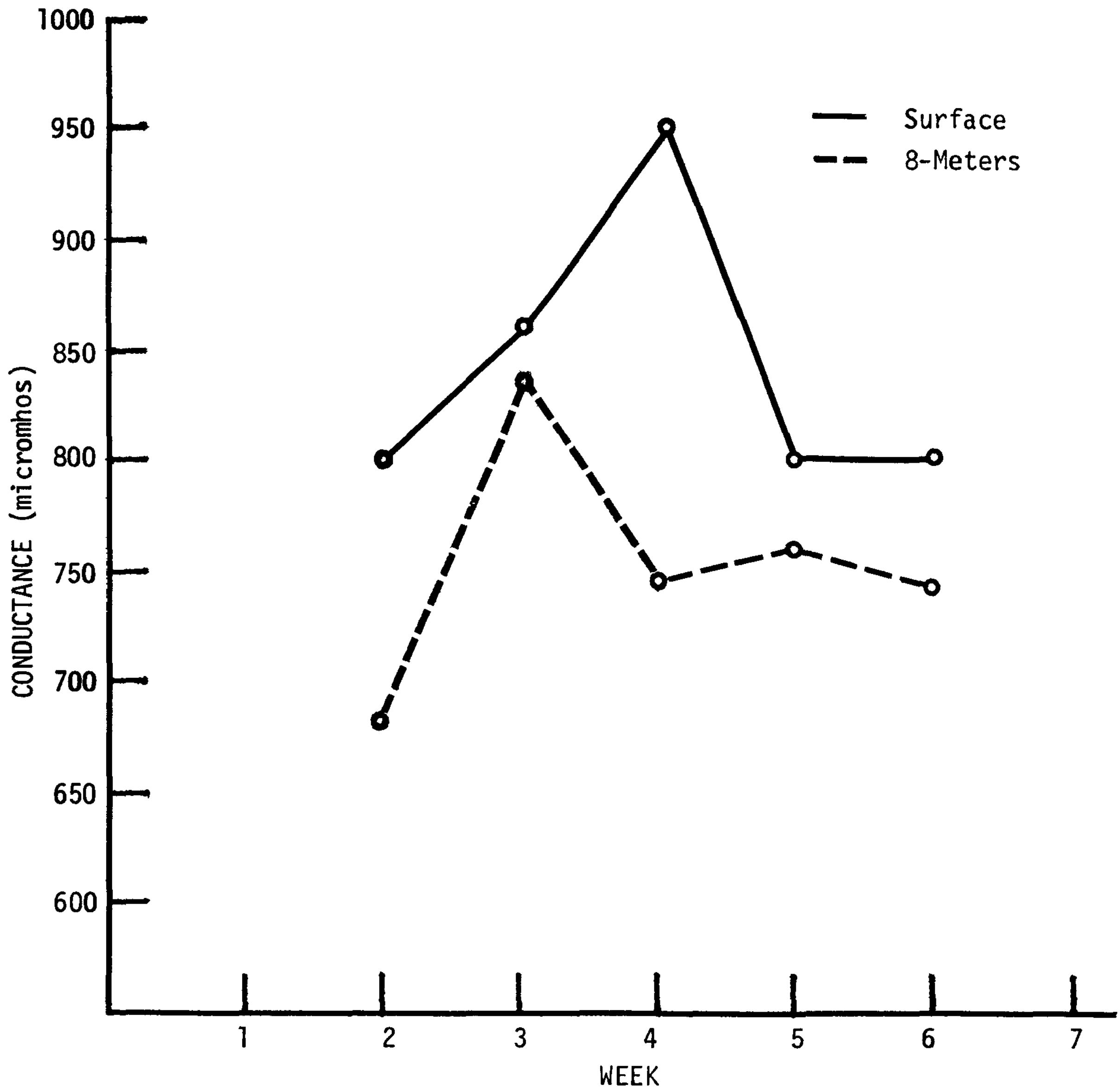

Figure 8. Weekly variations in conductance at Station 4.

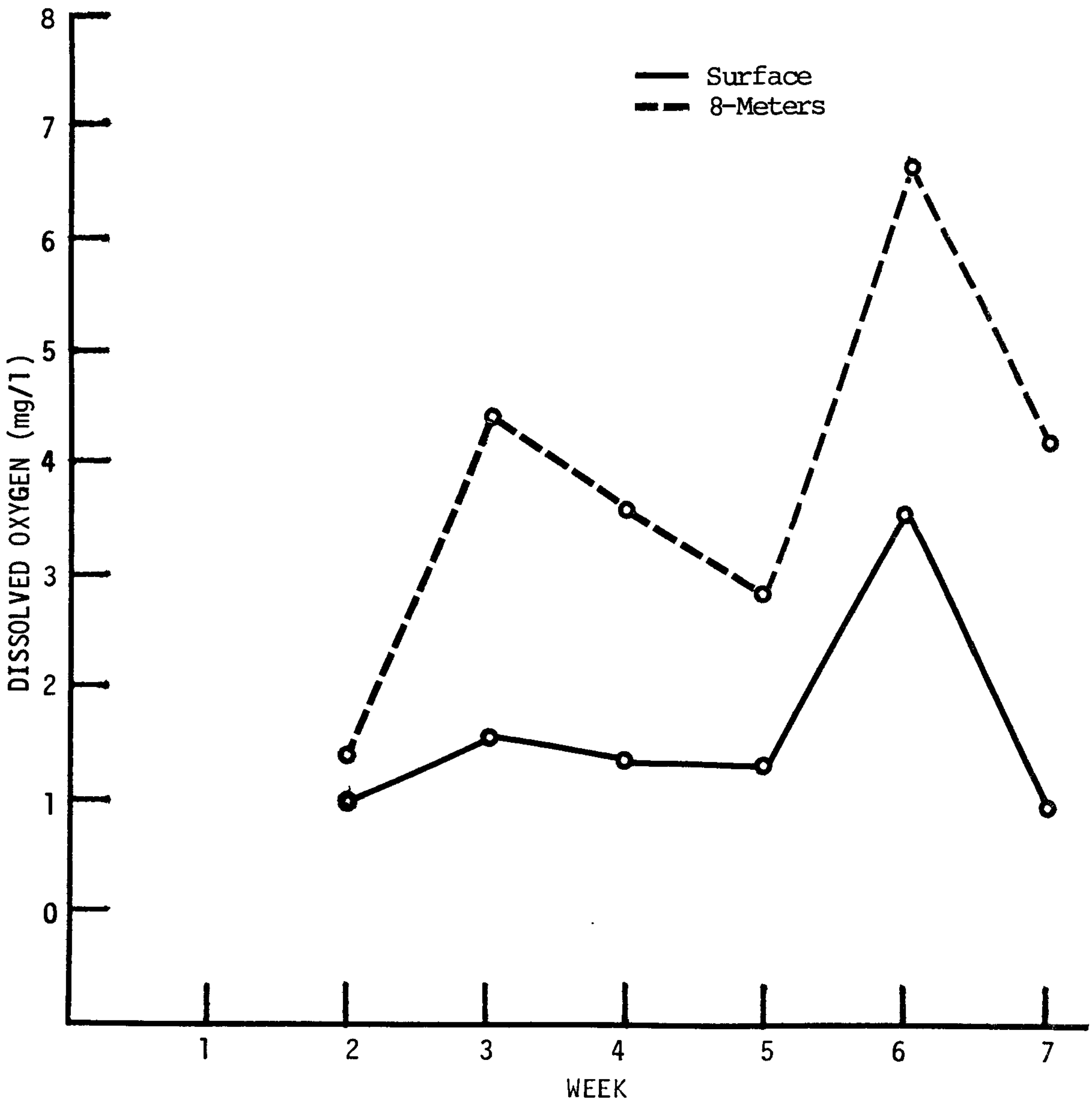

Figure 9. Weekly variations in dissolved oxygen at Station 4.

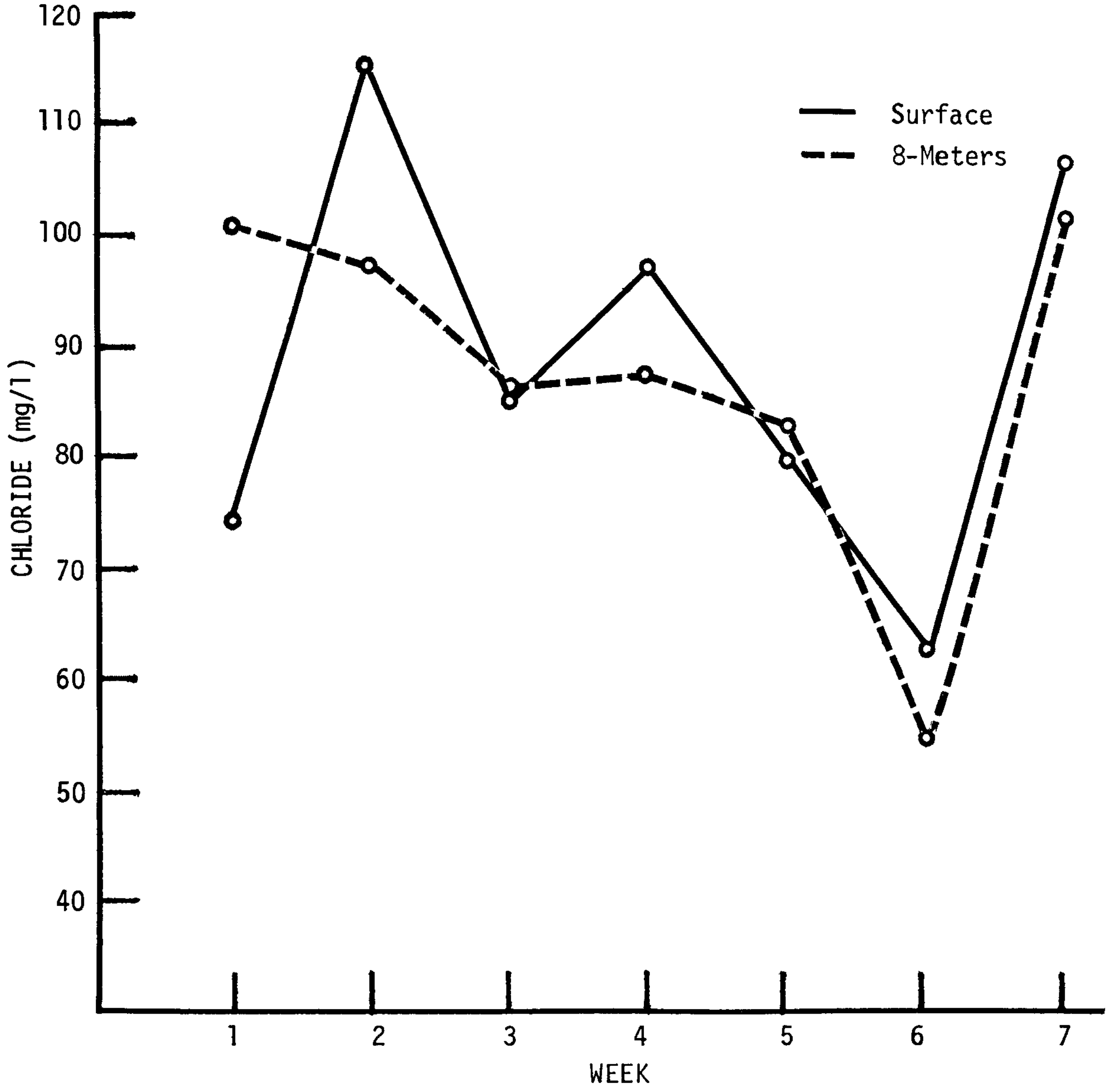

Figure 10. Weekly variations in chloride at Station 4.

SECTION VII

MODEL BACKGROUND

JUSTIFICATION OF NEED FOR A MODEL

The Cuyahoga River because of its recreational potential and because of the vast industrial complexes which span its shoreline and depend upon it as a route for transporting raw and finished goods, is an important river. It's importance, however, is being overshadowed by its pollution.

The current pollution problem in the Cuyahoga River is twofold:

1) The natural contour of the mouth and its delta have been altered by man in an effort to make this section navigable to large ocean going vessels. These alterations have decreased the velocity of water, which have alternately decreased the river's capacity for natural aeration of water in this section; and

2) Industries and municipalities have become dependent upon the river as a receptacle for their discharged waste. This waste, which had generally been improperly treated or untreated, has created a condition of anoxia and physical degradation in certain sections of the river.

Both the above conditions have resulted in decreased dissolved oxygen in sections of the river.

Because dissolved oxygen is vital to maintaining a homeostatic environment in stream ecosystems, one is justifiably concerned about the low dissolved oxygen content in sections of the Cuyahoga River. This concern is not only for the effect that low dissolved oxygen may have upon the plant and animal life in the river, but also for the effect that it may have upon the near shore water quality in Lake Erie.

In order to determine the effect of discharged waste upon dissolved oxygen in the river and the effect of river dissolved oxygen upon dissolved oxygen at the confluence of Lake Erie a mathematical simulation computer model was developed. A model is advantageous for resolution of problems of this nature because parameters can be manipulated and hypothetical situations can be tested.

The ECO-LABS Mathematical Simulation Computer Model of the Cuyahoga River (EMSCM - CR) addresses itself to the problem of dissolved oxygen. It is designed specifically for use in the Cuyahoga River, however, minor variations make it adaptable to any stream possessing similar hydraulic - physical conditions.

JUSTIFICATION FOR TYPE OF MODEL

A review of literature pertaining to water quality simulation models of similar aquatic systems indicated a need for three different models:

I. Steady State (Non-dispersive)

II. Finite difference (Steady State - dispersive)

III. Time - variant (Finite Difference - dispersive)

A non-dispersive steady state model (Model I) based upon Streeter - Phelps equations (Streeter and Phelps, 1925) was utilized where no mixing due to diffusion or dispersion of materials occurred. Studies (Stanley Engineering Co., 1966; Havens and Emerson, 1968; Dalton, Dalton & Little, 1971; and Garrett, 1974) indicated that these equations rroduce reliable results for approximately 94% of the Cuyahoga River system.

Of the remaining 6% of the river system (navigation channel - m.p. 6.0- m.p. 0.0) dispersion was considered extremely important because of the tidal effects resulting from intrusion of Lake Erie water at the mouth of the river. Bella and Dobbins (1968) considered even a small amount of dispersion to be important in tidal rivers such as the Cuyahoga. Therefore, a finite difference - steady state model (Model II) was utilized for the 6% of the river affected by dispersion.

The finite difference approach (O'Connor, 1965; Hetling and O'Connell, 1966; Grenney and Bella, 1972; and Thomann, 1972) proceeded by dividing the stream into sections, i.e., lengths of river where hydrologic and water quality conditions remained constant (Figure 11). Each section was considered completely mixed. Each constituent was, therefore, represented by one equation and a solution was obtained by matrix inversion.

The lower one mile of the Cuyahoga River system was shown to be most profoundly effected by Lake Erie intrusion. To simulate this section, Model III, a one-dimensional, time-variant model (Fisher, 1969)

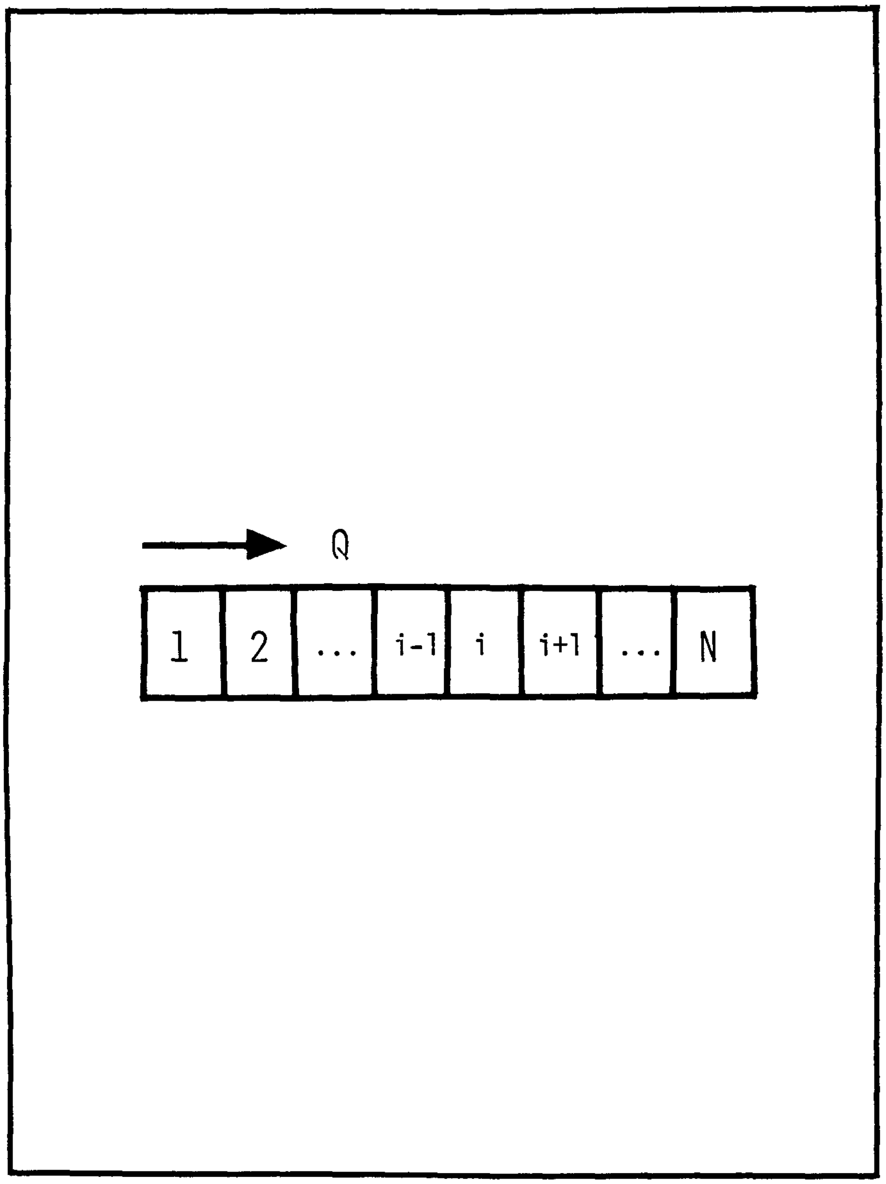

Figure 11. Conceptual division of a river into "N" sections.

was utilized because of its Lagrangian approach and provision for dispersion between segments. Numerical dispersion which occurred in the convective step is minimized in this type of model because spatial grids are not established.

The EMSCM - CR, therefore, consists of a non-dispersive steady state (Model I), a dispersive steady state - finite difference (Model II), and a time - variant (Model III) model. Each model is structured for a particular application as a one-dimensional network approximation of a system of interconnecting segments.

SECTION VIII

MODEL DESCRIPTION AND DEVELOPMENT

MODEL I (STEADY STATE, NON-DISPERSIVE RIVER MODEL)

The reach of river above the navigation channel (m.p. 6.0) is relatively shallow and has a relatively small cross-sectional area as compared with the navigation channel (See Table 1). Flows within this reach thus produce sufficiently large velocities. Plug flow is, therefore, an acceptable assumption here.

Figure (12) illustrates a river situation which has point sources of carbonaceous BOD (CBOD) and an initial upstream dissolved oxygen (DO) deficit (D). While flows and stream cross-section usually vary with distance, it is sufficient to assume that they are constant within the reach lying between waste load input points (nodes). These 'nodes' then serve as points at which new instream concentrations are evaluated. This process is repeated for each successive downstream reach.

If the upstream loading of CBOD is L_u then the new initial value of CBOD (L_o) at the outfall is given by a mass balance at the outfall as:

$$L_o = \frac{W + L_u Q_r}{Q_r + Q_w} \qquad (1)$$

TABLE 1

AVERAGE WIDTHS AND DEPTHS AT VARIOUS MILE POINTS IN THE CUYAHOGA RIVER*
(M.P. 57.8 - M.P. 6.8 From EPA - Columbus, Ohio; M.P. 6.0 - M.P. 0.0 Estimated From Corps of Engineers Dredging Maps - Cleveland, Ohio)

LOCATION	MILE POINT	WIDTH	DEPTH
Lake Rockwell Dam	57.8	38'	2.0'
Breakneck Creek	56.8	55'	3.0'
Kent Dam	55.0	55'	3.5'
Kent STP	54.0	50'	3.0'
Plum Creek	53.8	125'	7.0'
Fish Creek	52.3	240'	8.0'
Munroe Falls Dam	50.1	140'	6.0'
Cuyahoga Falls Dam (1st)	46.6	125'	7.0'
Cuyahoga Falls Dam (2nd)	46.4	100'	0.2'
Ohio Edison Dam Pool	46.0	110'	13.0'
Ohio Edison Outfall	44.8	300'	20.0'
Ohio Edison Dam	44.3	20'	0.6'
Ohio Edison Gorge (bottom)	43.3	90'	0.4'
Little Cuyahoga River	42.0	80'	1.0'
Old Portage	39.9	60'	1.6'
Mud Creek & Sand Run	39.5	80'	1.1'
Akron STP	37.2	65'	2.2'
Yellow Creek	37.0	62'	2.3'
Furnace Run	33.1	76'	1.1'
Peninsula	29.1	92'	2.3'
Brandywine Creek	24.2	89'	1.9'
Chippewa Creek	21.2	90'	4.0'
Ohio Canal Diversion Dam	21.1	90'	1.4'
Brecksville STP	19.1	87'	1.8'
Sagamore Creek	18.5	92'	2.1'
Tinkers Creek	17.2	95'	1.8'
Swan Creek	15.9	95'	2.0'
Independence	13.8	95'	2.5'
Mill Creek	11.8	100'	2.0'
Cleveland Southerly	11.0	110'	7.9'
Associated Japanning	8.0	120'	7.9'
U.S. Steel	7.5	130'	7.9'
Big Creek	7.4	140'	10.0'
Harshaw Chemical	7.3	150'	10.0'
Republic Steel	6.8	200'	10.0'
Navigation Channel	6.0	150	20.0
Navigation Channel	5.0	176	25.0
Navigation Channel	4.0	204	25.0
Navigation Channel	3.0	296	25.0
Navigation Channel	2.0	248	25.0
Navigation Channel	1.0	180	25.0
Navigation Channel	0.0	300	27.3

*Measurements taken during period of Critical Flow. (See Table 2).

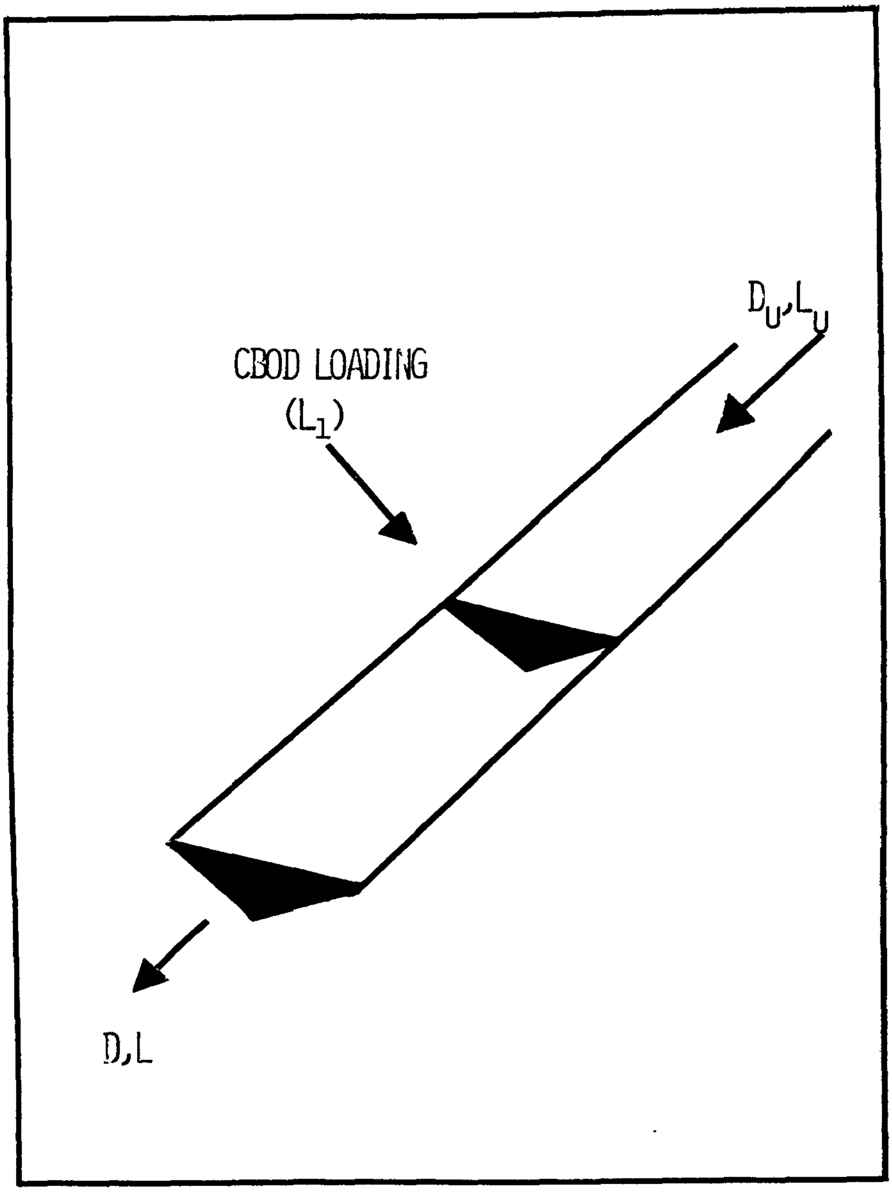

Figure 12. Sectionalized Stream.

where W = mass rate of discharge of CBOD from the waste source (or tributary)

Q_r = river flow

Q_w = waste flow

L_u = upstream concentration of CBOD

DO deficit (D) at some point downstream is represented as:

$$D = \left(\frac{K_1}{K_r - K_1} \{\exp[-(K_1/U)X] - \exp[-(K_r/U)X]\} \right) L_o + D_o \exp[-(K_r/U)X] \quad (2)$$

where K_1 = deoxygenation coefficient for CBOD (base e)

K_r = reaeration coefficient

X = distance downstream from outfall

U = velocity within reach

CBOD (L) at the same downstream location is similarly represented as:

$$L = L_o \exp[-(K_1/U)X] \quad (3)$$

where terms are defined as above.

In practice, the above set of equations are evaluated repeatedly at node points downstream wherever a waste input or tributary enters, or where stream geometry changes significantly. Where a tributary enters and introduces water having a DO deficit different from that of the receiving stream an equation analogous to L_o is utilized to evaluate the new D_o :

$$D_o = \frac{D_t + D_u Q_r}{Q_r + Q_t} \quad (4)$$

Where D_t = DO deficit loading in the tributary

Q_t = Flow from the tributary

D_u = Upstream DO deficit concentration

The above set of algebraic equations are coded in Fortran IV level G language to provide for digital simulation of DO deficit and CBOD within the region of the Cuyahoga River above mile point 6. This model is appended to the dispersive, finite-difference model and permits tributary and waste loads to be added to the river at any point above the navigation channel. It applies equations (1) through (4) at each mode point and evaluates D and L entering the navigation channel. A complete description of program operation and data input requirements is contained in Appendix C.

MODEL II (DISPERSIVE RIVER MODEL - FINITE-DIFFERENCE APPROACH)

The navigation channel is the dredged portion of the lower Cuyahoga River which extends from its mouth to mile point 6. Dredging maintains the navigaiton channel at a depth of approximately 25 feet. While lake water intrusion is largely restricted to the lower one mile of the navigation channel the hydraulic effect of lake level fluctuations is suspected to exist throughout much of the channel. This hydraulic effect tends to increase longitudinal mixing within the channel much as tidal flux increases longitudinal mixing in estuaries. In the case of estuaries the dispersive effects of tidal fluxing are generally experienced well above that point where there is a measurable salinity change. Within the navigation channel, then, one might expect dispersion to influence water quality to varying degrees. The most significant influence is observed during periods of critical flow* (See Table 2). Because the degree of effect of mixing and its significance to water quality was not previously determined, our model of the navigation channel is designed to incorporate dispersion.

Many forms of models have been developed for estuaries in which dispersion is important and must be incorporated. Of the many forms available, the finite difference approach is selected because of its logical parallelism to the Cuyahoga River and because of its amenability to computerization. This modeling approach is described in detail by Thomann, 1972. The following briefly reviews this approach.

Conceptually, the navigation channel is divided into twenty sections, each having a length of 0.3 miles (Figure 13). The choice of the number of sections is dictated by the hydrology and geometry of the channel and by the amount of computer time required to obtain a solution. Since the solution methodology requires inversion of a matrix of order N (where N equals the number of sections in the river),

*The Ohio Department of Health has defined "Critical" flow as the lowest flow which, according to the past records, may be anticipated to occur for seven consecutive days, once every 10 years.

TABLE 2

CRITICAL FLOWS IN CUYAHOGA RIVER, CFS

(Based on Present Discharges from Akron and Cleveland Southerly Sewage Treatment Plants)

	7-day - 10 yr.	7-day - 5 yr,	Flow exceeded 95% of the time	Flow exceeded 90% of the time	Flow exceeded 80% of the time	Mean Daily
Lake Rockwell Ravenna Road	5.0	8.0	9	10	12	
Kent Middlebury Road	10.6	13.0	15	18	22	
Akron Cuyahoga St. Bridge	14.0	17.0	25	30	35	
North Portage Gauge (404 sq. miles)	35.0	40.0	55	68	95	404
Little Cuyahoga River	(19.0)	(27.0)	(28.0)	(35.0)	(45.0)	
Bath Road	131	137	154	168	196	
River Above Diversion	137	146	183	207	256	
Flow in the Canal	60* (65)	60 (65)	60 (65)	60 (65)	60 (65)	
Independence Gauge (707 sq. mi.)	81 (76)	91 (86)	123 (118)	147 (142)	196 (191)	743 (738)
Lower Harvard	210 (205)	220 (215)	252 (247)	276 (271)	325 (320)	
Turning Basins	270	280	312	336	385	
Center Street Bridge	295	305	337	361	410	

*60 & (65 cfs) figures for canal diversion
(allows 5 cfs to leak back to river since 65 cfs is usually diverted.)
Akron STP considered as 96 cfs
Southerly STP considered as 109 cfs
18 cfs from industries in navigation channel
7 cfs from minor stream
20 cfs from Big Creek

From Havens & Emerson, 1968

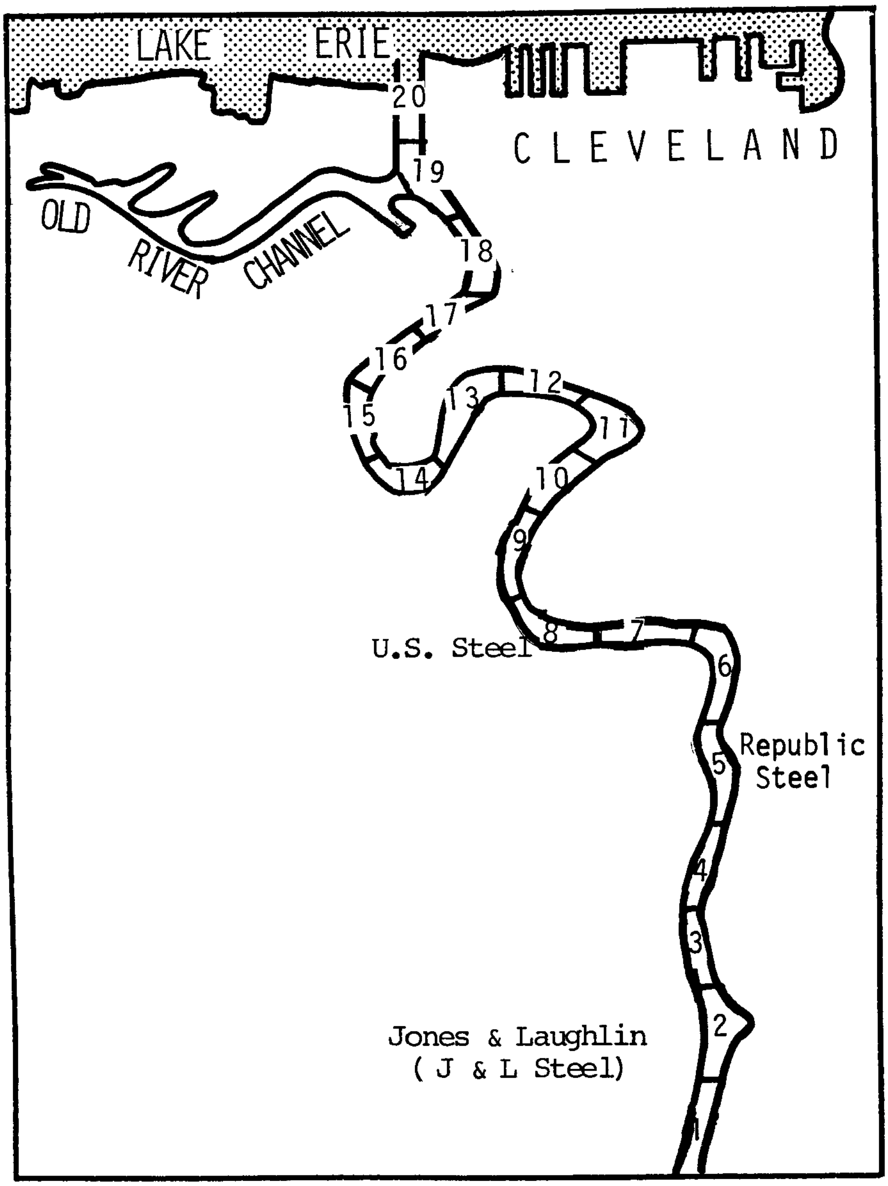

Figure 13. Navigation channel divided into twenty 0.3 mile sections.

as N increases the time to obtain a solution increases significantly. Each section is considered completely mixed, and hence it is assume that no vertical or horizontal variations within a section of the river exist.

Model II (as are all the models developed under this contract) is a one-dimensional model. Mass balances are constructed around each section with respect to DO deficit and CBOD. The balances incorporate flow from section to section and dispersion between adjacent sections. Any input to or output from a given section is written into the mass balance equations for that section. Sources and sink terms for processes occuring within a section are also written into the mass balance equations.

The significant aspects of the mathematical development of the finite-difference model are presented below.

The time rate of change of CBOD mass in section i is represented as:

$$V_i \frac{dL_i}{dt} \tag{5}$$

where L_i is the concentration of CBOD in section i having volume V_i. V_i is the product of the average area (A) and the average length (L_i). The flux of CBOD transported into section i (F_i) is written as:

$$F_i = (Q_{i-1,i})\ (L_{i-1,i}) \tag{6}$$

and the flux of L transported out of section i (F_i) is equal to:

$$F_0 = (Q_{i,\ i+1})\ (L_{i,\ i+1}). \tag{7}$$

Here double subscripts represent the interface between adjacent sections (See Figure 14).

Flow is measured at the interfaces. Concentrations at the interfaces are determined by conveniently writing:

$$L_{i-1,\ i} = \alpha_{i-1,i}\ L_{i-1} + \beta_{\ i-1,i}\ L_i \tag{8}$$

and

$$L_{i,i+1} = \alpha_{i,i+1} L_i + \beta_{i,i+1}\ L_{i+1} \tag{9}$$

where α and $\beta = 1 - \alpha$ are weights which can be calculated from advective and dispersive characteristics. Where the sections are all of the same lengths, as with the model developed here, $\alpha = \beta = 0.5$.

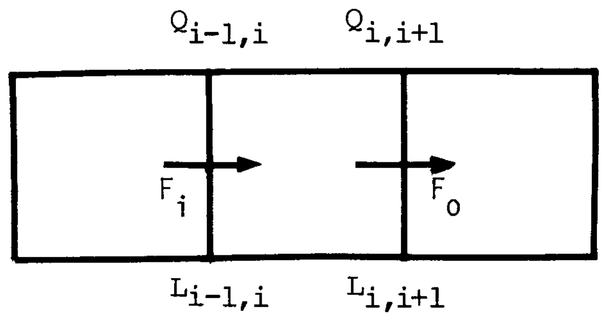

Figure 14. The flux of CBOD across the interface of section i-1 and i (F_i).

Substitution of the weighting relationship into (6) and (7) gives the flux of BOD due to net river flow as:

$$Q_{i-1,i}\ (\alpha_{i-1,i}\ L_{i-1} + \beta_{i-1,i} L_i) - Q_{i,i+1}\ (\alpha_{i,i+1}\ L_i + \beta_{i,i+1}\ L_{i+1}). \qquad (10)$$

Dispersive exchange is written as:

$$\frac{E_{i-1,i} A_{i-1,i}}{\Gamma_{i-1,i}} (L_{i-1} - L_i) \qquad (11)$$

and

$$\frac{E_{i,i+1}\ A_{i,i+1}}{\Gamma_{i,i+1}} (L_{i+1} - L_i) \qquad (12)$$

for exchange between sections i-1 and i and secitons i and i + 1 respectively, where $E_{i,j}$ = the dispersion coefficient evaluated at the interface of sections i and j.

$\Gamma_{i,j}$ = the average length of sections i and j

For decay of CBOD according to first order processes, the effect is written as:

$$-V_i K_{1i} L_i \qquad (13)$$

where K_{1i} equals the deoxygenation coefficient (base e) for CBOD in section i :

$$\begin{aligned} V_i \frac{dL_i}{dt} = \; & Q_{i-1,i}\ (\alpha_{i-1,i}\ L_{i-1} + \beta_{i-1,i}\ L_i) \\ & - Q_{i,i+1}\ (\alpha_{i,i+1}\ L_i + \beta_{i,i+1}\ L_{i+1}) \\ & + E'_{i-1,i}\ (L_{i-1,i} - L_i) + E'_{i,i+1}\ (L_{i+1} - L_i) \\ & - V_i K_{1i} L_i + W_i \end{aligned} \qquad (14)$$

where $E' = \frac{EA}{\Gamma}$ and is a bulk dispersion coefficient.

Twenty such equations are developed, one for each of the 0.3 mile sections between the head of the navigation channel and the mouth of the river. Under steady state assumptions $\frac{V_i dL_i}{dt} = 0$, and the system reduces to a set of twenty simulataneous algebraic equations.

Grouping all terms in L_{i-1}, L_i and L_{i+1} on the left and allowing:

$$A_{i,i-1} = 0.5\, Q_{i-1,i} - E'_{i-1,i} \tag{15}$$

$$A_{i,i} = 0.5\, Q_{i,i+1} - 0.5\, Q_{i-1,i} + E'_{i-1,i} + E'_{i,i+1} + V_i K_{1i} \tag{16}$$

$$A_{i,i+1} = 0.5\, Q_{i,i+1} - E'_{i,i+1} \tag{17}$$

the complete set of equations is written as:

$$\begin{array}{cccccccccccccc}
A_{11}L_1 & + & A_{12}L_2 & + & 0 & + & 0 & + & 0 & + & 0 & = & W'_1 \\
A_{21}L_1 & + & A_{22}L_2 & + & A_{23}L_3 & + & 0 & + & 0 & + & 0 & = & W'_2 \\
0 & + & A_{32}L_3 & + & A_{33}L_3 & + & A_{34}L_4 & + & 0 & + & 0 & = & W'_3 \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & & \cdot \\
0 & + & 0 & + & 0 & + & 0 & + & A_{20,19}L_{19} & + & A_{20,20}L_{20} & = & W'_{20}
\end{array} \tag{18}$$

or in matrix form:

$$\begin{bmatrix}
A_{11} & A_{12} & 0. \ldots 0 & 0 & 0 \\
A_{21} & A_{22} & A_{23} \quad 0 & 0 & 0 \\
0 & A_{32} & A_{33} \quad A_{34} \quad 0 & 0 & 0 \\
\cdot & \cdot & \cdot \quad \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot \quad \cdot\ \cdot & \cdot & \cdot \\
0 & \cdot & \cdot \quad \cdot\ 0 & A_{20,19} & A_{20,20}
\end{bmatrix}
\begin{pmatrix} L_1 \\ L_2 \\ L_3 \\ \cdot \\ \cdot \\ L_{20} \end{pmatrix}
=
\begin{pmatrix} W'_1 \\ W'_2 \\ W'_3 \\ \cdot \\ \cdot \\ W'_{20} \end{pmatrix} \tag{19}$$

Solution is obtained by inversion to yield:

$$(L) = [A]^{-1}\ (W) \tag{20}$$

Corrections for upstream and downstream boundary conditions (i.e. CBOD and DO deficit) are applied to Sections 1 and 20 (corrected terms written as W' above).

In order to insure that all elements of the solution vector (L) are positive it is necessary that

$$0 > 0.5\ Q_{i,i+1} - E'_{i,i+1} \tag{21}$$

be true for all sections. This requirement places certain restrictions upon the relationship between flow and dispersion which affect the minimum section length necessary to obtain a positive solution. As a result the sizes of the matrices and vectors required are also restricted.

For DO deficit (D) an equation similar to (14) is developed:

$$V_i \frac{dD_i}{dt} = Q_{i-1,i} (0.5\ D_{i-1} + 0.5\ D_i) - Q_{i,i+1} (0.5\ D_i + 0.5\ D_{i+1}) + E'_{i-1,i} (D_{i-1,i} - D_i) + E'_{i,i+1} (D_{i+1} - D_i) - V_i K_{2i} D_i + V_i K_{1i} D_i + Sb_i \tag{22}$$

where D_i = oxygen deficit in section i

K_{2i}= reaeration coefficient for section i

Sb_i= benthic demand of bottom deposits of section i

Reaeration is estimated from the empirical relationship formulated by O'Connor (1965) as:

$$K_2 = \frac{12.9U^{0.5}}{H^{1.5}} \tag{23}$$

where U = average stream velocity (ft/sec)

H = average depth (ft)

Logic analagous to that used in the development of the CBOD solution leads to:

$$(D) = [B]^{-1} (VK_1) (L) + [B]^{-1} (Sb) \tag{24}$$

where B, with the exception of the diagonal terms which contain V_iK_{2i} instead of V_iK_{1i}, is a matrix identical to A.

Since $(L) = [A]^{-1}$ (W), equation (24) is rewritten as:

$$(D) = [C] \ (W) + [B]^{-1} \ (Sb) \qquad (25)$$

where

$$[C] = [B]^{-1}(V\ K_1)\ [A]^{-1} \qquad (26)$$

The matrix[C] is a compound steady state transfer matrix which relates the DO deficit response for any section of the river to the waste discharged into any section. Matrix [C] produces a table (See Transfer Matrix-Table 12) which is very useful for management decision making with regard to waste load allocations. This transfer matrix and its applications are discussed in more detail in a following section.

MODEL III (TIME VARIANT MODEL)

The section of the navigation channel from mile point 1 to the mouth of the river is the most dynamic and complex section of the river. It is within this region that Lake Erie water intrudes as a wedge, much as the salt water wedge from an ocean intrudes into an estuary (Figure 15). This intrusion produces vertical gradients for most water quality parameters, including temperature and conductivity. Midway through this reach the old river channel enters the main channel. Because of the complexity and dynamic nature of this region, a time variant model of a conservative substance was developed.

The time variant model is constructed by first dividing the study area into five reaches (See Figure 16). It is assumed that river flow, dispersion coefficients, and area remain constant within each reach. The values of each reach correspond to measurements made at the upstream face of that reach. Each reach is then subdivided into twenty sections.

Because of the considerable vertical stratification of the river within the study area, this model provides only rough approximations of the actual in situ values. It is anticipated that a modification of this approach will eventually be required. One such modification is to utilize a multi-dimensional model which accommodates vertical, as well as, longitudinal variations. The development of such a model depends largely upon the degree of detail required for its application.

An equation for CBOD mass balance within any section i was developed for model II. Therefore, by dividing equation (14) developed for Model II by V_i we obtain a new equation which determines the change in CBOD with respect to time:

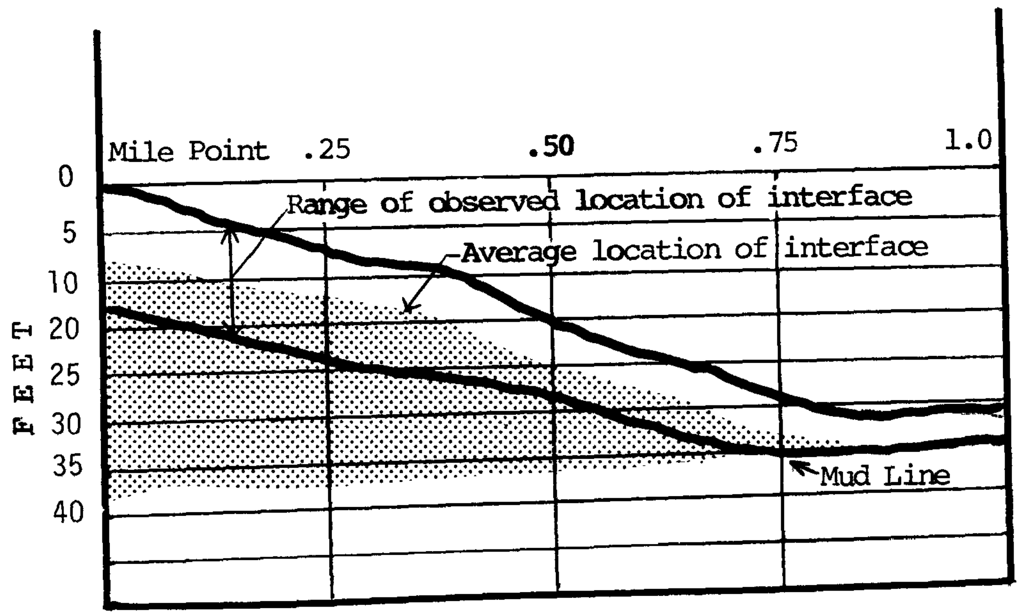

Figure 15. Stratification of Cuyahoga River and harbor water. From Havens and Emerson (1968).

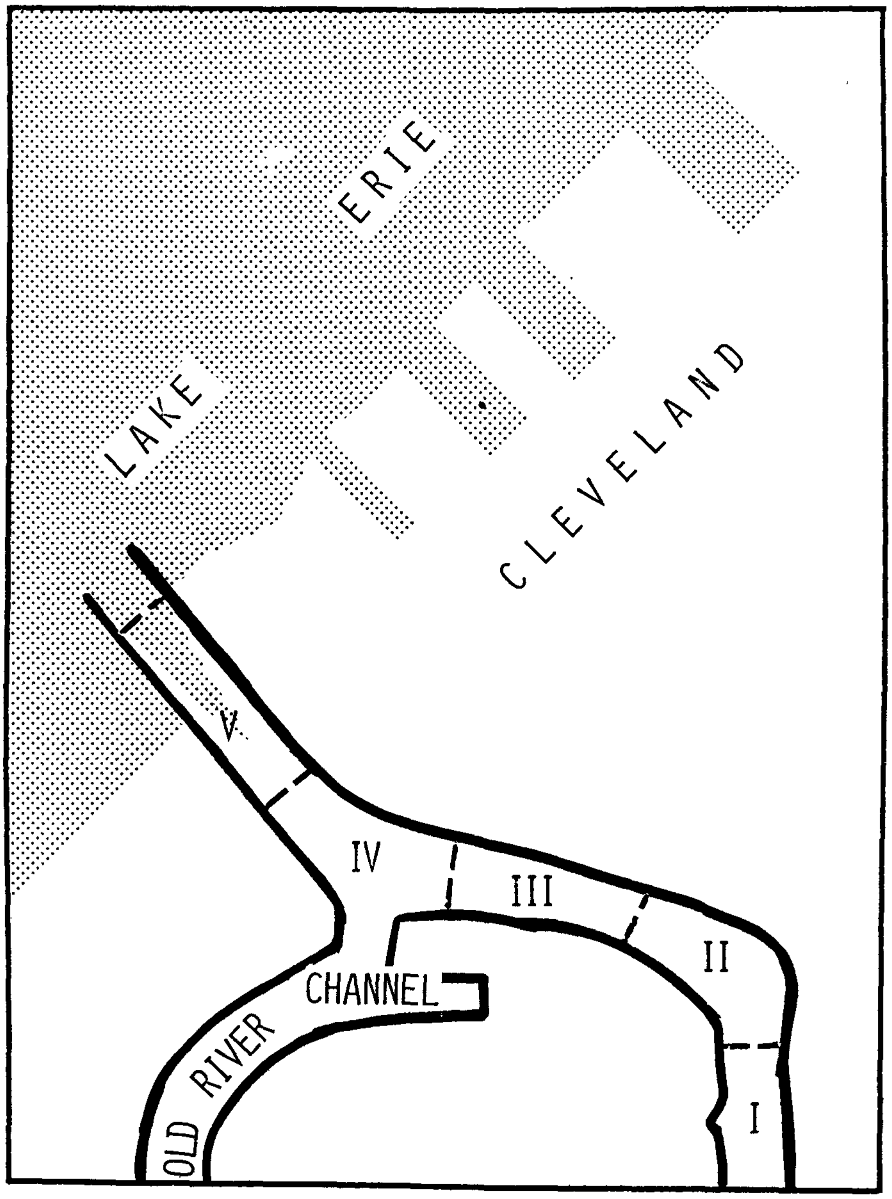

Figure 16. River divided into reaches.

$$\frac{dL_i}{dt} = \frac{Q_{i-1,i}}{V_i} (\alpha_{i-1,i}L_{i-1} + \beta_{i-1,i}L_i)$$

$$- \frac{Q_{i,i+1}}{V_i} (\alpha_{i,i+1}L_i + \beta_{i,i+1} L_{i+1}) \tag{27}$$

$$+ \frac{E'_{i-1,i}}{V_i} (L_{i-1,i}-L_i) + \frac{E'_{i,i+1}}{V_i}(L_{i+1}-L_i)-$$

$$-K_{1i}L_i + \frac{W_i}{V_i}$$

A similar equation for DO deficit (D) concentration is developed by dividing equation (22) by V_i:

$$\frac{dD_i}{dt} = \frac{Q_{i-1,i}}{V_i} (0.5D_{i-1} + 0.5D_i)$$

$$- \frac{Q_{i,i+1}}{V_i} (0.5 D_i + 0.5 D_{i+1})$$

$$+ \frac{E'_{i-1,i}}{V_i} (D_{i-1,i}-D_i) + \frac{E'_{i,i+1}}{V_i} (D_{i+1} -D_i) \tag{28}$$

$$- K_{2i}D_i + K_{1i}D_i + \frac{Sb_i}{V_i}$$

Computational procedures begin with a set of initial values in all sections for L_i and D_i. Time is assumed to be zero. A time interval d_i and dD_i is calculated. Next a numerical approximation model is used to approximate new values for L_i and D_i at time $T + \Delta T$ These values become the initial values for the next time interval calculation. The solution advances the procedure to the next time interval.

A short discussion of the basic numerical approximation model used in the above procedure follows:

The basic numerical approximation model uses average depth for each section. The form of the model for a conservative material such as chloride is:

mass in segment η = mass in segment η + net mass exchange
at time $T + \Delta T$ at time T during ΔT

Neglecting runnoff or addition along the reach, the net mass exchange for a conservative material will result from advection and dispersion.

If one considers a mass balance of pollutants within segment η as mass at end of ΔT = mass at start of ΔT - mass advected out during ΔT + mass advected in during ΔT then by letting $C(\eta, T+\Delta T)$ equal the concentration of material within segment η at time $T+\Delta T$ we may write:

$$C(\eta,T+\Delta T) = C(\eta,T) + \frac{U\Delta T}{\Delta X}\left[C(\eta-1,T) - C(\eta,T)\right] \qquad (29)$$

Where U and A vary within a reach; equation (29) becomes:

$$\begin{aligned} C(\eta,T+\Delta T) = {} & \frac{C(\eta,T)\ A(\eta,T)}{A(\eta,T+\Delta T)\Delta X} \\ & + \frac{UA(\eta-1/2,T)\ C(\eta-1,T)\Delta T}{A(\eta,T+\Delta T)\Delta X} \\ & - \frac{UA(\eta+1/2,T)\ C(\eta,T)\Delta T}{A(\eta,T+\Delta T)\Delta X} \end{aligned} \qquad (30)$$

Under conditions of low river flow and a rough lake with strong on-shore winds, it is possible for upstream flow to occur. In this case equation (30) may be replaced by:

$$\begin{aligned} C(\eta,T+\Delta T) = {} & \frac{C(\eta,T)\ A(\eta,T)}{A(\eta,T+\Delta T)\Delta X} \\ & + \frac{UA(\eta+1/2,T)\ C(\eta-1,T)\Delta T}{A(\eta,T+\Delta T)\Delta X} \\ & - \frac{UA(\eta-1/2,T)\ C(\eta,T)\Delta T}{A(\eta,T+\Delta T)\Delta X} \end{aligned} \qquad (31)$$

As noted by the terms $UA(\eta-1/2,\tau)$ and $UA(\eta+1/2,\tau)$ velocity is evaluated at the interface of each segment. Both equations (30) and (31) are programmed subject to the restriction $U\Delta\tau \leq \Delta X$. Futhermore, equations (30) and (31) produce a numerical mixing error. This error results from the one-dimensional assumptions of the model. This error is compensated for by calculating a psedudo-dispersion coefficient:

$$DP = U/2\ (\Delta X - U\Delta\tau) \tag{32}$$

and substracting equation (32) from the empirical dispersion coefficient for each time interval.

Using an argument analogous to that used in the development of equation (30) dispersion may be described as:

$$\begin{aligned} C(\eta,\tau+\Delta\tau) = {} & C(\eta,\tau) \\ & + \frac{D_L A\ (\eta-1/2,\tau)\Delta\tau}{A(\eta,\tau)\ \Delta X^2}\ [C(\eta-1,\tau) - C(\eta,\tau)] \\ & + \frac{D_L A\ (\eta+1/2,\tau)\Delta\tau}{A(\eta,\tau)\Delta X^2}\ [C(\eta+1,\tau) - C(\eta,\tau)] \end{aligned} \tag{33}$$

where D_L is the logitudinal dispersion coefficient.

To prevent an oscillation error:

$$\frac{D_L A\ (\eta-1/2,\tau)}{A(\eta,\tau)} + \frac{D_L A\ (\eta+1/2,\tau)}{A(\eta,\tau)} < \frac{\Delta X^2}{\tau} \tag{34}$$

Model III can be modified for simulation of non-conservative substances. Estimates of decay coefficients for BOD are available and can be utilized to further develop this model.

It would be interesting to examine the effects of new flow from the old channel upon various water quality parameters in the main channel. At present our data indicate that very little exchange occurs, however, if the Westerly Sewage Treatment Plant were to locate its outfall in this channel, it is probable that considerable chloride may be washed into the main channel. The distribution and magnitude of the effect can be studied with Model III.

Model III, however, is expensive to utilize because, in order to achieve numerical stability in the integration steps, it is necessary to repeat calculations many times. Therefore, the larger the magnitude of the dispersion coefficient and the smaller the study area, the larger the number of repetitions.

SECTION IX

DATA REQUIREMENTS

The data required as inputs to the EMCSM-CR are classified under three headings: (1) coefficient determination data, (2) field data and (3) simulation run data. Coefficient determination data and field data are necessary to adapt the model's parameters to those of the Cuyahoga River system. Simulation run data is necessary to exercise the model utilizing various sets of system conditions.

COEFFICIENT DETERMINATION DATA AND SENSITIVITY ANALYSES

The coefficients considered in the EMSCM-CR are longitudinal dispersion, benthal uptake, deoxygenation, and nitrification.

Longintudinal Dispersion (D_L) within the channel was estimated from chloride distributions. Within the lower one mile, where lake intrusion is dominant, regression techniques produced estimates of longitudinal mixing coefficients on the order of 1.0-2.5 mi^2/day. It was observed that mixing effects were most intense within this region but became less intense as one proceeded upstream. Since longitudinal dispersion had never been measured upstream, the rate of decrease in magnitude of dispersion was not known. However, reasonable estimates were obtained from historical data on upstream chloride distributions. As will be noted in the following discussion, such errors as those involved in 'educated guessing' were found to be relatively unimportant to the general system's behavior.

The chloride data for the study area was utilized to estimate dispersion coefficients (Figure 17-23) for the last mile of the channel. While the data were scattered, samples collected on 9-12-73, 9-19-73 and 10-18-73 exhibited a pattern. In utilizing the data the station within the old river channel was not included. The following approach was utilized.

If at the time of sampling it was assumed that the chlorides approximated a steady state in the study area with the major input through the upstream boundary, and if it was further assumed that no spatial variations in coefficients existed within a reach, then:

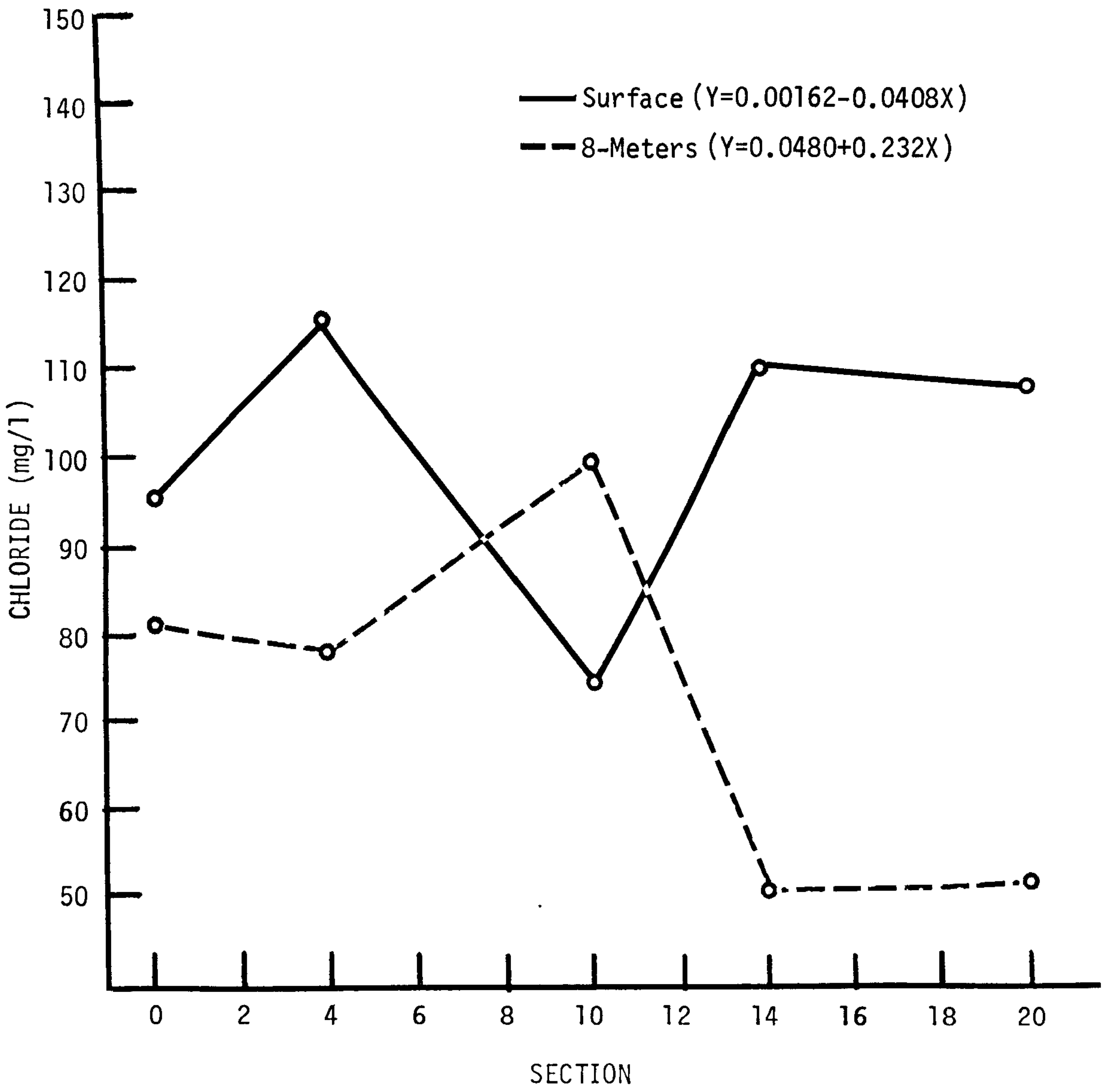

Figure 17. Chloride distribution in navigation channel on 9/5/73.

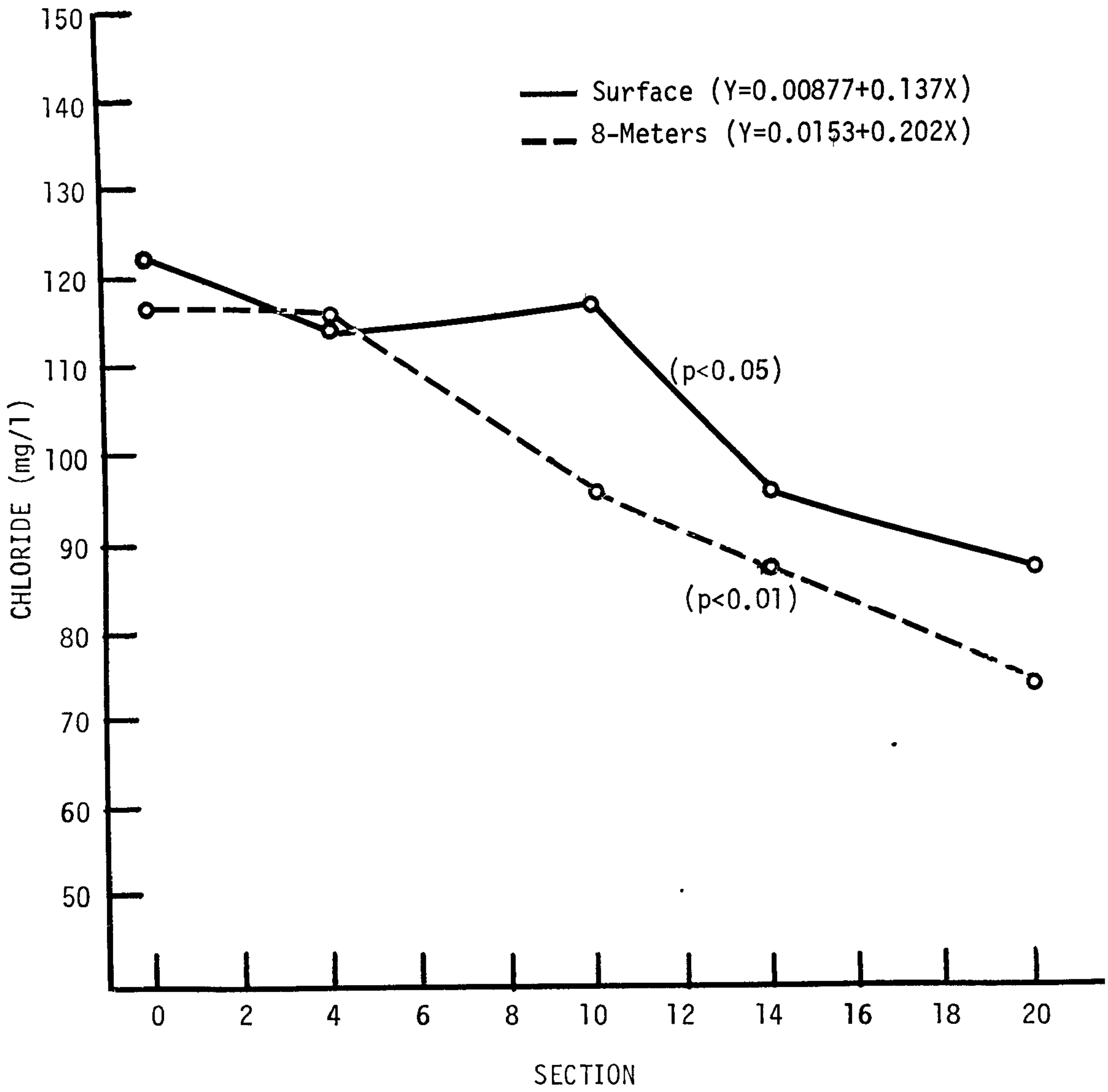

Figure 18. Chloride distribution in navigation channel on 9/12/73.

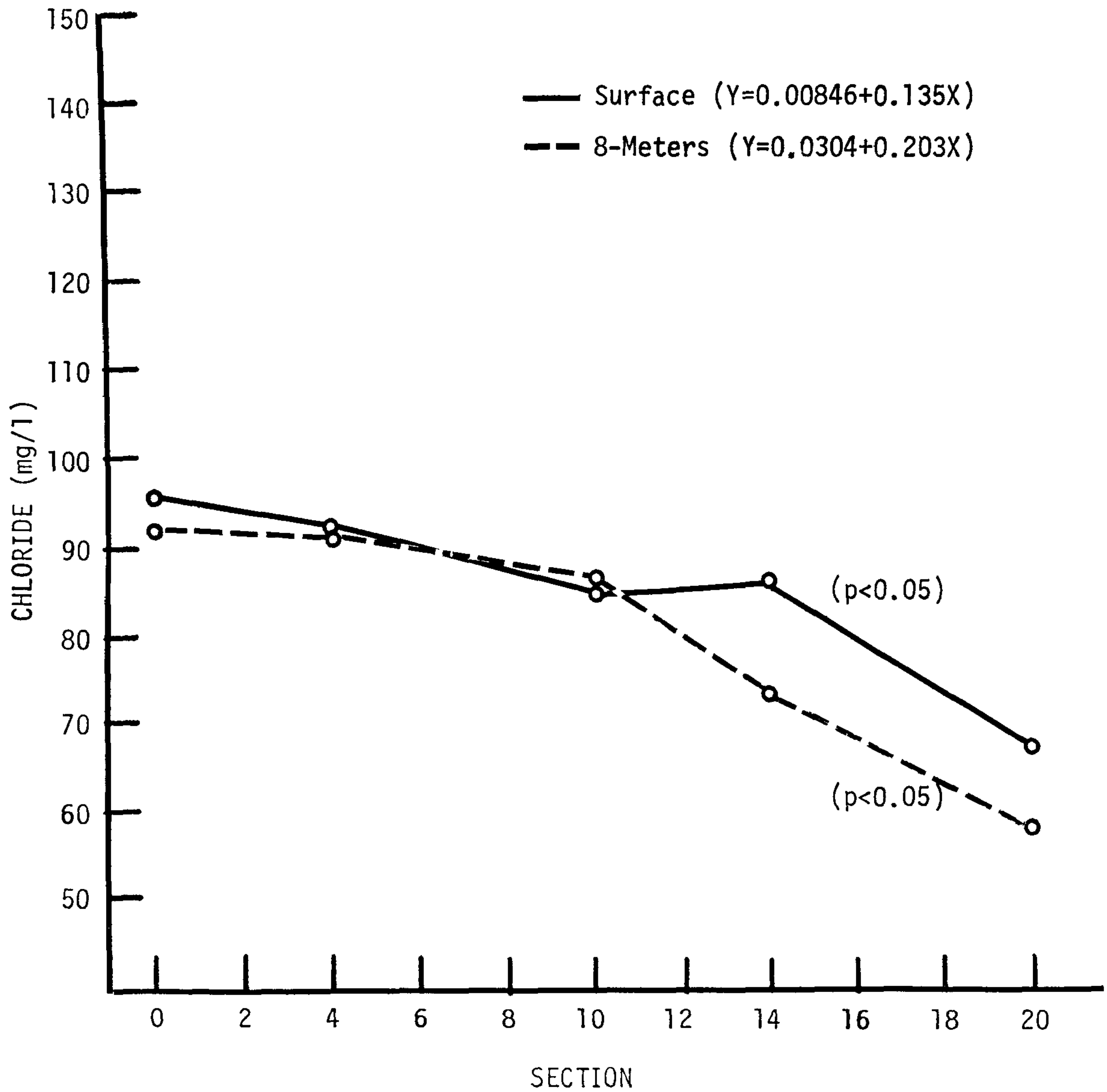

Figure 19. Chloride distribution in navigation channel on 9/19/73.

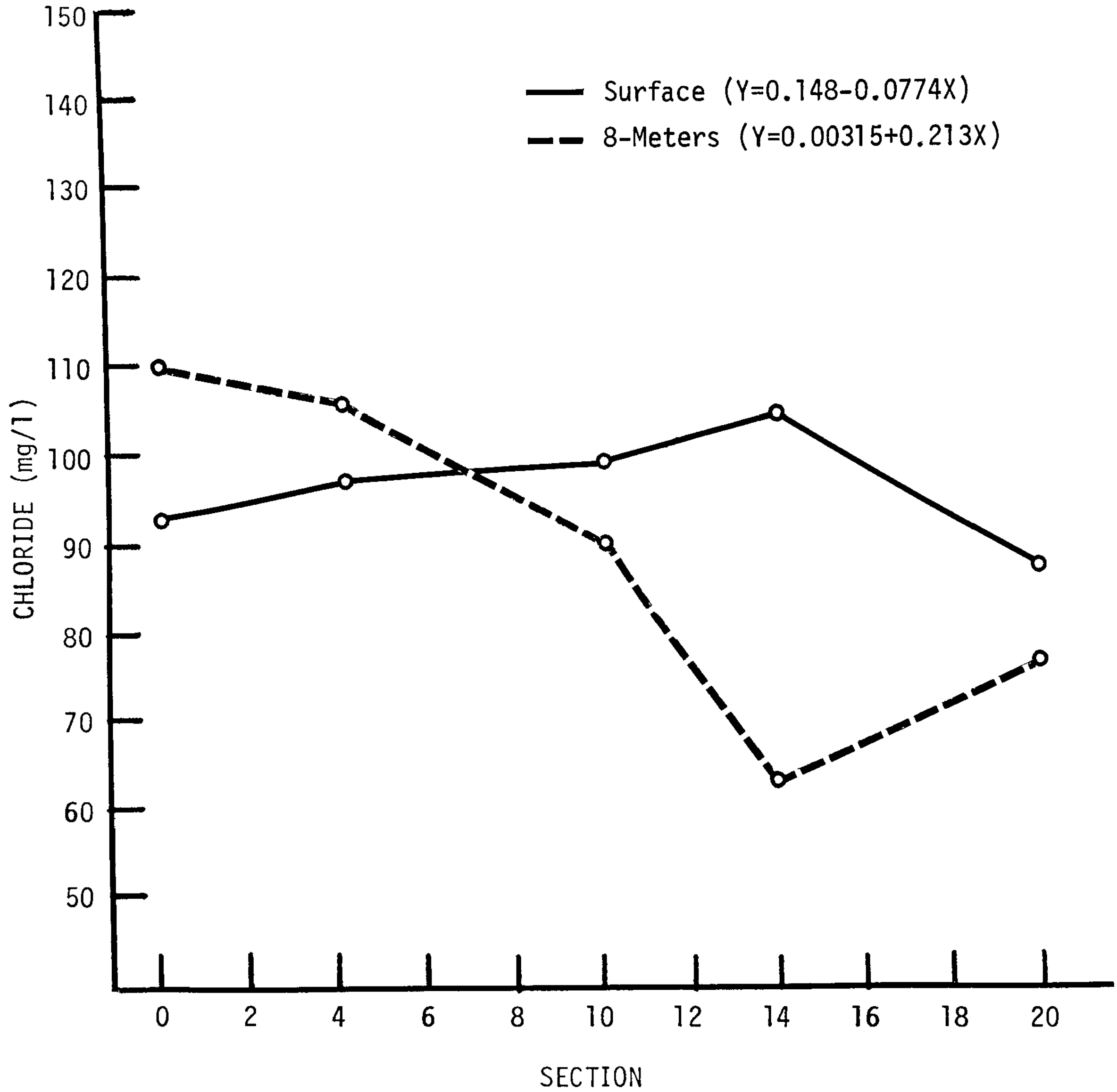

Figure 20. Chloride distribution in navigation channel on 9/28/73.

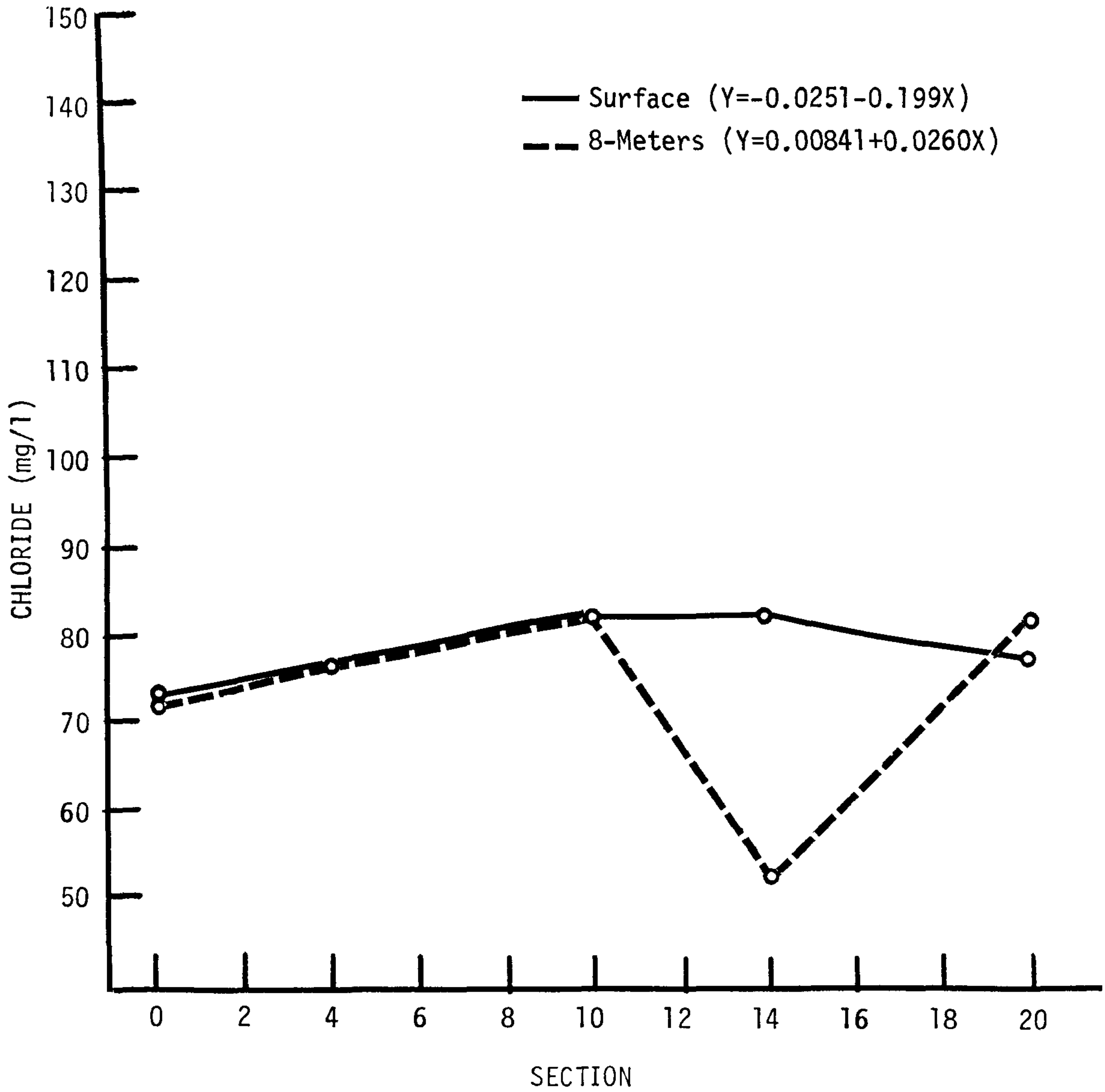

Figure 21. Chloride distribution in navigation channel on 10/11/73.

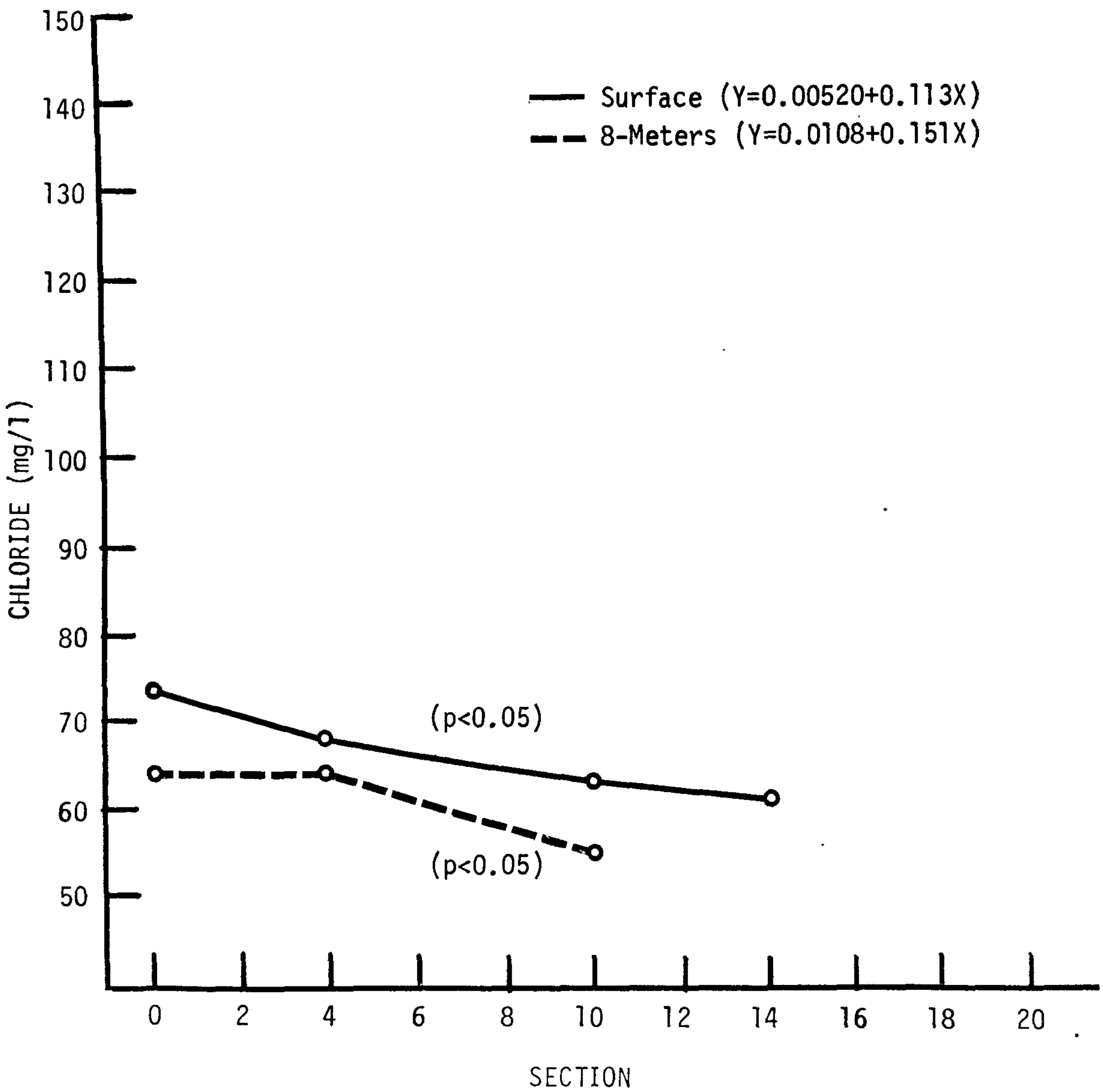

Figure 22. Chloride distribution in navigation channel on 10/18/73.

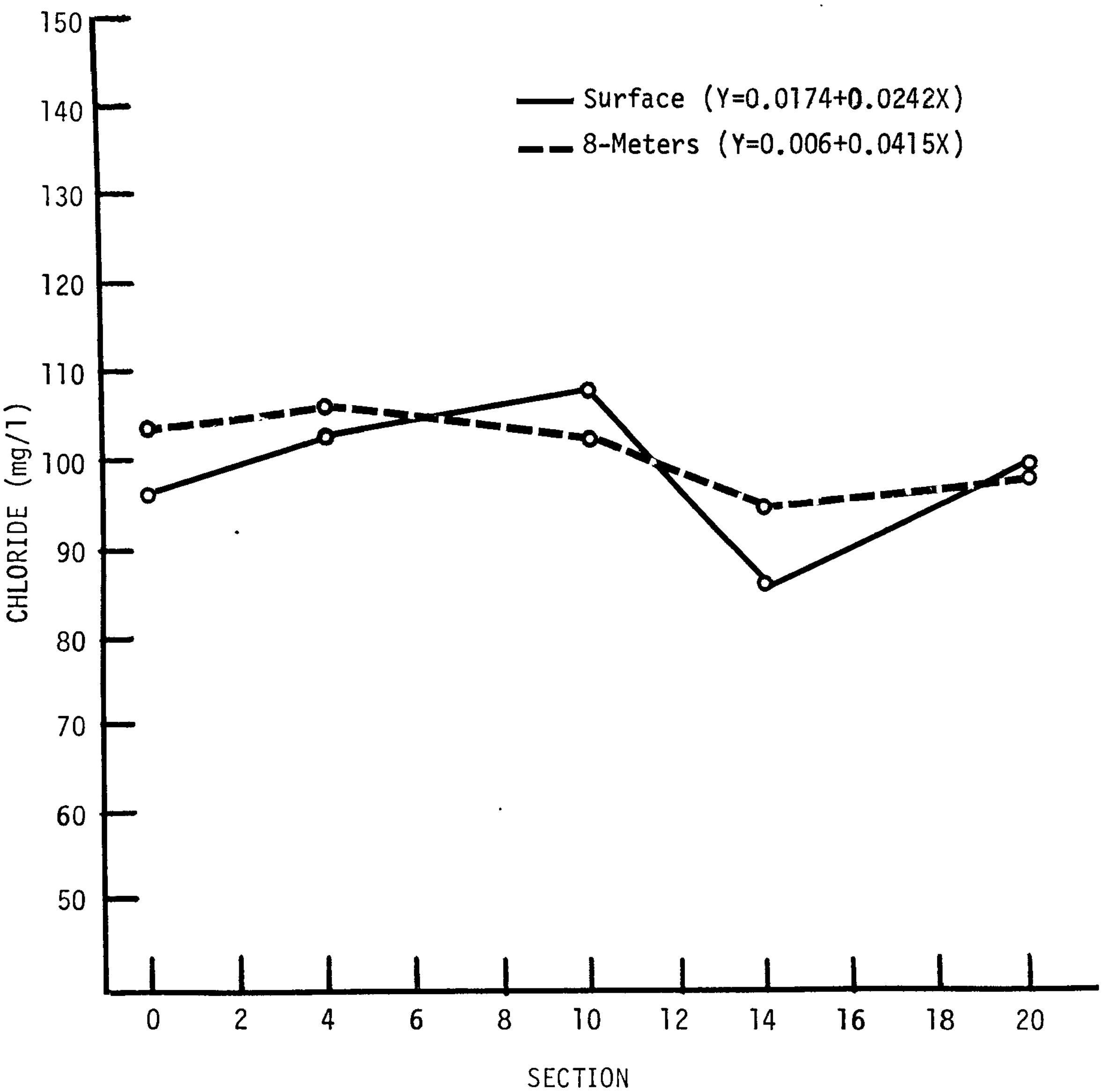

Figure 23. Chloride distribution in navigation channel on 10/25/73.

$$0 = -U \frac{dC}{dX} + D_L \frac{d^2C}{dz} \qquad (35)$$

Where C = chloride concentration

U = average water velocity

D_L = average longitudinal dispersion coefficient

If $X = 0$ at the upstream boundary, then for $X < 0$

$$C = C_0 \exp \frac{(UX)}{D_L} \qquad (36)$$

and

$$\ln \frac{C}{C_0} = \frac{U}{D_L} X \qquad (37)$$

Where C = chloride concentration at $X = 0$

The above linear form was utilized and X regressed against (C/CO) to determine the slope $\frac{U}{D_L}$ for each sampling period. Plots of chloride concentration vs. distance (X) are shown in Figure 17 through 23 with the associated results of the regression analysis. The chloride distributions on 9-12-73, 9-19-73, and 10-18-73 appeared to fit the assumptions mentioned previously since the regression was significant at the 5% level on all three of these dates and at both the surface and 8 meters in each case. Because of the highly significant fit on these dates, data collected on 9-12-73 and 9-19-73 were utilized.

System parameters utilized to simulate chloride distribution in the study area are presented in Table 3. In the model, the river is divided into 5 reaches and constant system parameters applied throughout each reach.

Preliminary use of the model indicates that the one-dimensional approach approximated the average values of chloride fairly closely over the study area. Simulation runs were conducted to calibrate the model output for chloride distributions and results of one such run are shown in Figure 24 .

Benthal Uptake (Sb) had never been measured within the navigation channel and consequently no data was available regarding the magnitude of this sink in the river. A decision not to design a study to measured benthal uptake was based upon current investigations being conducted at Cleveland State University. These investigations are attempting to evaluate the design of benthal respirometers of the bell jar variety.

TABLE 3

SYSTEM PARAMETERS FOR LOWER CUYAHOGA RIVER
(9-12-73 and 9-19-73)

REACH	SECTION	LENGTH (FT.)	CROSS SECTIONAL AREA (FT.^{2})†	AVG VELOCITY (mi/day)	ESTIMATED DISPERSION COEF.* (mi^2/day)
I	1 2 3	790	4500 ± 800	1.1	2.9 ± 0.5
II	4 5	530	9000 ± 350	0.75	1.9 ± 0.4
III	6 7 8 9	1060	7200 ± 450	0.8	2.1 ± 0.6
IV	10 11 12 13 14	1320	7600 ± 700	0.97	2.7 ± 0.6
V	15 16 17 18 19 20	1580	8700 ± 150	0.70	1.9 ± 0.5

† Avg. area of sections with ± one standard deviation included.

* Avg. area of two depths at each station with ± one standard deviation.

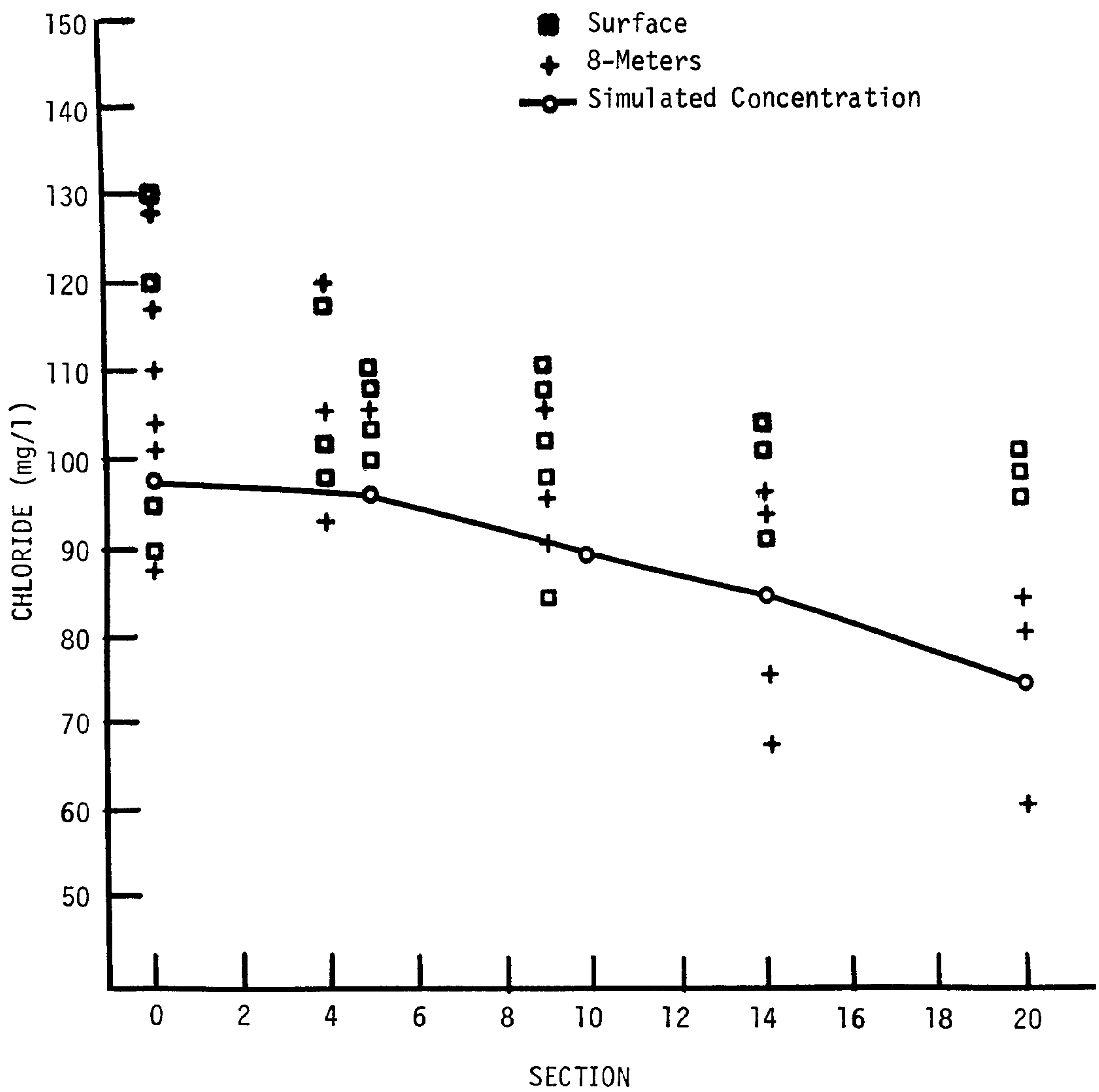

Figure 24. Simulation of chloride in the lower one mile of the Cuyahoga River.

Preliminary results of the above mentioned investigations indicate numerous problems resulting from the use of this type respirometer and tend to cast doubt upon measurements obtained from its use. Additionally, Model II does not appear to be very sensitive to changes in benthal uptake (See section on Sensitivity Analysis) because it was found that increasing the benthal uptake by a factor of two and four produced very little error in the calculated dissolved oxygen content in the water; therefore, since it was felt that the cost and time required to conduct such a study was not justifiable, a study of benthal uptake was not undertaken. Literature estimates of benthal uptake in rivers such as the Cuyahoga indicate a range of values from 2-10 $gm/m^2/day$. An estimated uptake from the channel of 5 $gm/m^2/day$ was therefore used.

Deoxygenation coefficients (K_1) in the lower Cuyahoga River were estimated from previous Cuyahoga River studies. Values utilized by Dalton, Dalton and Little (1971) ranged from 0.2 to 0.07 liters per day (base e). These estimates were derived from an emprical equation developed by O'Connor (1965) which utilized a combination of parameters, including river depth, to estimate K_1. Small variations in the value of K_1 were found to have fairly large effects upon dissolved oxygen steady-state concentrations in the navigation channel.

Since accurate assessment of deoxygenation kinetics is a prerequisite to estimation of water quality, regardless of the numerical method utilized, it is recommended that an experimental study to determine K_1 be conducted in the navigation channel. Such a study was conducted by the Ohio Department of Health in 1965 at mile points 7.2, 13.8, 38.6, and 41.6 but it did not include any points within the navigation channel.

Nitrogenous Demand (Nitrification) was assumed to be negligible. Some investigators assume the process to be important, while others (Dalton, Dalton & Little, 1971) consider it unlikely that nitrification occurs. O'Connor (1973) suggests that nitrification is typically observed when dissolved oxygen exceeds 1-2 mg/l. This is generally true for rivers which do not receive a high concentration of various industrial wastes which inhibit bacterial growth; however, the navigation channel, because of its high industrial waste load, does not necessarily meet the conditions for this assumption. The basic arguments against nitrification are based upon the assumption that river and water quality conditions existing at critical low flow periods are not suitable for growth of nitrifying bacteria. No reliable experimental study of the nitrification process within the lower Cuyahoga exists despite the fact that loadings of ammonia are significant enough to result, through potential nitrification, in depletion of DO within the navigation channel.

Reaeration (K_2) was estimated as previously discussed (see Equation 23).

SENSITIVITY ANALYSES

One of the more useful applications of water quality models is to test the response of the water quality parameters under observation to changes in system parameters. By holding all but one parameter constant, it is possible to determine the relative effects of each parameter on DO. Parameters used in the sensitivity analyses were taken from Table 11.

The effect of variations in dispersion coefficients is illustrated in Figure (25). Doubling the dispersion coefficients while holding flow and temperature constant had very little effect upon the results. This suggests that a 2- or 4- fold error in dispersion estimates would not appreciably affect the simulation output.

Figure (26) indicates that the maximum difference in DO which results from a 4- fold change in benthal uptake is only about 1 mg/l (Parameters are shown in Table 8). Although benthal uptake has not been measured in the river, it is doubtful that it is greater than 10 gm/m^2/day. Hence an error in estimating benthal uptake by 2- to 4- fold was also not very critical to the simulation of the DO sag in the channel.

Figure (27) illustrates the results of varying the deoxygenation coefficient (K_1) in the channel. It is immediately apparent that the magnitude of the sag is quite sensitive to relatively small changes in K_1. For example, decreasing K_1 from 0.15 to 0.07 resulted in an increase of nearly 1.5 mg/l in the minimum DO. Literature values of K_1 in the Cuyahoga River ranged from 0.25 to 0.07, therefore, for critical tuning of the model a study of deoxygenation coefficients in the channel during critical low flow conditions is recommended.

Figure (28) illustrates the effect upon DO concentration of improving the quality of the water entering the channel. Notice that the effect of improving water quality by 1 mg/l at the head of the channel increases the minimum DO near mile point 2.0 by approximately 0.5 mg/l. To obtain water having 1 mg/l of DO at mile point 2.0 would require inputing upstream water of quality better than 5 mg/l DO.

A transfer Matrix, discussed later, is utilized directly to determine the effect of a 10,000 lb/day waste loading to the river upon river water quality.

FIELD DATA

A sampling program was designed to supplement gaps and under-emphasis in current available data on the Cuyahoga River. The data collected during this program was discussed in the section entitled "Study of Lake Intrusion". This data dealt primarily with the first mile of the navigation channel (m.p. 0.0-m.p. 1.0) because the original intention was to model only this section of the river. The decision to develop a finite-difference model of the total navigation channel resulted in the need for additional data.

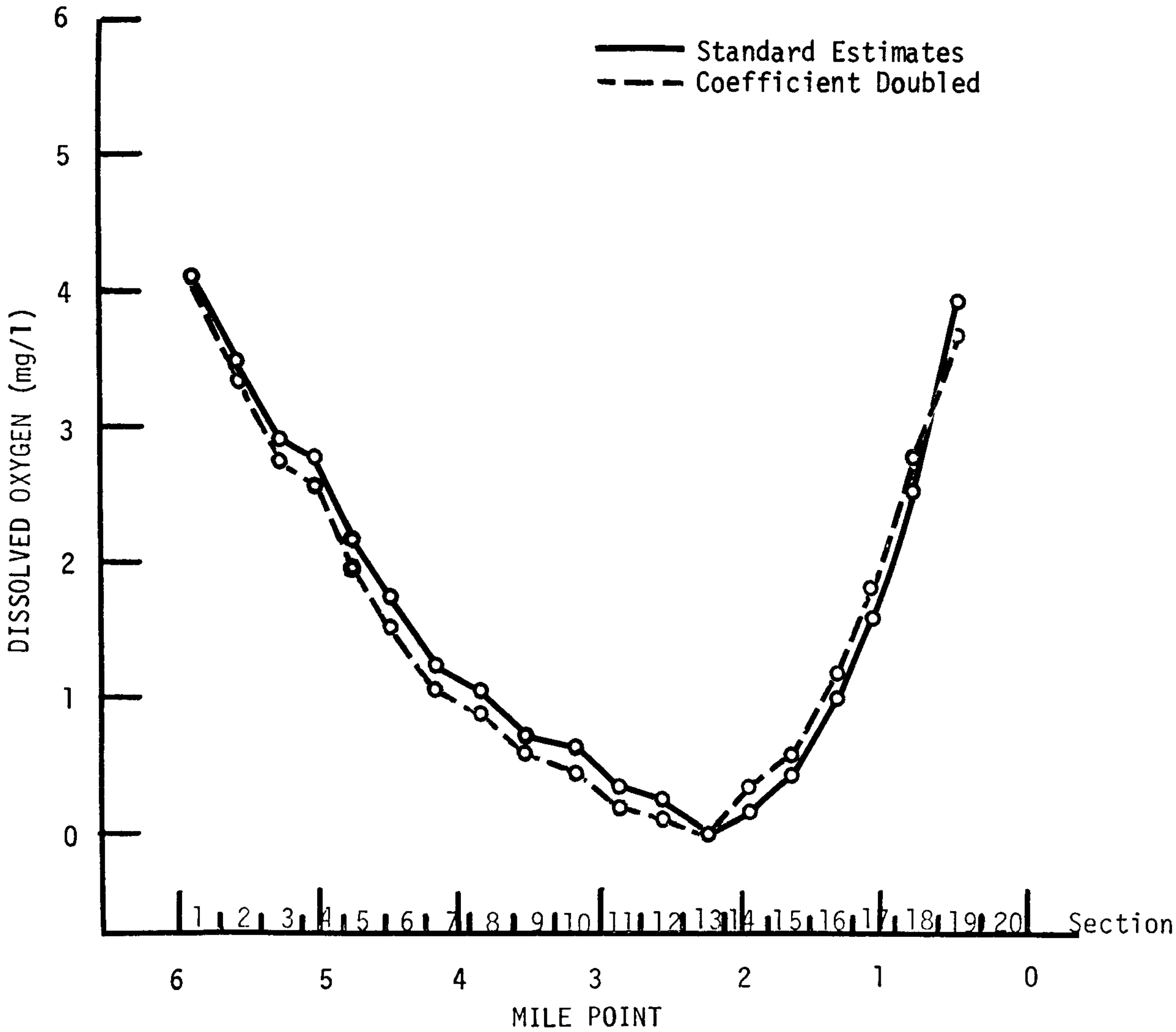

Figure 25. Sensitivity analysis of dispersion coefficients.
(K_1=0.15; Sb=5.0; Flow=900 cfs.)

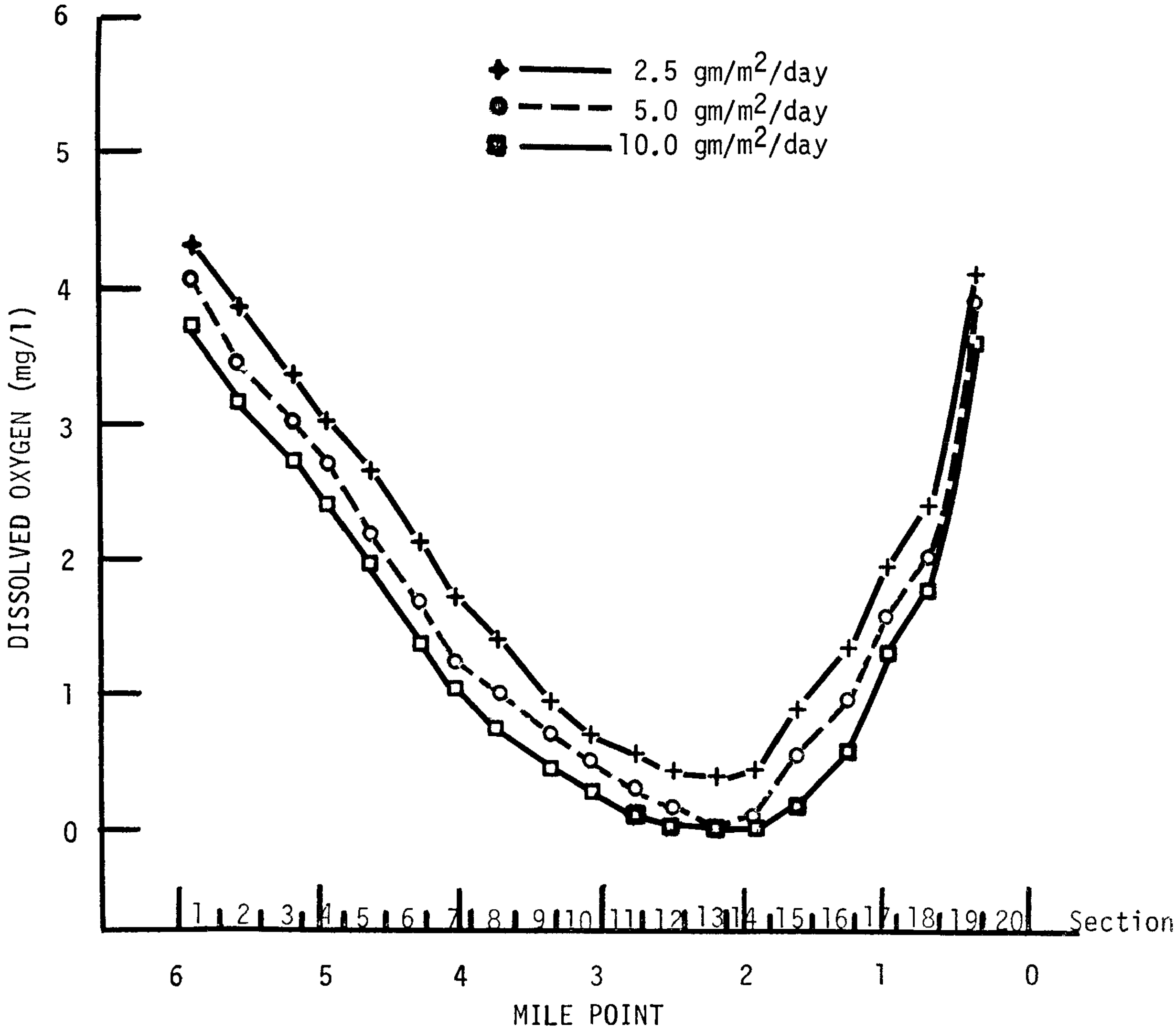

Figure 26. Sensitivity analysis of benthal uptake. (K_1=0.15; Sb=5.0; Flow=900 cfs.)

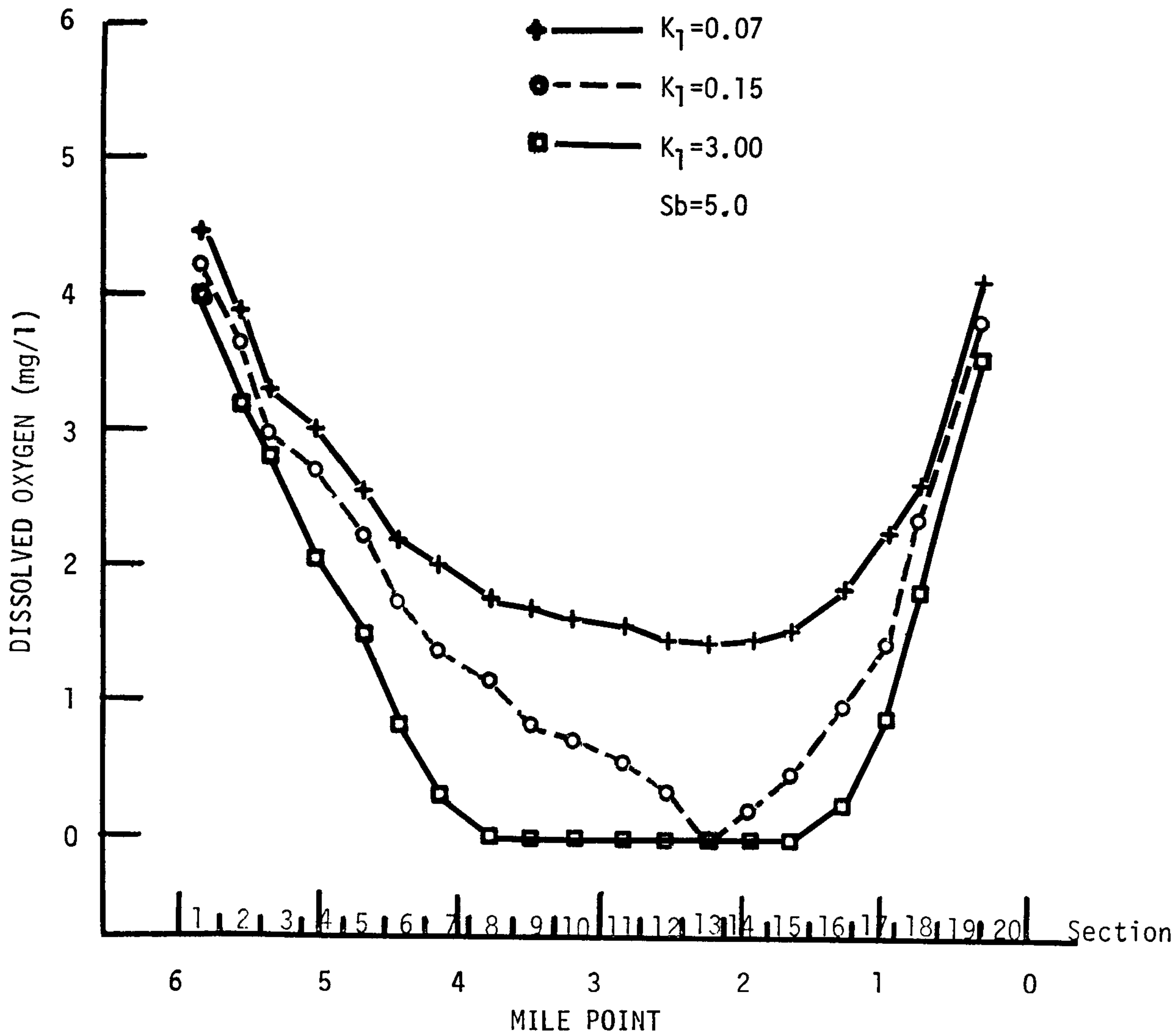

Figure 27. Sensitivity analysis of deoxygenation coefficient (K_1).

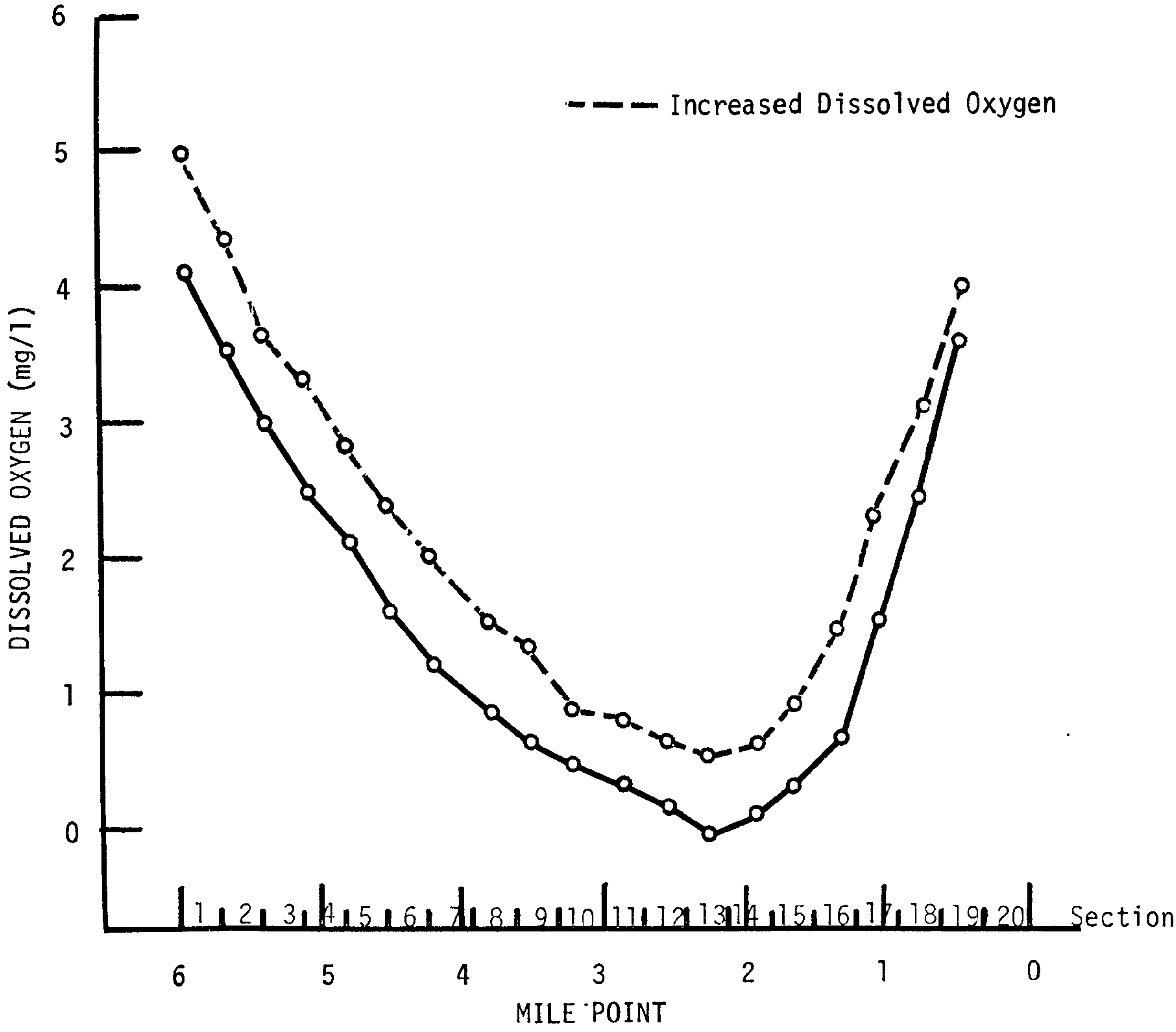

Figure 28. Effect of increasing upstream dissolved oxygen by 1.0 mg/l.

A problem encountered in utilizing data collected by other agencies was that the parameters and sample locations available were not necessarily those which could be utilized by us. For example, the City of Cleveland samples regularly on Wednesdays at three stations in the lower river. These stations, which are located at the Harvard-Denison Bridge (m.p. 7.2), 3rd Street Bridge (m.p. 3.2), and Center Street Bridge (m.p. 1.0), were also the stations utilized by Havens and Emerson in a previous study (H & E, 1968). Of these stations only two are located within the navigation channel.

Because there was no data available for simulataneous DO at are stations within the channel, a sampling run was conducted in the channel on August 28, 1974 to supply us with this information. Results of this sampling run are presented in Table (4). By slightly adjusting dispersion coefficients for the upper reach of the channel it was possible to obtain a simulation for the river conditions on August 28, 1974. This adjustment of dispersion coefficients can be justified since the sensitivity analysis indicated that variables in dispersion were of minor importance.

The major trend in dissolved oxygen fluctuations was duplicated by the model. From upstream to downstream the shape of the observed data was successfully modeled, however, it is assumed that biological and random influences which were not incorporated in the model, resulted in the slight variations at each sample point.

Figure (29) indicates that the model is valid and, if properly utilized, can give significant insight and understanding into water quality trends in the lower Cuyahoga River.

An eight week study of water quality in three streams tributary to the Cuyahoga River (Figure 30) was requested by and conducted in co-operation with the Three River's Watershed Authority and the Ohio EPA. The analytical data from the tributary study can be recalled under the following Storet numbers:

LOCATION	STORET
Tinker's Creek @ Glenwillow	59209
Tinker's Creek @ Canal Road	50210
Mill Creek	50211
Big Creek	50212

TABLE 4

Field Measurements Obtained 8-28-78
(Channel Flow - 700 CFS)

LOCATION (MP)	DEPTH (M)	SIMULATED DO (PPM)	FIELD DO (PPM)	FIELD BOD (PPM)
6.0	0 4.5	4.00	4.57 4.22	- -
5.1	0 4.5	2.90	3.92 3.64	- -
4.5	0 4.5	2.00	2.75 2.03	- -
3.5	0 4.5	0.30	0.71 0.78	8.5 9.8
3.2	0 4.5	0.10	0.63 0.71	6.0 6.5
3.0	0 4.5	0.05	0.56 0.46	5.0 10.5
2.8	0 4.5	0.01	0.52 0.38	6.0 7.2
2.3	0 4.5	0.00	0.41 0.22	5.5 9.7
1.8	0 4.5	0.00	0.63 0.69	5.6 4.8
1.5	0 4.5	0.00	0.37 0.67	5.7 6.1
1.0	0 4.5	0.05	0.70 1.00	1.0 11.4
0.5	0 4.5	0.30	0.74 0.97	4.9 11.0
0.0	0 4.5	1.50	1.10 3.30	17.6 10.9

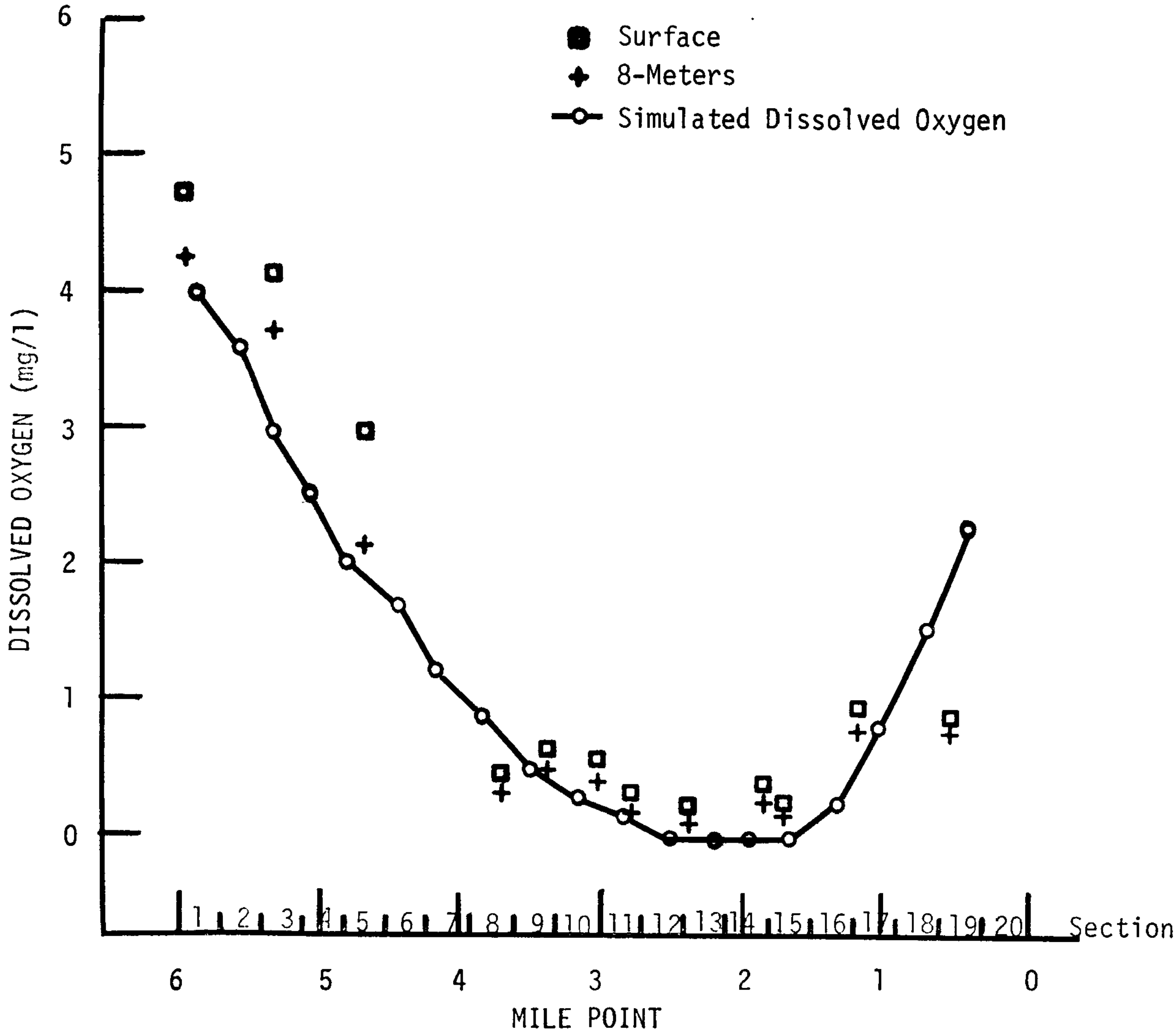

Figure 29. Comparison of simulated dissolved oxygen with field measurements obtained on 8/28/74.

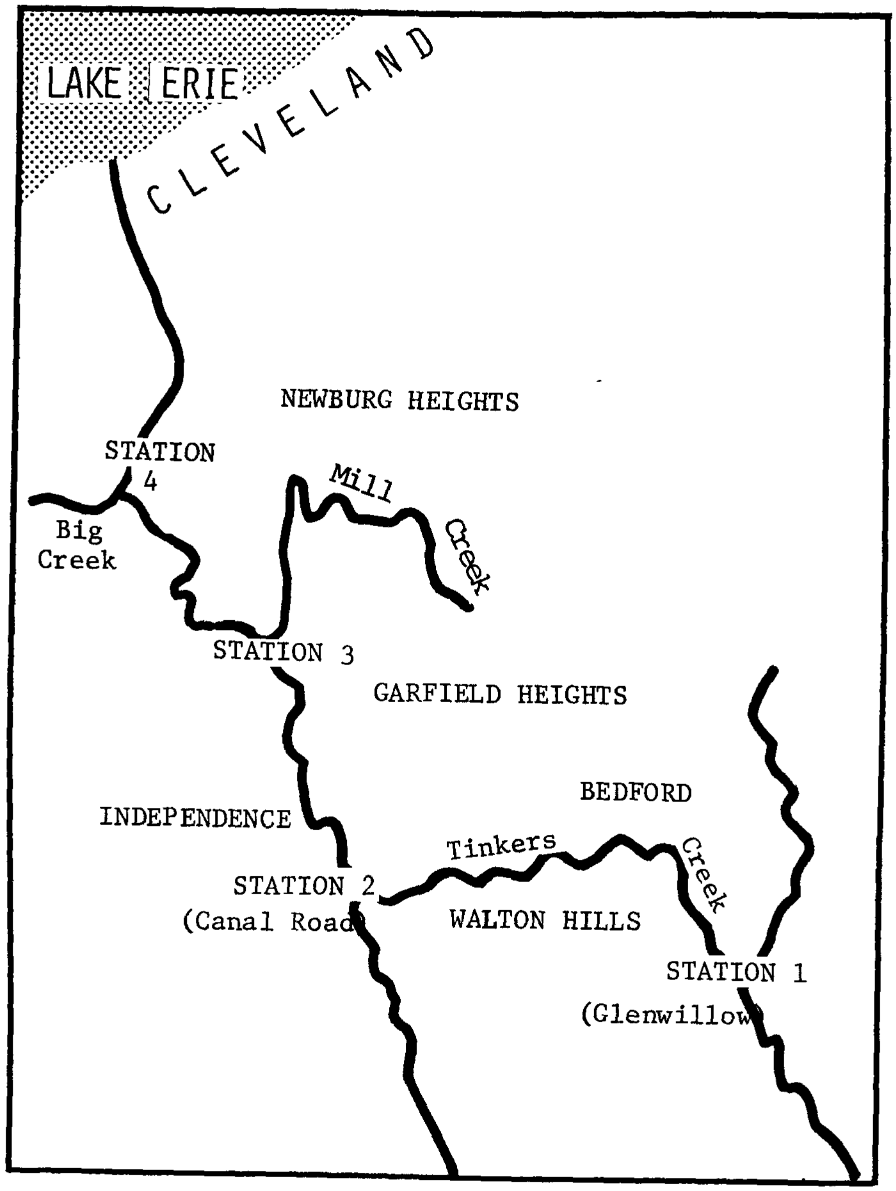

Figure 30. Tributary Sampling Program.

SIMULATION RUN DATA

A variety of simulation runs were made. These runs took into account variations in waste load allocations where input values were altered to reflect changes in waste load conditions (BOD and flow). The simulation runs were used to assess the influence of alternate waste quality control measures on the overall dissolved oxygen quality in the system.

The program is written so that the values for cross-sectional area, flow, and BOD must be input with each simulation run. Photosynthesis, if signigicant can also be input. Cross-sectional areas at the interface of adjacent sections, where dispersion is considered, were obtained from U.S. Army Corps of Engineers' dredging maps. Where necessary, water levels were adjusted to late-summer, early-fall depths.

Flow within the navigation channel is relatively constant with respect to distance. Small increases in flow occur near the upper end of the channel due to the Ohio Canal return and, to a much lesser degree, Morgan Run and Burke Brook. Flow data utilized in the simulations conducted within the navigation channel are averages obtained from Havens and Emerson (1968) and from the United States Geological Survey Water Resources Data for Ohio (1973 and 1974). A low flow of 345 cfs and an average flow of 850 cfs are used.

Photosynthesis, a major biological source of DO, is considered to be insignificant within the navigation channel. Here water is turbid and it is doubtful that any signigicant photosynthesis occurs except at the surface. Chlorophyll analyses of both surface and bottom water within the lower channel indicated no measurable chlorphyll.

BOD loadings were determined from 1970 waste load permit applications and Ohio EPA records. All records indicated that most of the industries within the navigation channel which discharge significant amounts of waste were located above section 10 (m.p. 3.15). Simulation runs utilized data from both sources. The results of these runs are presented and compared in the following section.

The industrial loading data for the channel which are utilized in the runs are outlined in Tables (5), (6), and (7).

TABLE 5

Data collected from the 1970 Waste Load Permit Application Forms. (U.S. EPA - Fairview Park, Ohio)

SECTION	MILE POINT	WASTE LOADING (lbs/day)	SOURCE
1	5.7	530	J & L Steel
2	5.5	560	J & L Steel
4	5.1	160	Morgan & Burke Brooks
5	4.8	8540	Republic Steel

TABLE 6

1973 Summer-Fall loading data obtained from Ohio EPA (B.Clymer - Ohio EPA - Columbus, Ohio)

SECTION	MILE POINT	WASTE LOADING (lbs/day)	SOURCE
2	5.5	1437	J & L Steel
4	5.1	510	Morgan & Burke Brooks
5	4.7	9990	Republic Steel
8	3.7	1602	U.S. Steel

TABLE 7

1978 PROJECTED SUMMER-FALL LOADINGS (B. CLYMER - OHIO EPA - COLUMBUS, OHIO)

MILE POINT*	SOURCE	LOADING (BOD-LB/DAY)
57.8	Lake Rockwell	124
56.8	Breakneck Creek	245
54.0	Kent STP	319
53.8	Plum Creek	49
52.3	Fish Creek	87
42.0	Little Cuyahoga	909
39.5	Mud Creek and Sand Run	438
37.2	Akron STP	6780
37.0	Yellow Creek	288
33.1	Furnace Run	89
24.2	Brandywine Creek	386
21.2	Chippewa Creek	55
19.1	Brecksville STP	425
18.5	Sagamore Creek	87
16.8	Tinkers Creek	482
15.5	Swan Creek	99
11.4	Mill Creek	139
10.8	Cleveland Southerly STP	5747
8.1	U.S. Steel	840
7.1	Big Creek	761
6.4	Republic Steel	2928
5.6	J & L Steel	1437
5.1	Morgan-Burke Brooks	300
4.7	Republic Steel	5878
3.9	U. S. Steel	1602

*Exact mile point location of outfalls and confluences may vary slightly from source to source.

SECTION X

RESULTS

Public Law 92-500 (Federal Water Pollution Control Act Amendments of 1972) calls for the achievement of the best practical treatment of waste by 1978, the achievement of the best available treatment by 1983, and the possible elimination of all waste containing pollutants by 1985. Reduction of these waste containing pollutants should result in improved water quality within waterways.

Although the exact extent of improvement can only be determined subsequent to the discontinuation of discharging pollutants, a model, such as the EMCSM-CR, is a systematic and reliable alternative to speculating what changes and improvements might occur.

The following disucssion outlines procedures for planning a management program tailored to the physical, hydrological, and economic circumstances of the Cuyahoga River. It also provides guidelines to promote river water quality management techniques.

In utilizing the EMCSM-CR in a management program three questions must be addressed:

1. How can the EMCSM-CR determine the upstream water quality required to achieve the water quality standards set for the Cuyahoga River's navigation channel?

2. How can the EMCSM-CR be utilized to determine the best physical system for achieving that quality?

3. How can the EMCSM-CR assist in determining the most optimal system for administering and managing water quality?

To answer the above questions seven (7) basic simulation runs were made. Additional simulation runs can, of course, be made as needed.

SIMULATION 1

The first simulation illustrates the effect of present municipal and industrial discharges on water quality during low flow conditions. It was assumed that if all other water quality parameters remained constant or improved, this simulation would represent the poorest expected water quality profile for the navigation channel.

Section 402 of Public Law 92-500 established a National Pollutant Discharge Elimination System (NPDES) which requires all municipalities and industries to obtain a permit to discharge waste into waterways. A review of the 1970 NPDES application forms established the lbs/day waste load inputs listed in column W on Table (8). Depth, area, flow, dispersion (DISP), waste loads (W), benthal uptake (Sb), deoxygenation coefficient (K), and temperature (°C) are listed for each section in Table 8. An upstream (above m.p. 6.0) BOD of 8.0 mg/l and DO of 3.0 mg/l were taken from data supplied by the Ohio EPA. A Lake BOD and DO of 6.0 mg/l were used.

The results (figure 31) of this simulation show that discharges into Section 2, 4, and 5 degrade water quality until the DO reaches zero in Section 5 (m.p. 4.65). More waste is discharged into Section 8 (m.p. 3.75) but its effect is not observed since DO has already reached zero. Based upon this simulation run one expects the river to be anoxic from Section 5 to Section 19 (m.p. .45). At Section 19 water quality improves slightly because of lake water intrusion.

The following simulation runs manipulate flow, BOD, and DO to illustrate how the model can be used as a management tool. A summary of simulation runs and the variables manipulated is given in Table 9.

SIMULATION 2

Because water quality data varied from source to source a simulation run utilizing data from another source was conducted. For this simulation 1973 Summer-Fall waste load monitoring data utilized by the Ohio EPA (Columbus) for the navigation channel was input into our model. Table 10, column W, shows slightly higher waste loads entering at Section 2,4, and 5. A low flow of 345 cfs, upstream BOD of 8.0 mg/l, DO of 3.0 mg/l, lake BOD of 6.0 mg/l, and lake DO of 6.0 mg/l were again utilized.

The results (Figure 32) of this simulation run are essentially the same as those of Simulation (1). The DO again decreases rapidly to zero in Section 5 and remains there until the effect of lake water intrustion is felt in Section 19. There is thus little difference in water quality due to the slightly different loadings.

TABLE 8

SYSTEM PARAMETERS FOR THE NAVIGATION CHANNEL

(Loading data obtained from available 1970 permit application)

SECTION	DEPTH	AREA	FLOW	DISP	W	Sb	K	TEMP.
1	0.200E+02	0.300E+04	315	0.250E+00	530	0.500E+01	0.150E+00	0.286E+02
2	0.200E+02	0.350E+04	315	0.220E+00	560	0.500E+01	0.150E+00	0.295E+02
3	0.250E+02	0.420E+04	315	0.220E+06	0	0.500E+01	0.150E+00	0.305E+02
4	0.250E+02	0.440E+04	345	0.220E+00	160	0.500E+01	0.150E+00	0.307E+02
5	0.250E+02	0.430E+04	345	0.220E+00	8540	0.500E+01	0.150E+00	0.309E+02
6	0.250E+02	0.900E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.311E+02
7	0.250E+02	0.470E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.314E+02
8	0.250E+02	0.510E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.313E+02
9	0.250E+02	0.490E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.312E+02
10	0.250E+02	0.550E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.311E+02
11	0.250E+02	0.740E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.309E+02
12	0.250E+02	0.420E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.306E+02
13	0.250E+02	0.900E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.304E+02
14	0.250E+02	0.620E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.302E+02
15	0.250E+02	0.620E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.302E+02
16	0.250E+02	0.650E+04	345	0.400E+00	0	0.500E+01	0.150E+00	0.295E+02
17	0.250E+02	0.650E+04	345	0.600E+00	0	0.500E+01	0.150E+00	0.289E+02
18	0.250E+02	0.450E+04	345	0.800E+00	0	0.500E+01	0.150E+00	0.286E+02
19	0.250E+02	0.700E+04	345	0.100E+01	0	0.500E+01	0.150E+00	0.283E+02
20	0.250E+02	0.750E+04	345	0.100E+01	0	0.500E+01	0.150E+00	0.280E+02
21	0.0	0.820E+04	345	0.120E+01	0	0.0	0.0	0.0

SIMULATION RUN NO. 1

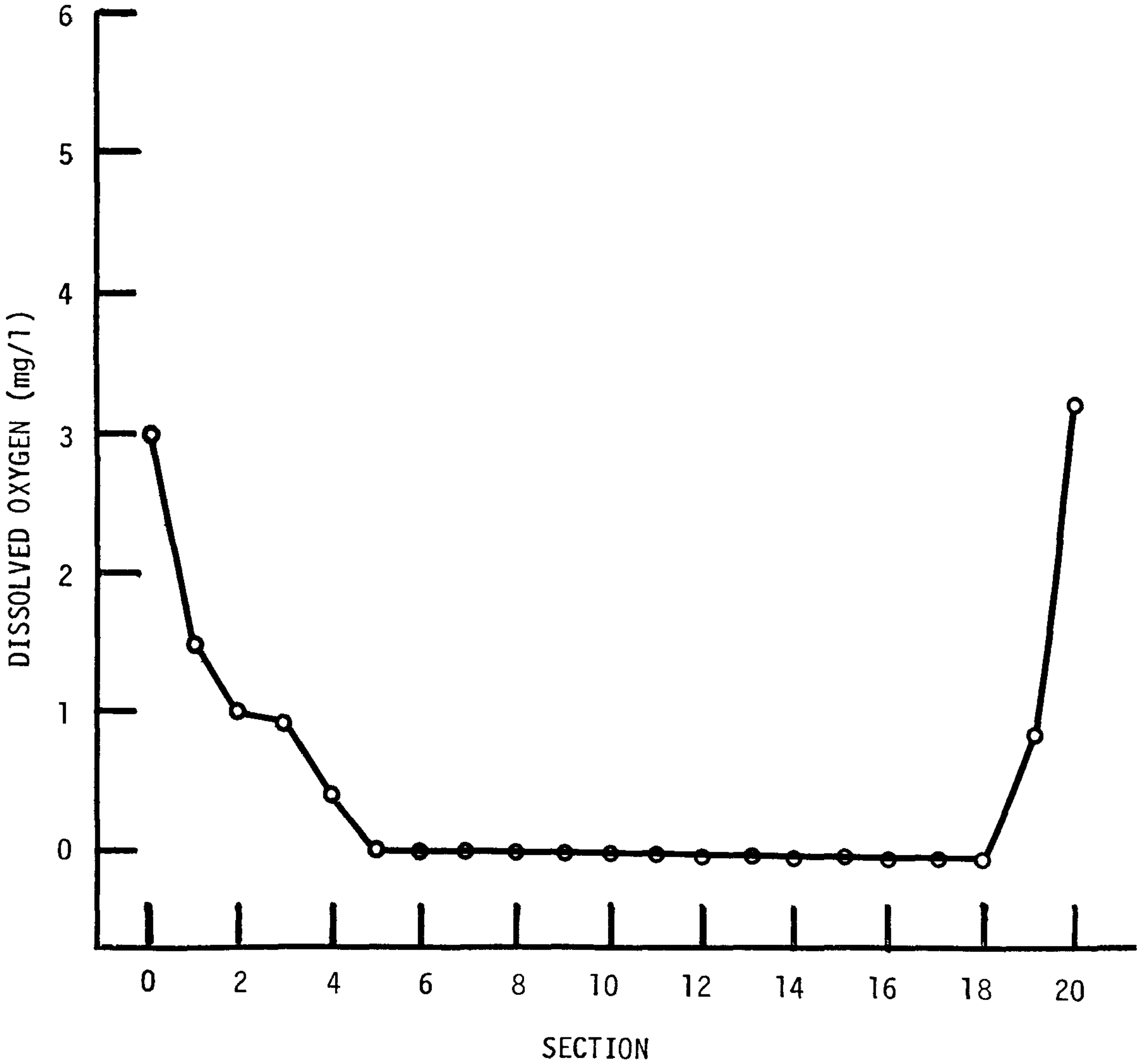

Figure 31. Simulation Run #1.

TABLE 9

SUMMARY OF PARAMETERS MANIPULATED IN SIMULATION RUNS

SIMULATION	FLOW	LOADING	BOUNDARY Upstream BOD (mg/l)	CONDITIONS* Upstream DO (mg/l)	Downstream BOD (mg/l)	Downstream DO (mg/l)
1	345	1970-permits	8	3	6	6
2	345	1973-OEPA	8	3	6	6
3	850	1973-OEPA	8	3	6	6
4	345	1978-OEPA	-	3.5	6	6
5	345	50% 1973	8	4	6	6
6	345	1973-OPEA	8	5	6	6
7	850	1978-OEPA	8	5	6	6

*Runs 1,2,3 and 6 were conducted for the navigation channel only. Boundary conditions were obtained from Ohio EPA. Runs 4 and 5 were conducted for the river from mile pt. 58 to the mouth using Ohio EPA projected loadings and flow.

TABLE 10

SYSTEM PARAMETERS FOR THE NAVIGATION CHANNEL

(1973 Summer - Fall Data Obtained From Ohio EPA).

SECTION	DEPTH	AREA	FLOW	DISP	W	Sb	K	TEMP
1	0.200E+02	0.300E+04	315	0.250E+00	0	0.500E+01	0.150E+00	0.286E+02
2	0.200E+02	0.350E+04	315	0.220E+00	1437	0.500E+01	0.150E+00	01295E+02
3	0.250E+02	0.420E+04	315	0.220E+03	0	0.500E+01	0.150E+00	0.305E+02
4	0.250E+02	0.440E+04	345	0.220E+00	510	0.500E+00	0.150E+00	0.307E+02
5	0.250E+02	0.430E+04	345	0.200E+00	9990	0.500E+01	0.150E+00	0.309E+02
6	0.250E+02	0.900E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.311E+02
7	0.250E+02	0.470E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.314E+02
8	0.250E+02	0.510E+04	345	0.220E+00	1602	0.500E+01	0.510E+00	0.313E+02
9	0.250E+02	0.490E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.312E+02
10	0.250E+02	0.550E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.311E+02
11	0.250E+02	0.740E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.309E+02
12	0.250E+02	0.420E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.306E+02
13	0.250E+02	0.900E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.304E+02
14	0.250E+02	0.620E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.302E+02
15	0.250E+02	0.620E+04	345	0.220E+00	0	0.500E+01	0.150E+00	0.302E+02
16	0.250E+02	0.650E+04	345	0.400E+00	0	0.500E+01	0.150E+00	0.295E+02
17	0.250E+02	0.650E+04	345	0.600E+00	0	0.500E+01	0.150E+00	0.289E+02
18	0.250E+02	0.450E+04	345	0.800E+00	0	0.500E+01	0.150E+00	0.286E+02
19	0.250E+02	0.700E+04	345	0.100E+00	0	0.500E+01	0.150E+00	0.283E+02
20	0.250E+02	0.750E+04	345	0.100E+00	0	0.500E+01	0.150E+00	0.280E+02
21	0.0	0.820E+04	345	0.120E+01	0	0.0	0.0	0.0

SIMULATION RUN NO. 2

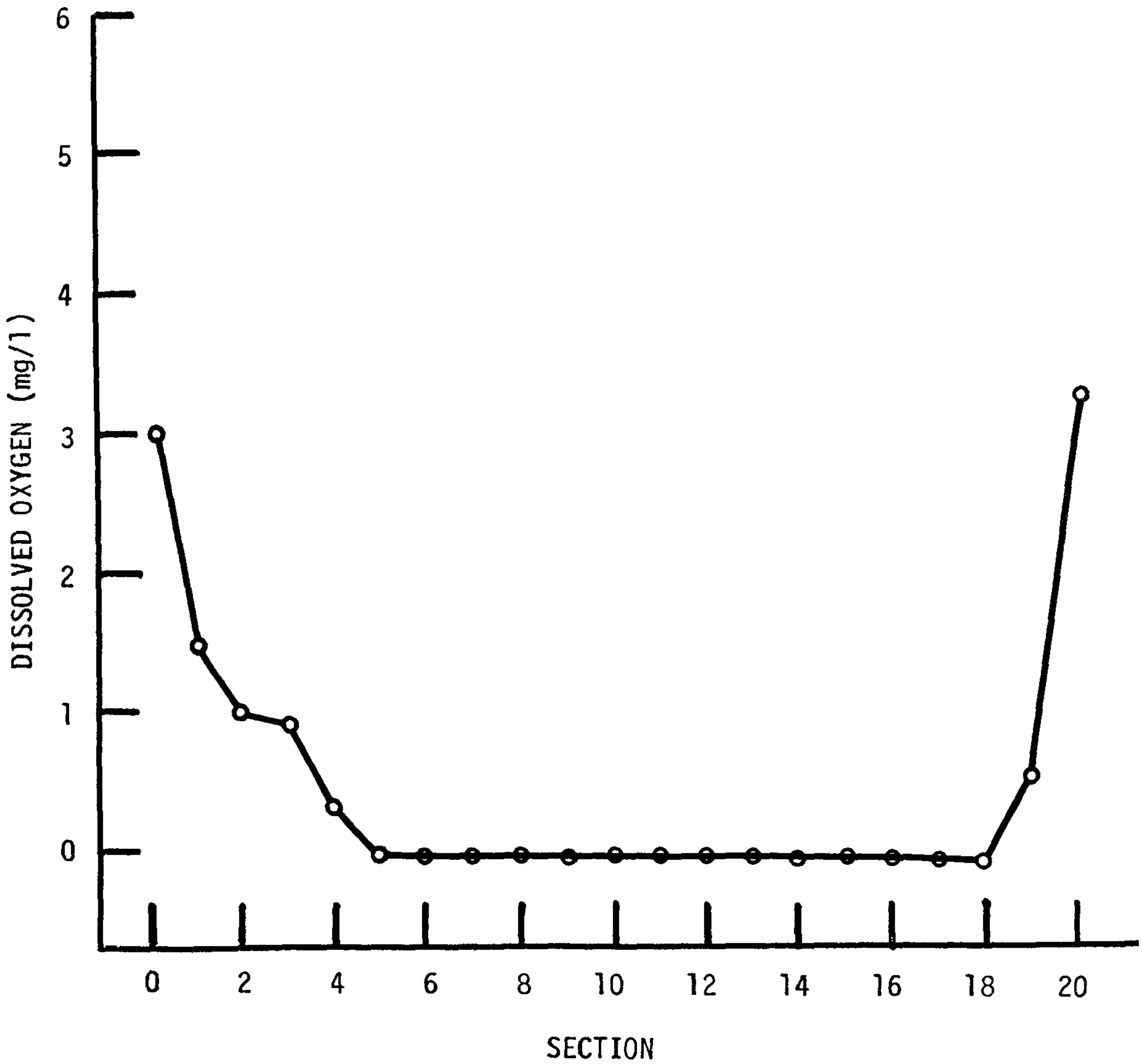

Figure 32. Simulation Run #2.

SIMULATION 3

The effect of flow upon DO was tested in Simulation (3). The data used (Table 11) were the same as those used in Simulation 2 with the exception of flow. An average flow of 850 cfs was used as the flow in the navigation channel. Figure (33) shows that DO begins to drop slowly until zero DO is reached in Section 10 (m.p. 3.15).

When comparing Simulations (2) and (3), it is apparent that for identical conditions, river water quality during low flow is greatly reduced. This is primarily due to the low velocity and high holding time in each section during low flow. In general, it could then be assumed that water quality in the Cuyahoga River could be improved if the concentration of waste being discharged during low flow periods is reduced. This could be accomplished by temporarily storing the waste and releasing it when river flow is high or by storing water in large reservoirs and releasing it as dilution water when river flow is low.

SIMULATION 4

If the best practical treatment guidelines are met by 1978 it is expected that the DO in the navigation channel will improve. Projected 1978 waste load reductions were obtained from the Ohio EPA in Columbus for the River from mile point 58 to the mouth. These values were input to illustrate the degree of improvement which could be anticipated.

The same conditions were used as for Simulation 2 (flow=345 cfs) with the exception of using OEPA projected 1978 Summer-Fall waste load data (See Table 7).

Results are shown in Figure (34). Since all other conditions are identical to Run #2 the trend in DO is expected to be similar. As expected, zero DO occurs in Section 5. While water quality improves slightly as lb/day of waste load decreases the improvement does not appear to be very significant.

SIMULATION 5

Simulation (5) was conducted to observe how dissolved oxygen is affected when all waste loads are decreased to 50% of 1973 values. The conditions used for Simulation (5) were thus the same as those used for Simulation (4) with the exception of waste loads. The results of this simulation are compared in Figure 35 with those of Simulation 2 and 4.

SIMULATION 6

Improving water quality in the navigation channel by further improving upstream water quality was examined in Simulation 6. Entering BOD was 8.0 mg/l as before; however, DO concentration entering the channel was assumed to

TABLE 11

SYSTEM PARAMETERS FOR THE NAVIGATION CHANNEL

(1973 Summer - Fall Data Obtained From Ohio EPA).

SECTION	DEPTH	AREA	FLOW	DISP	W	Sb	K	TEMP
1	0.200E+02	0.300E+04	820	0.250E+00	0	0.500E+01	0.150E+00	0.286E+02
2	0.200E+02	0.350E+04	820	0.220E+00	1437	0.500E+01	0.150E+00	01295E+02
3	0.250E+02	0.420E+04	820	0.220E+03	0	0.500E+01	0.150E+00	0.305E+02
4	0.250E+02	0.440E+04	820	0.220E+00	510	0.500E+00	0.150E+00	0.307E+02
5	0.250E+02	0.430E+04	850	0.200E+00	9990	0.500E+01	0.150E+00	0.309E+02
6	0.250E+02	0.900E+04	850	0.220E+00	0	0.500E+01	0.150E+00	0.311E+02
7	0.250E+02	0.470E+04	850	0.220E+00	0	0.500E+01	0.150E+00	0.314E+02
8	0.250E+02	0.510E+04	850	0.220E+00	1602	0.500E+01	0.510E+00	0.313E+02
9	0.250E+02	0.490E+04	850	0.220E+00	0	0.500E+01	0.150E+00	0.312E+02
10	0.250E+02	0.550E+04	850	0.220E+00	0	0.500E+01	0.150E+00	0.311E+02
11	0.250E+02	0.740E+04	850	0.220E+00	0	0.500E+01	0.150E+00	0.309E+02
12	0.250E+02	0.420E+04	850	0.220E+00	0	0.500E+01	0.150E+00	0.306E+02
13	0.250E+02	0.900E+04	850	0.220E+00	0	0.500E+01	0.150E+00	0.304E+02
14	0.250E+02	0.620E+04	850	0.220E+00	0	0.500E+01	0.150E+00	0.302E+02
15	0.250E+02	0.620E+04	850	0.220E+00	0	0.500E+01	0.150E+00	0.302E+02
16	0.250E+02	0.650E+04	850	0.400E+00	0	0.500E+01	0.150E+00	0.295E+02
17	0.250E+02	0.650E+04	850	0.600E+00	0	0.500E+01	0.150E+00	0.289E+02
18	0.250E+02	0.450E+04	850	0.800E+00	0	0.500E+01	0.150E+00	0.286E+02
19	0.250E+02	0.700E+04	850	0.100E+00	0	0.500E+01	0.150E+00	0.283E+02
20	0.250E+02	0.750E+04	850	0.100E+00	0	0.500E+01	0.150E+00	0.280E+02
21	0.0	0.820E+04	850	0.120E+01	0	0.0	0.0	0.0

SIMULATION RUN NO. 3

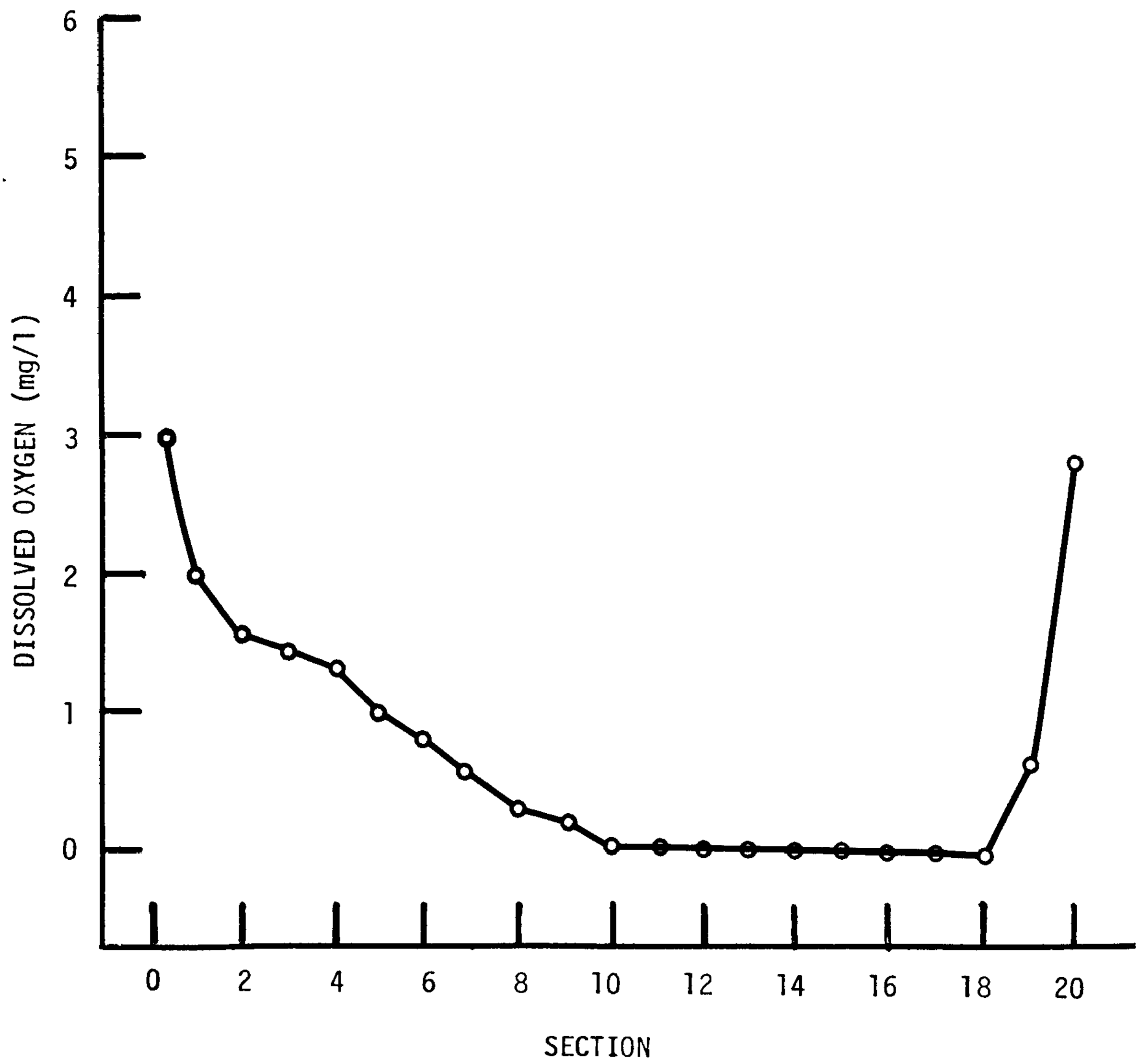

Figure 33. Simulation Run #3.

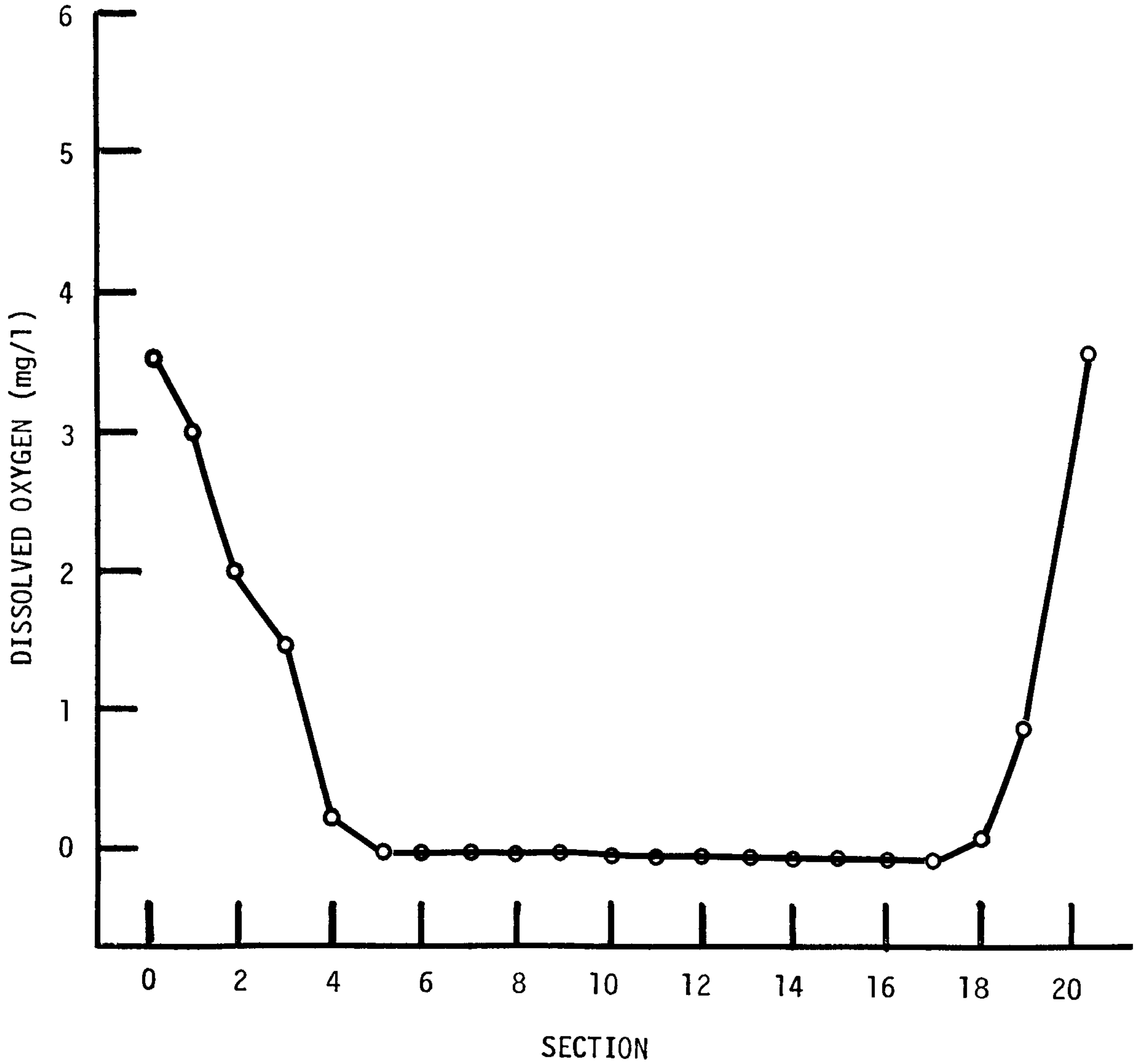

Figure 34. Simulation Run #4.

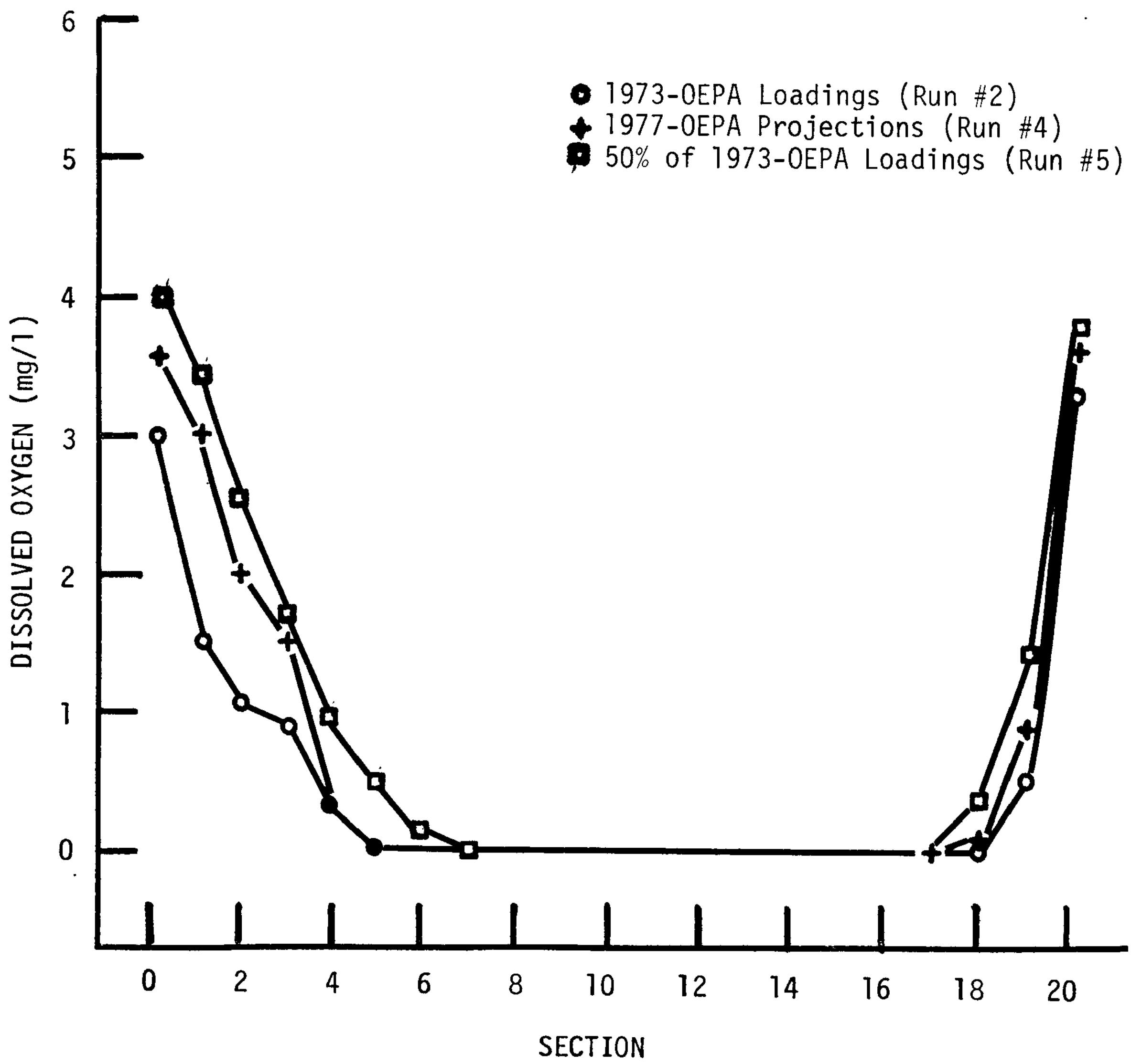

Figure 35. Comparison of Simulation Run #5 with Simulation Runs #2 and #4.

be 5 mg/l. With a low flow of 345 cfs in the channel, DO drops to zero in Section 7 (mile point 4.05) and remains there until intruding lake water causes it to rise in sections 19 and 20 (see Figure 36). From the results of this simulation it is estimated that upstream water with greater then 9 mg/l DO would be required to prevent a sag to zero within the navigation channel at low flow.

SIMULATION 7

Simulation 7 was run to test the combined effects of improved upstream water quality (entering DO = 5 mg/l, BOD = 8 mg/l), reduced loadings (1978 projections), and augmented flow (850 cfs). Under these combined conditions DO drops slowly reaching a low of 0.35 mg/l at mile point 1.35 (Section 16) (See Figure 37). Thus a combination of improved upstream water quality, reduced waste loading, and increased flow produce a significant improvement in DO concentrations within the channel.

UTILIZING THE TRANSFER MARTIX

As Model II calculates the DO deficit response for each section, the DO drop for each section is computed and listed in a tabular format (See Table 12). The changes in DO from one section to another resulting from variations in waste load allocations can thus be directly and quickly determined from the matrix shown in Table 12 (The complete Tranfer Matrix is illustrated in the User's Guide - Appendix C).

As an example in the use of this matrix consider the DO profile for the channel shown on Figure 38 as "1973 channel loadings". This profile results from a flow of 900 cfs in the channel, a DO of 4.4 mg/l and a BOD of 8.0 mg/l for water entering the channel, and the waste loadings shown in Table 8.

Suppose that Republic Steel and U. S. Steel were to reduce their waste loadings to zero. This would result in a removal of approximately 10,000 lbs/days of waste from Section 5 (Republic Steel) and a removal of approximately 1,600 lbs/day from Section 8 (U.S. Steel).

Table 12 indicates the decease in DO (Sections 1-20) resulting from waste inputs to Sections 1-10. It also can be interpreted to read the increase in DO in Sections 1-20 resulting from waste reductions in Sections 1-10. Thus a 10,000 lb/day waste removal from Section 5 would result in the increases in DO shown in Column 2 of Table 13 (taken directly from Table 12). A removal of 1600 lbs./day of waste from Section 8 would produce the response shown in Column 3 of Table 13 (obtained by taking the values from Table 12 and multiplying each by 1600/10000 = .16).

The total response is shown as the sum of the two responses in Column 4

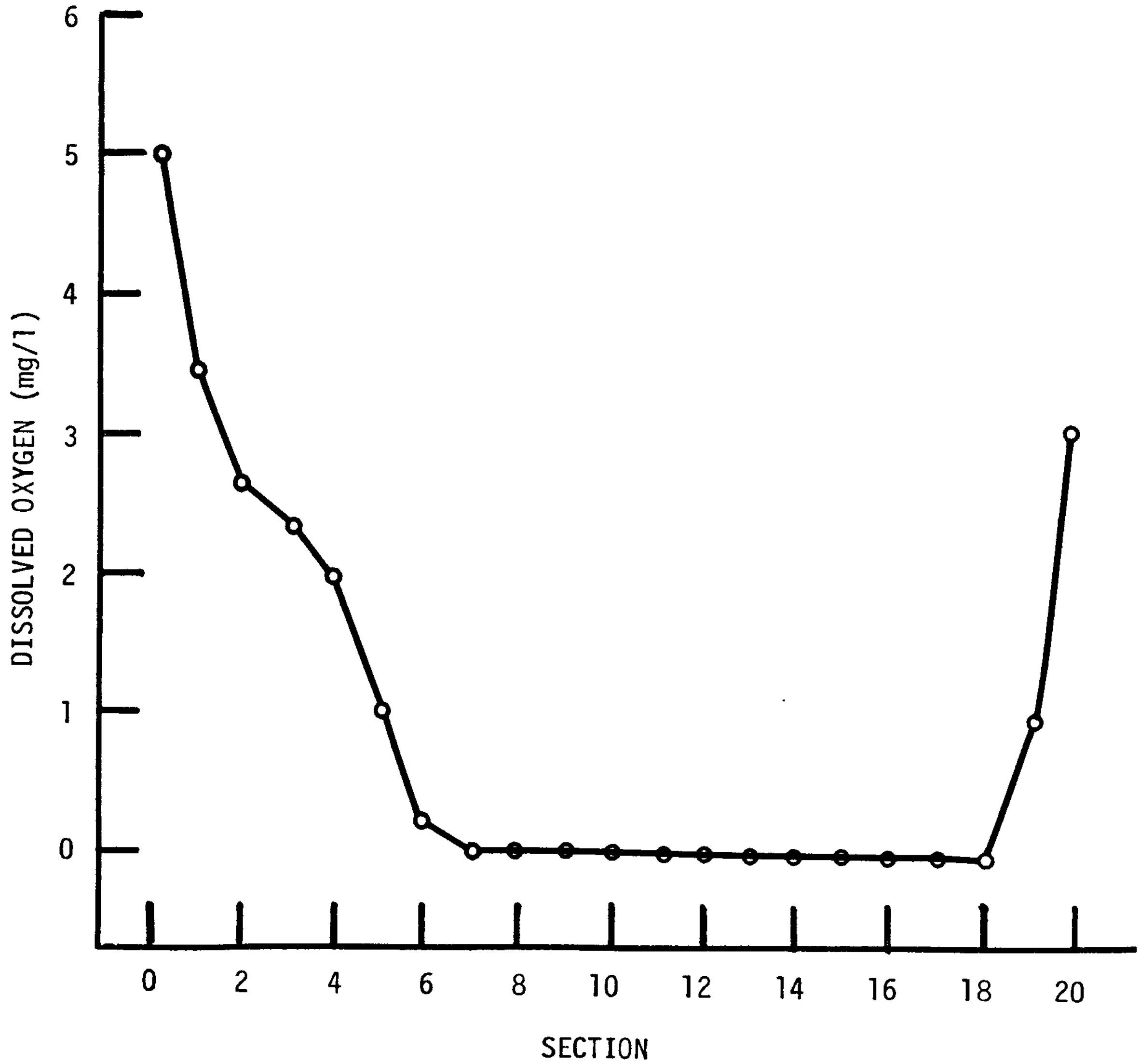

Figure 36. Simulation Run #6.

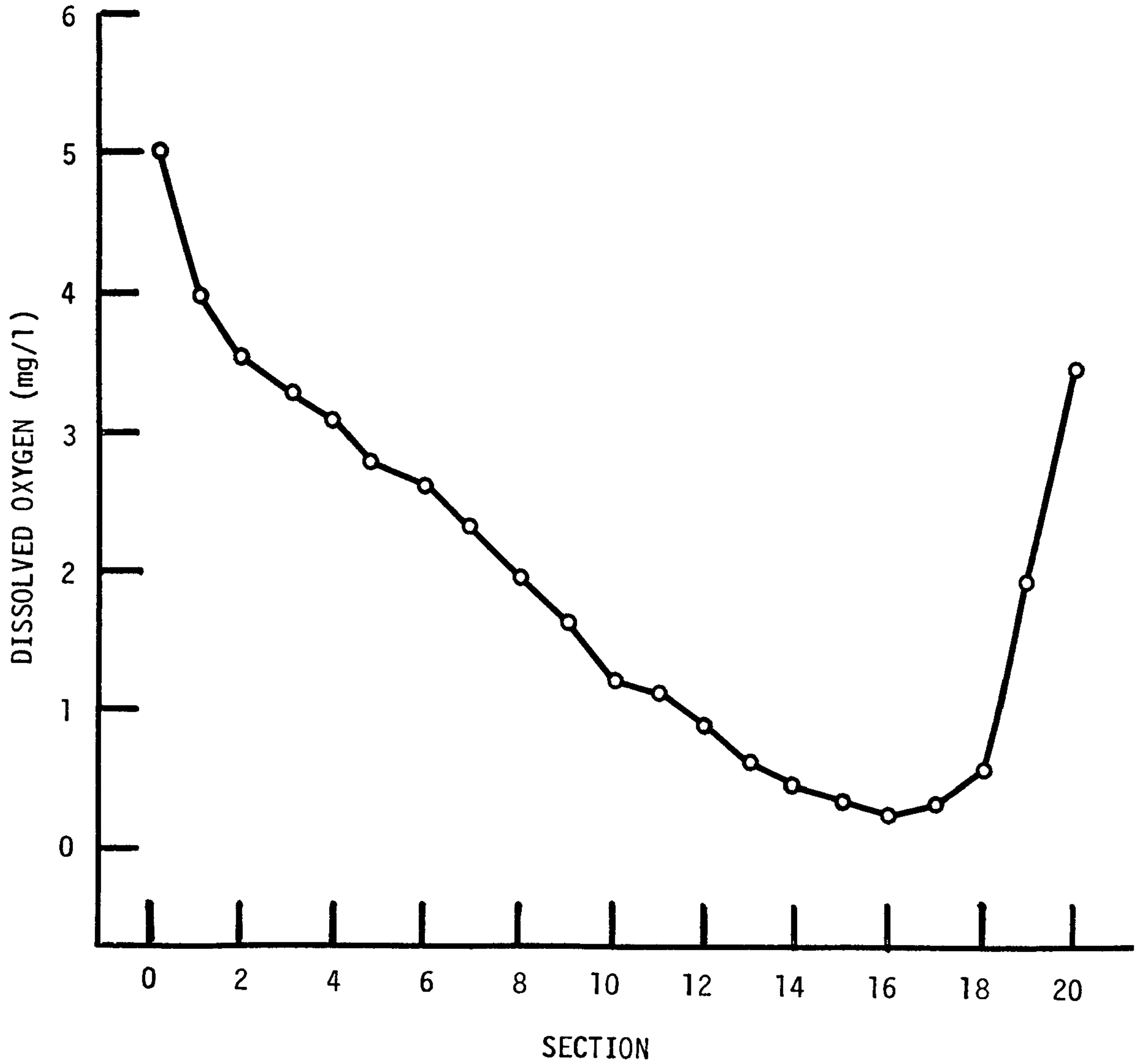

Figure 37. Simulation Run #7.

TABLE 12
(Transfer Matrix)

DROP IN DO (mg/l) FOR SECTIONS 1-20 WHEN A WASTE LOAD OF 10,000 LBS/DAY OF BOD IS DISCHARGED INTO ANY ONE SECTION BETWEEN 1 AND 10

Section	1	2	3	4	5	6	7	8	9	10
1	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-
4	0.12	0.11	-	0.04	-	-	-	-	-	-
5	0.15	0.15	0.13	0.09	0.08	0.03	-	-	-	-
6	0.17	0.17	0.15	0.12	0.12	0.08	-	-	-	-
7	0.19	0.20	0.19	0.16	0.18	0.14	0.05	-	-	-
8	0.22	0.23	0.22	0.19	0.24	0.20	0.09	0.05	-	-
9	0.24	0.26	0.26	0.23	0.29	0.26	0.14	0.09	0.05	-
10	0.27	0.29	0.29	0.26	0.35	0.32	0.18	0.14	0.10	0.07
11	0.28	0.31	0.32	0.29	0.39	0.37	0.22	0.18	0.14	0.12
12	0.31	0.34	0.35	0.32	0.45	0.43	0.26	0.23	0.19	0.19
13	0.32	0.36	0.37	0.35	0.49	0.46	0.29	0.26	0.23	9.23
14	0.34	0.38	0.40	0.38	0.53	0.51	0.32	0.30	0.27	0.28
15	0.36	0.40	0.42	0.40	0.57	0.56	0.36	0.34	0.31	0.34
16	0.36	0.41	0.43	0.41	0.59	0.58	0.58	0.36	0.33	0.37
17	0.34	0.39	0.41	0.40	0.57	0.56	0.37	0.35	0.33	0.37
18	0.26	0.29	0.31	0.30	0.44	0.43	0.28	0.27	0.26	0.29
19	0.18	0.20	0.22	0.21	0.30	0.30	0.20	0.19	0.18	0.20
20	-	0.10	0.11	0.10	0.15	0.15	0.10	0.09	0.09	0.10
LAKE	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0

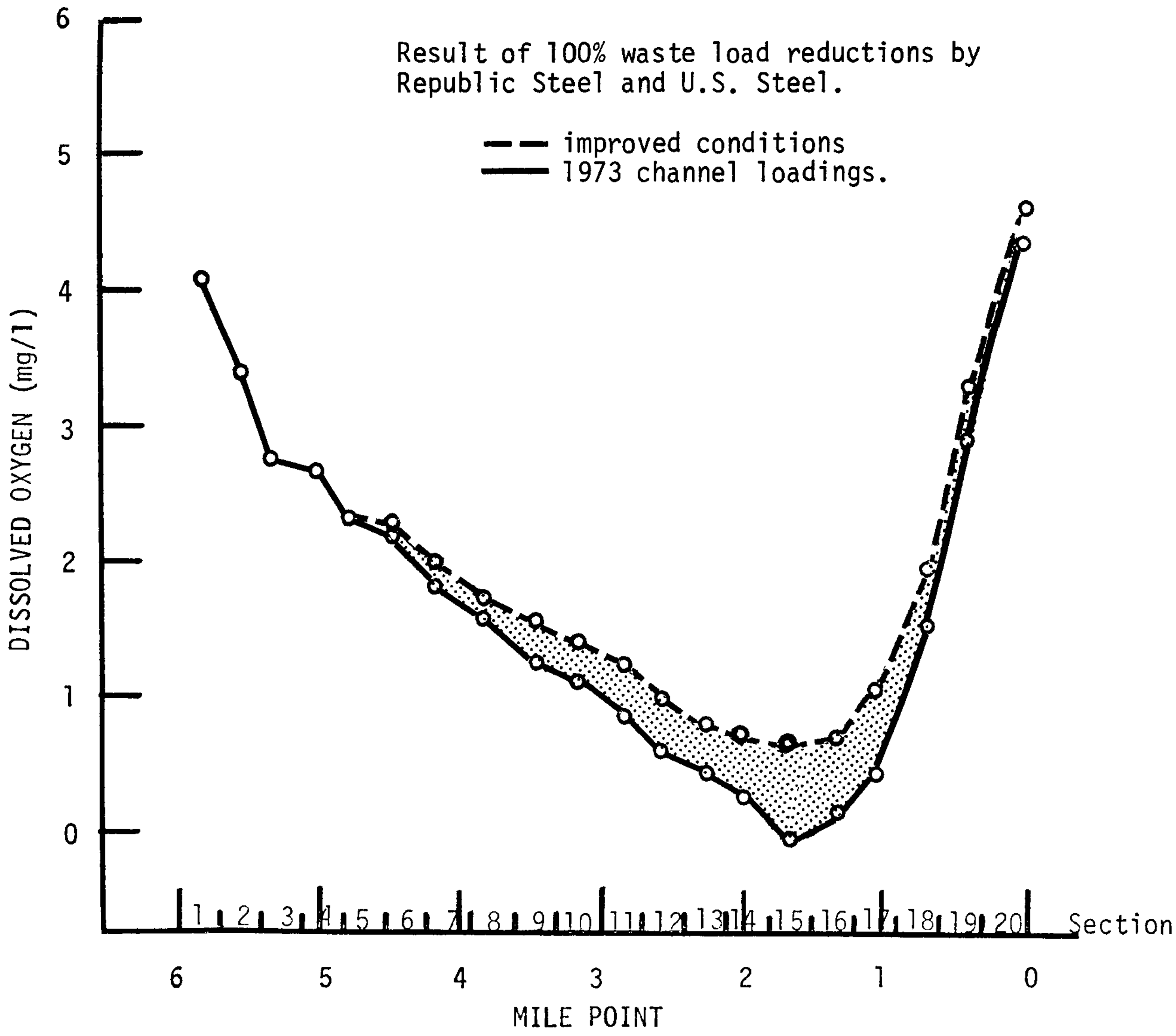

Figure 38. Use of Transfer Matrix in hypothetical waste load reallocation.(Good upstream quality, Flow=850 cfs.).

TABLE 13

Section	Increase in DO due to removing 10,000 lbs/day waste from Section 5	Increase in DO due to removing 1,600 165 lbs/day from Section 8	Total increase
1	-	-	-
2	-	-	-
3	-	-	-
4	-	-	-
5	0.08	-	0.08
6	0.12	-	0.12
7	0.18	-	0.18
8	0.29	0.022	0.24
10	0.35	0.029	0.38
11	0.39	0.034	0.43
12	0.45	0.042	0.49
13	0.49	0.046	0.53
14	0.53	0.052	0.58
15	0.57	0.058	0.63
16	0.59	0.061	0.65
17	0.57	0.059	0.63
18	0.44	0.045	0.48
19	0.30	0.031	0.33
20	0.15	-	0.15

of Table 13 and as the line labled improved conditions in Figure 38.

These operations allow a decision maker to immediately assess the results of a hypothetical waste load allocation without running the model. In addition the matrix immediately indicates that Section 16 is the most sensitive region of the channel and will receive its maximum effect (a drop in DO of 0.59 mg/l) when 10,000 lbs/day of waste is discharged into Section 5.

UTILIZING SIMULATIONS 1-7 AS A MANAGEMENT TOOL

By Utilizing Simulations 1-7 it is possible to answer the three questions presented on page 77.

Question 1: How can the EMCSM-CR determine the upstream water quality required to achieve the water quality standards set for the Cuyahoga River's navigation channel?

Answer 1: In order to maintain the standards set for the river, water quality in sections 14-16 must be controlled. Therefore, upstream flow, BOD, DO, and waste inputs must be manipulated until an acceptable DO is obtained in Sections 14-16. Simulations 1-7 demonstrate the expected changes which would occur when manipulating each of these parameters. Additional manipulations require only changing the input data.

Question 2: How can the EMCSM-CR be utilized to determine the best physical system for achieving that water quality?

Answer 2: Once the desired DO level is obtained in Sections 14-16, one must simple determine the most economic or most efficient means for effectuating the required changes. For example, if flow is doubled and BOD is decreased by half then one must decide how to double the flow and decrease the BOD. Such alternatives as storing dilution water to augment flow, eliminating all discharges, and etc. must be approached from an economical point of view; however, the response to using combinations of the different alternatives can be observed from the model.

Question 3: How can the EMSCM-CR assist in determining the most optimal system for administering and managing water quality?

Answer 3: The Transfer Matrix (Table 12) provides an excellent tool for determining the most optimal locations for outfalls and the most optimal waste load inputs because this matrix points out the sections which can least tolerate and most tolerate a waste load. With the assistance of the Transfer Matrix many management decision can be made.

COMPARING MODEL II (STEADY-STATE) OUTPUT WITH A TIME-VARIANT MODEL OF THE NAVIGATION CHANNEL.

A comparison of the results from the steady-state model simulation with the five day results from a time-variant model simulation (Ramm 1975) is illustrated in Table (14). System parameters used for these simulations were the same as those used to simulate Figure (29), with the exception of flow which was 700 cfs.

The simulated results of the time-variant model answered two important questions which could not have been answered by the simulated results of the steady-state model. These questions were:

1. How long does it take the Cuyahoga River to achieve an approximate steady-state under constant waste loading?

2. What effect does the inability of the model to simulate the absence of BOD at zero DO have upon the system output?

To answer the above questions simulations ulitizing the system parameters from Table 10 were made. Results of a five day simulation are shown in the column labeled "Standard Run" in Table (14). From this Table it can be seen that the system essentially reaches steady-state in five days. This time period is short enough to justify the use of steady-state values in the interpretation of water quality in the lower Cuyahoga River.

An additional time-variant simulation run was conducted in which the deoxygentation coefficient (K_1 = 0.15/day; base) was set to zero whenever DO reached zero and was reset to 0.15/day when DO returned to a positive value. The results of this run are shown in the column labeled "Feedback Included" (See Table 14). In general, it was found that the effect of including feedback did not significantly change the five-day profile. Including feedback did result in a positive DO value near m.p. 1.0 rather than m.p. 0.5. The "Feedback Included" values are therefore in slightly closer agreement with the measurements made in the lower one mile of the navigation channel than are values resulting from the steady-state simulation. However, the run time for the five day simulation is approximately eight minutes on an IBM 370 computer (approximately $40.00). This compares with a run time of approximately 30 seconds ($2.50) for the steady-state model. In the Cuyahoga River application it is clear that the marginal gain in information is far outweighed by the considerable increase in cost.

TABLE 14

COMPARISON OF RESULTS FROM THE STEADY-STATE MODEL SIMULATION
WITH FIVE DAY RESULTS FROM THE TIME-VARIANT MODEL SIMULATION
(NUMBERS REPRESENT MG/L DISSOLVED OXYGEN)

		TIME-VARIANT	
MILE POINT	STEADY-STATE	STANDARD RUN	FEEDBACK INCLUDED
5.85	4.14	4.10	4.14
5.55	3.74	3.67	3.74
5.25	3.04	2.99	3.04
4.95	2.73	2.71	2.73
4.65	2.06	2.15	2.06
4.35	1.71	1.85	1.71
4.05	1.32	1.44	1.32
3.75	1.00	1.11	1.01
3.45	0.64	0.76	0.65
3.15	0.17	0.38	0.22
2.85	0.00	0.10	0.00
2.55	0.00	0.00	0.00
2.25	0.00	0.00	0.00
1.95	0.00	0.00	0.00
1.65	0.00	0.00	0.00
1.35	0.00	0.00	0.00
1.05	0.00	0.00	0.07
0.75	0.00	0.00	0.42
0.45	0.25	0.66	0.82
0.15	1.03	1.44	1.30

SECTION XI

SUMMARY

Through an understanding of the many complex physical, chemical, and biological events occurring simultaneously within the system, the EMCSM-CR has demonstrated its ability to simulate the dissolved oxygen profile in the river by using mathematical procedures. The oxygen profiles resulting from use of the EMCSM-CR, when compared with field measurements, provided a reasonable fit and gave reliable estimates of the dynamic behavior of the discharged wastes and the stream (See Figure 29).

The EMCSM-CR, therefore, allows a water planner to assess the impact of alternate water quality control measures on the river system by varying the treatment levels at each discharge point and the water quality conditions in Lake Erie at its mouth. By increasing flow while holding discharge constant the model can also estimate the volume of dilution water required to meet dissolved oxygen standards in the river.

SECTION XII

REFERENCES CITED

Bella, D.A. and W. Dobbins. Difference Modeling of Stream Pollution. J. San. Eng. Div. ASCE, 94:955. 1968.

Cleveland Daily Plain Dealer. Vol. XXIV, #110. Wednesday, May 5, 1868. p. 3.

Cooke, G.D. The Cuyahoga River Watershed. (Proceeding of a Symposium held at Kent State University, Kent, Ohio. November 1, 1968.) p. 83-85.

Cuyahoga River Stream Pollution Survey. (Field notebook found in G. Garrett's file cabinet at OEPA, Columbus, Ohio. 1947.)

Dalton, Dalton & Little. Industrial Waste Survey Program for the Lower Cuyahoga River. Cleveland, Ohio. January 1971.

Fischer, H.B. A Lagrangian Method for Predicting Pollutant Disposal in Bolinas Lagoon, California. Biological Survey - Water Resources Division, Menlo Park, California. 1969.

Garlauskas, A.B. Water Quality Baseline Assessment for Cleveland Area-Lake Erie. Volume I-Synthesis. U.S. Environmental Protection Agency, Chicago, Illinois. Publication Number EPA - 905/9 - 74 - 005. May 30, 1974. 158 p.

Garrett, G. Cuyahoga River Model. Ohio Environmental Protection Agency, Columbus, Ohio. 1974 (unpublished edition).

Great Lakes Water Quality Board. Great Lakes Water Quality - Annual Report to the International Joint Commission. April 1973. 315 p.

Grenney, W.J. and D.A. Bella. Field Study and Mathematical Model of the Slack-Water Buildup of a Pollutant in a Tidal River. Limnology and Oceanography. 17(2):229. 1972.

Havens & Emerson. Master Plan for Pollution Abatement. City of Cleveland, Ohio. July 1968.

Havens & Emerson. A Plan for Water Quality Management in the Central Cuyahoga Basin. Three Rivers Watershed District, Clevelan, Ohio. 1970.

Havens & Emerson. Water Quality Assessment and Basin Modeling - Rocky River and Tinker's Creek. Three Rivers Watershed District, Cleveland, Ohio. February 1974.

Hetling, L. J. and R. L. O'Connell. A Study of Tidal Dispersion in the Potomac River. Water Resources Research 2 (4):825. 1966.

Northington, C. W. Lake Erie - Sick, Dying, or Well. Lake Erie Field Station Report. March 28, 1965. 16 p.

O'Connor, D. J. Estuarine Distribution of Non - Conservative Substances. Jour. San. Eng. Div. ASCE. Vol 91. No. SA 1. February 1965. p.23.

O'Connor, D. J. et al. Dynamic Water Quality Forecasting and Management. Environmental Protection Agency. Publication Number 600/3 - 73 - 009. August 1973.

Ohio Dept. of Health. Report of Water Pollution - Study of Cuyahoga River Basin 1954 - 1956. Sewage and Waste Unit, Columbus, Ohio. August 1960.

Ohio Dept. of Health. Deoxygentation Study - Cuyahoga River. Columbus, Ohio. 1965.

Ohio Enironmental Protection Agency. Ohio Surface Water Monitoring Program. Division of Surveillance, Twinsburg, Ohio. 1974.

Ramm, A. E. A Time-Variant Model of the Cuyahoga River. 1975 (Unpublished).

Schroeder, M.E. and C. R. Collier. Water Quality Variations in the Cuyahoga River at Cleveland, Ohio. U.S. Geological Survey Prof. Paper Number 550 - C. 1966. p. C251 - C255.

Stanley Engineering Company. Report on Water Quality and Use. Three Rivers Watershed District, Cleveland, Ohio 1966.

Streeter, H.D. and E. B. Phelps. U.S. Public Health Service, Washington, D. C. Public Health Bulletin 146. 1925.

Thomann, R. V. System Analysis and Water Quality Management. New York. Environmental Science Services Division, 1972. 286 p.

U. S. Army Corps of Engineers. A Pilot Wastewater Management Program for Chicago, Cleveland, Detorit, San Francisco, and Merrimack Basin. Office, Chief of Engineers. March 1971.

U. S. Army Corps of Engineers. Wastewater Management Study: 1970. Corps of Engineers, Buffalo, New York. August 1973. 207 p.

U. S. Department of Interior, Lake Erie Report - A Plan for Water Pollution Control. Federal Water Pollution Control Administration, Great Lakes Region. Publication Number GPO - 808 - 895 - 6. August 1968. 107 p.

U. S. Department of Interior, Water Resources Data for Ohio. 1973.

U. S. Department of Interior, Water Resources Data for Ohio. Part 1. Surface Water Records. 1974.

Winslow, J. D., G. D. White, and E. E. Webber. The Water Resources of Cuyahoga County Ohio. U.S. Geological Survey Water Resources Divison, Columbus, Ohio. Bulletin Number 26. August 1953.

APPENDIX A

Ohio EPA - Regulation EP-1- Water Quality Standards

(Dissolved Oxygen Standards which apply to the Cuyahoga River)

EP-1-02 General Standard

Except as other regulations in this Chapter, EP-1, establish different standards, the water quality standards of the state shall be as follows.

(C) Dissolved oxygen shall not be less than a daily average of 5.0 mg/l nor less than 4.0 mg/l at any time.

FOR AQUATIC LIFE (WARM WATER FISHERY)

The following criteria are for evaluation of conditions for the maintenance of a well-balanced, warm-water fish population. They are applicable at any point in the stream except for the minimum area necessary for the admixture of waste effluents with stream water:

1. Dissolved Oxygen: Not less than an average of 5.0 mg/l per calendar day and not less than 4.0 mg/l at any time.

EP-1-09 Lower Cuyahoga River.

(A) The water quality standards in the Lower Cuyahoga River shall be the the water quality standards in regulation EP-1-02, except that, to the extent that subsequent provisions of this regulation, EP-1-09, established different standards, the latter standards shall apply:

(1) In that portion of the Cuyahoga River extending from the confluence of the Cuyahoga River and Big Creek to the mouth of the Cuyahoga River,

(a) The dissolved oxygen standards in EP-1-02 (C) need not be met during the months of July, August, September, and October.

APPENDIX B

ANALYTICAL RESULTS: CUYAHOGA RIVER SAMPLING

CUYAHOGA RIVER

CHEMICAL ANALYSES

DATE	Station 1 Surface	Station 1 8m.	Station 2 Surface	Station 2 8m.	Station 3 Surface	Station 4 Surface	Station 4 8m.	Station 5 Surface	Station 5 8m.	Station 6 Surface	Station 6 8m.
Depth (feet)											
9/05/73	--	--	--	--	--	--	--	--	--	--	--
9/12/73	35	35	35	35	32	25	25	20	20	27	27
9/19/73	35	35	27	27	27	28	28	25	25	30	30
9/28/73	33	33	33	33	25	28	28	36	36	30	30
10/11/73	35	35	32	32	25	26	26	26	26	30	30
10/18/73	--	--	--	--	30	30	30	25	25	23	23
10/25/73	34	34	25	25	32	25	25	25	25	29	29
Wind (mph)											
9/05/73	---	---	---	---	---	---	---	---	---	---	---
9/12/73	6-10	6-10	6-10	6-10	4-8	2-6	2-6	6-10	6-10	0-2	0-2
9/19/73	10-12	10-12	15-19	15-19	6-8	2-8	2-8	6-10	6-10	3-4	3-4
9/28/73	4-6	4-6	1-3	1-3	4-6	2-4	2-4	2-4	2-4	2-4	2-4
10/11/73	8-10	8-10	0-2	0-2	2-4	4-6	4-6	2-4	2-4	2-4	2-4
10/18/73	---	---	---	---	---	---	---	---	---	---	---
10/25/73	---	---	---	---	---	---	---	---	---	---	---
Chemical Oxygen Demand (mg/l)											
9/05/73	17	20	16	27	13	77	66	28	77	63	70
9/12/73	52	38	49	38	38	56	49	38	59	45	45
9/19/73	15	13	22	42	42	48	55	110	48	48	75
9/28/73	7	7	10	10	20	13	13	20	0	0	129
10/11/73	6	14	17	12	21	19	22	24	28	36	29
10/18/73	--	--	24	--	32	20	7	26	19	22	19
10/25/73	23	27	30	30	30	16	27	16	30	16	23
Water Temperature (C°)											
9/05/73	28.0	23.0	28.0	23.0	24.0	27.0	23.0	--	--	--	29.0
9/12/73	22.5	22.5	25.0	23.0	23.0	25.5	23.5	27.5	26.0	28.0	25.0
9/19/73	23.0	21.5	25.0	22.0	21.0	25.0	22.0	25.5	23.0	26.0	23.0
9/28/73	23.0	20.5	27.0	24.0	26.0	29.0	25.0	29.0	26.0	30.0	26.0
10/11/73	23.0	19.5	23.0	20.0	22.0	23.5	21.0	24.0	23.0	24.0	23.0
10/18/73	--	--	18.0	18.0	18.0	19.0	17.5	21.0	20.0	22.0	21.0
10/25/73	19.0	16.0	19.0	16.0	18.0	21.0	16.5	22.0	17.5	22.5	18.0

CUYAHOGA RIVER

CHEMICAL ANALYSES

DATE	Station 1 Surface	Station 1 8m.	Station 2 Surface	Station 2 8m.	Station 3 Surface	Station 4 Surface	Station 4 8m.	Station 5 Surface	Station 5 8m.	Station 6 Surface	Station 6 8m.
Suspended Solids (mg/l)											
9/05/73	17	22	14	16	11	22	21	18	33	—	34
9/12/73	17	27	23	27	18	14	22	15	91	20	19
9/19/73	17	6	14	14	11	10	13	61	23	16	27
9/28/73	14	22	19	64	71	23	121	31	29	33	23
10/11/73	26	21	18	25	50	32	45	24	95	57	57
10/18/73	--	--	12	--	19	11	32	12	41	9	21
10/25/73	6	12	36	104	7	5	26	5	12	12	17
Total Solids (mg/l)											
9/05/73	499	299	520	282	343	403	471	541	377	708	428
9/12/73	454	380	498	454	493	507	434	583	618	589	558
9/19/73	433	398	523	475	445	550	519	562	554	607	608
9/28/73	467	545	612	429	811	588	601	636	540	608	708
10/11/73	531	552	550	381	592	555	533	534	555	590	564
10/18/73	---	---	473	---	1035	505	463	503	497	535	512
10/25/73	537	543	512	532	743	600	627	600	585	612	608
Nitrate (mg/l)											
9/05/73	7.5	3.0	5.5	2.0	4.5	4.5	5.0	26.5	5.0	8.5	7.0
9/12/73	6.5	7.0	5.8	23.0	7.0	7.5	7.5	9.0	9.5	11.0	30.5
9/19/73	2.8	21.0	2.3	2.8	2.8	3.5	3.8	4.0	3.4	3.8	2.9
9/28/73	3.3	3.5	5.3	3.8	5.3	5.3	3.0	29.5	2.9	5.4	3.5
10/11/73	23.5	7.3	23.0	10.8	23.8	23.0	21.5	5.5	21.8	5.3	30.5
10/18/73	---	---	4.8	---	3.8	4.6	5.4	5.3	5.8	7.0	5.9
10/25/73	5.4	4.6	5.9	5.3	7.2	9.2	8.6	8.7	7.1	0.6	8.7
Dissolved Oxygen - Field (mg/l)											
9/05/73	2.4	5.8	3.7	4.8	3.5	---	---	---	---	---	---
9/12/73	---	6.5	.6	2.0	4.2	1.0	1.3	.6	1.0	3.2	3.0
9/19/73	3.6	5.2	1.5	5.0	5.6	1.4	4.4	.9	2.2	0.5	3.2
9/28/73	3.2	11.4	1.4	4.8	1.8	1.2	3.6	1.4	3.8	1.0	2.6
10/11/73	1.4	4.8	1.0	5.2	1.0	1.2	3.0	1.0	0.9	1.0	1.0
10/18/73	---	---	4.8	4.2	2.6	3.4	6.4	2.2	2.8	1.6	2.2
10/25/73	3.6	7.2	4.2	5.4	1.6	1.0	4.2	1.0	4.0	0.8	3.6

CUYAHOGA RIVER

CHEMICAL ANALYSES

DATE	Station 1 Surface	Station 1 8m.	Station 2 Surface	Station 2 8m.	Station 3 Surface	Station 4 Surface	Station 4 8m.	Station 5 Surface	Station 5 8m.	Station 6 Surface	Station 6 8m.
Conductivity - Field (Micromhos)											
9/05/73	---	---	---	---	---	---	---	---	---	---	---
9/12/73	210	170	750	565	12	800	690	900	775	950	850
9/19/73	660	545	850	710	740	860	840	930	900	960	950
9/28/73	680	660	890	250	950	950	750	950	590	520	380
10/11/73	520	810	780	440	850	800	760	790	800	680	800
10/18/73	---	---	600	700	170	800	750	710	600	800	710
10/25/73	---	---	---	---	---	---	---	---	---	---	---
ph - Laboratory											
9/05/73	7.1	7.6	7.4	7.6	7.4	6.9	7.0	7.2	7.0	7.5	7.2
9/12/73	6.9	7.2	6.8	6.9	6.9	6.7	7.0	6.6	6.7	6.7	7.5
9/19/73	7.8	7.6	7.5	7.6	7.6	7.5	7.5	7.5	7.5	7.5	7.5
9/28/73	7.4	7.5	7.3	7.6	7.3	7.2	7.4	7.2	7.4	7.2	7.3
10/11/73	6.7	6.7	6.8	7.1	6.6	6.9	6.9	6.7	6.8	6.8	6.5
10/18/73	---	---	7.6	---	7.6	7.5	6.8	7.5	6.4	7.5	6.7
10/25/73	7.0	7.3	7.5	6.9	6.9	6.8	7.0	6.9	6.8	6.9	7.0
Chloride (mg/l)											
9/05/73	110	52	111	51	81	76	101	116	79	96	81
9/12/73	89	76	98	89	109	117	98	114	117	122	118
9/19/73	68	58	86	74	74	84	86	92	92	96	92
9/28/73	89	76	104	63	165	99	87	97	106	93	110
10/11/73	77	81	81	51	84	81	81	77	77	73	72
10/18/73	--	--	61	--	283	63	55	68	64	73	64
10/25/73	99	98	86	94	177	108	103	103	106	97	104
Dissolved Solids (mg/l)											
9/05/73	491	279	490	264	365	401	463	502	326	---	410
9/12/73	435	394	499	456	517	506	448	511	490	552	528
9/19/73	431	400	504	459	464	545	534	572	537	586	603
9/28/73	424	439	569	369	717	600	473	634	525	574	567
10/11/73	530	570	564	375	564	544	549	553	553	557	576
10/18/73	---	---	430	---	965	444	390	477	420	593	458
10/25/73	506	511	461	484	704	581	587	592	586	605	605

CUYAHOGA RIVER

CHEMICAL ANALYSES

DATE	Station 1 Surface	Station 1 8m.	Station 2 Surface	Station 2 8m.	Station 3 Surface	Station 4 Surface	Station 4	Station 5 Surface	Station 5 8m.	Station 6 Surface	Station 6 8m.
					BOD_5 (mg/l)						
9/05/73	7	5	5	5	5	6	5	10	5	90	4
9/12/73	9	13	10	7	14	14	13	12	11	11	10
9/19/73	10	38	58	44	41	57	48	53	42	44	53
9/28/73	50	54	56	56	55	55	58	57	38	66	44
10/11/73	10	6	21	5	13	8	6	16	6	15	15
10/18/73	-	-	0	-	4	3	4	2	2	2	3
10/25/73	34	120	24	140	28	70	6	6	5	7	113
					BOD_{21} (mg/l)						
9/05/73	13	15	9	7	8	14	13	13	13	.2	14
9/12/73	12	13	13	15	15	14	15	10	14	13	15
9/19/73	59	59	60	62	61	64	62	60	61	55	61
9/28/73	62	51	57	59	59	59	60	54	59	68	59
10/11/73	49	83	77	87	94	79	65	78	75	80	77
10/18/73	-	-	9	-	14	16	15	15	19	15	17
10/25/73	105	85	125	186	184	135	183	160	123	112	171
					ORGANIC NITROGEN (mg/l)						
9/05/73	0	.32	0.72	0.48	0.56	0.64	1.34	0.77	0.90	1.18	1.01
9/12/73	1.34	0.67	1.68	5.82	0	0	0	0	0	1.52	0.70
9/19/73	1.34	3.17	1.19	1.23	0.90	0.90	2.46	3.02	0	0	0
9/28/73	0.70	0	0	0	0.07	0	0.05	0	0.14	5.10	3.29
10/11/73	1.96	1.68	2.66	1.68	2.80	1.26	1.05	.44	4.69	.22	2.66
10/18/73	-	-	1.79	-	2.46	.11	2.13	2.46	1.79	0	0
10/25/73	0	0	.69	.96	.72	1.44	2.24	0	0	0	0
					AMMONIA NITROGEN (mg/l)						
9/05/73	3.92	.16	1.6	.24	.56	3.84	5.66	3.85	2.24	2.91	2.91
9/12/73	3.58	.90	3.47	8.06	.56	2.35	1.01	3.02	.11	4.70	2.45
9/19/73	2.02	.84	3.09	1.23	1.34	2.46	1.46	2.80	2.91	6.38	6.80
9/28/73	.77	.35	1.75	1.40	.42	.14	.49	.21	1.40	1.40	1.05
10/11/73	.70	.90	3.22	4.70	2.59	3.01	3.85	2.69	3.64	2.69	4.55
10/18/73	-	-	0	-	2.13	.67	.45	6.16	.90	6.07	1.19
10/25/73	1.32	1.84	3.20	3.20	4.24	5.76	4.16	4.80	4.48	4.27	1.89

APPENDIX C

USER'S MANUAL - STEADY STATE MODELS

P U R P O S E

The function of the steady state model package is to provide a means for assessing the effect of waste loadings of CBOD to the Cuyahoga River upon the coupled CBOD - DO system in the river. The package has been designed to utilize a Streeter-Phelps non-dispersive approach above the navigation channel and a dispersive approach within the navigation channel. The model's output provides a transfer matrix table for the navigation channel which is useful in making decisions regarding waste load allocations.

This manual is designed to aid the user in inputing data to and interpreting output from the model. The mode is written to be compatible with all computers utilizing fortian IV (level G) language.

TABLE OF CONTENTS

P R O G R A M   A B S T R A C T

Title: CUYAHOGA RIVER STEADY STATE WATER QUALITY MODEL

Author Organization:

ECO-LABS, INC.
1836 Euclid Avenue
Cleveland, Ohio 44115

Direct Inquiries to:

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ECO-LABS, INC.
1836 Euclid Avenue
Cleveland, Ohio 44115

Summary Information:

Input - Card

Output - Printed Report

Run Frequency - Upon Request

Storage Requirement - 20K

Language: Fortran IV-G Level

Original System: IBM 360/70

PROGRAM DESCRIPTION

The Cuyahoga River Steady State Water Quality Model was developed specifically for the United States Environmental Protection Agency. It provides management information concerning dissolved oxygen levels in the river under varying conditions of flow and CBOD. The model's program is divided into two sections.

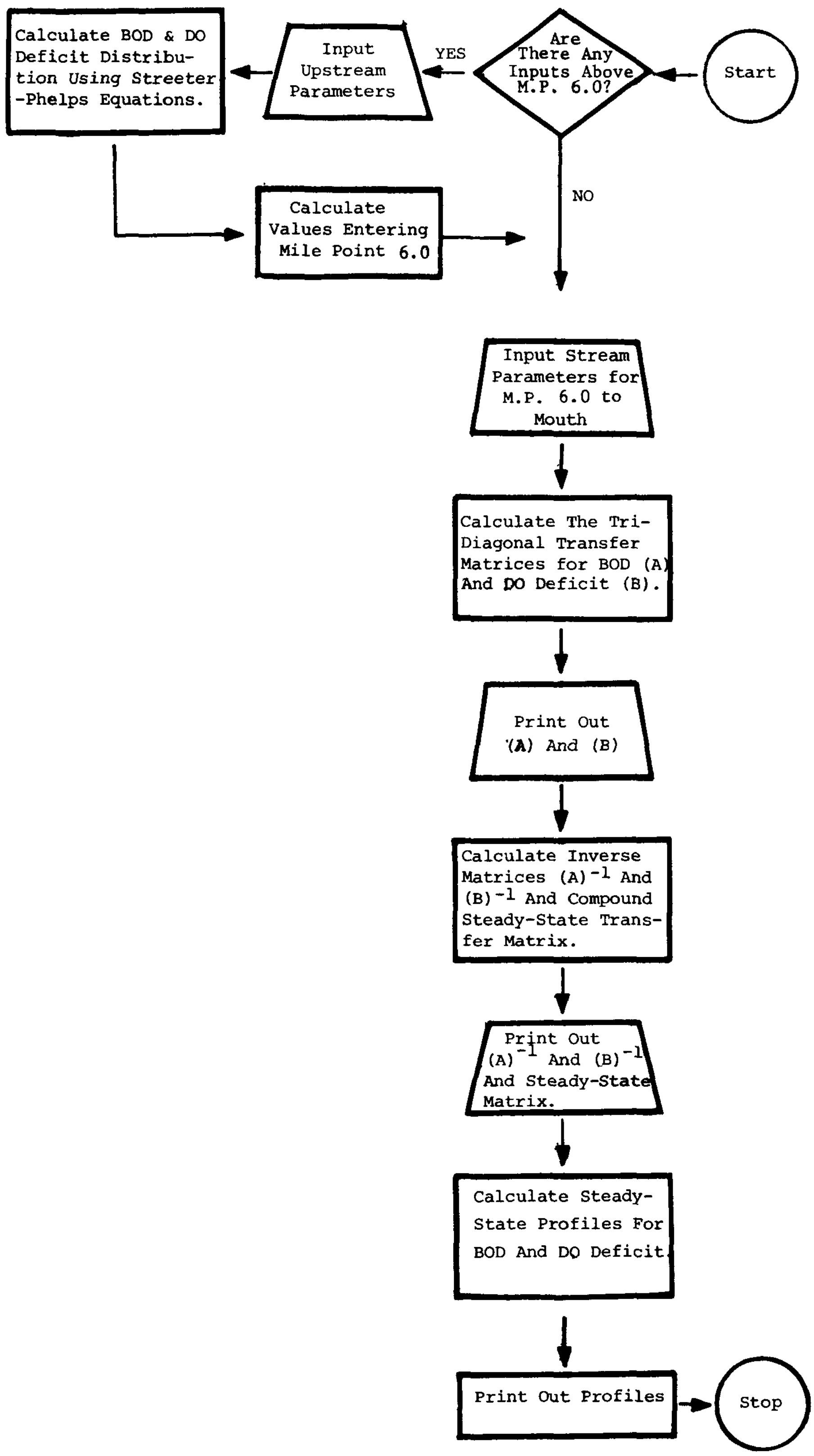
Section One, which is optional, permits input of waste loadings and associated river parameters at any point or series of points downstream from the river's source (m.p. 100.1) to the head of the river's navigation channel (m.p. 6.0). Utilizing a Streeter-Phelps equation set, the program evaluates the CBOD and DO deficit concentrations downstream from the waste outfall.

Section Two utilizes a finite - difference approach to simulate the CBOD - DO deficit concentrations within the navigation channel. Longitudinal dispersion is included in this section.

Output is in the form of tables and charts.

PROGRAM FLOWCHART

PROGRAM FLOWCHART



INPUT FORMAT

INPUT FORMAT

<u>Input</u>

IRUN:	Number of runs desired
START:	Option Selector. If zero, program begins at mile point 6. If non-zero, program begins above mile point 6.
ALO:	The upstream CBOD concentration (mg/l)
DO:	The upstream dissolved oxygen concentration (mg/l)
ALL:	The lake CBOD concentration (mg/l)
DOL:	The lake dissolved oxygen concentration (mg/l)
TEMPU:	The upstream water temperature (°C)
TEMPL:	The lake water temperature (°C)
INUMB:	The number of waste outfalls (and/or tributaries) above mile point 6.
ASTART:	Mile point of outfall (miles)
ASTOP:	Mile point of next outfall (miles)
AR:	Average cross sectional area of River between ASTART and ASTOP (ft^2)
GR:	Average flow of river between ASTART and ASTOP (million gallons per day - MGD)
W:	Waste loading form outfall (lb/day)
QW:	Flow from waste outfall (MGD)
AKW:	Deoxygenation coefficient (K_1-base e) of waste per day
AKA:	Reaeration coefficient between ASTART and ASTOP per day
RTEMP:	Temperature of the river through reach
WDO:	Oxygen concentrate from tributary (mg/l)

WTEMP:	Temperature of the tributary/outfall
H:	Average depth of a section within the navigation channel (ft)
AREA:	Cross sectional area of upper face of section (ft^2)
FLOW:	Flow at upper section face (cfs)
D:	Longitudinal dispersion coefficient at upper section face ($miles^2$/day)
WI:	Waste Loading into a section (lbs/day)
W2:	Benthic oxygen demand within a section ($gm/m^2/day$)
AK1:	Deoxygenation coefficient (K_1-base e) of waste within a section (per day)
TEMP:	Average water temperature within a Section (°C)
ALLOW:	CBOD concentration of waste outfall (mg/l)
DEFW:	Oxygen deficit from waste outfall (mg/l)
AH:	Average depth of river above mile point 6 (ft)

PUNCHED CARD AND DATA SEQUENCE

CARD #	COLUMNS TO	COLUMNS FROM	FIELD NAME	COMMENTS	TYPE
1	5	1	IRUN	Right oriented Column 5	INTEGER
2	10	1	START	REQUIRED	REAL +
2	20	11	ALO	REQUIRED	REAL +
2	30	21	DEF	REQUIRED	REAL +
2	40	31	ALL	REQUIRED	REAL +
2	50	41	DEFL	REQUIRED	REAL +
3	5	1	INUMB	OPTIONAL* Right oriented Column 5	INTEGER
4	10	1	ASTART	OPTIONAL*	REAL +
	20	11	ASTOP	OPTIONAL	REAL +
	30	21	AR	OPTIONAL	REAL +
	40	31	QR	OPTIONAL	REAL +
	50	41	ALO	OPTIONAL	REAL +
	60	51	QW	OPTIONAL	REAL +
	70	61	AKW	OPTIONAL	REAL +
	80	71	AH	OPTIONAL	REAL +
	10	1	RTEMP		
5	20	11	WDO	OPTIONAL	REAL +
	30	21	WTEMP		
6	10	1	H	REQUIRED	REAL +
	20	11	AREA	REQUIRED	REAL +

CARD #	COLUMNS TO	COLUMNS FROM	FIELD NAME	COMMENTS	TYPE
	30	21	FLOW	REQUIRED	REAL +
	40	31	D	REQUIRED	REAL +
	50	41	W1	REQUIRED	REAL +
	60	51	W2	REQUIRED	REAL +
	70	61	AK1	REQUIRED	REAL +
	80	71	TEMP	REQUIRED	REAL +

* Omit if Astart = 0
+ All real numbers must contain a decimal point
  Repeat card six for each section

PROGRAM LISTING
WITH
DOCUMENTATION

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FORTRAN/LISTING OF FORTRAN/CLEVLND/AWAR    AT 11:21:11    MONDAY 08/25/75 FOR          *************************

        B 5 7 0 0    F O R T R A N    C O M P I L A T I O N   XVI.0.14,     MONDAY, 08/25/75, 11:21 AM.

                                  C L E V L N D / S T A T E
                                  = = = = = = = = = = = = =

FILE  S=READER,UNIT=READER                                               00000050 R  0000
C                                                                        00000100 R  0000
C         DIMENSION VARIABLES                                            00000200 R  0000
C                                                                        00000300 R  0000
                                                              START OF SEGMENT **********   1
      DIMENSION W3(21),W4(21),TEMP(21),AK1(21)                           00000400 R  0000
      DIMENSION DET(20,20),LENG(20,20),MVECT(20,20)                      00000500 R  0000
      DIMENSION A(20,20), W(20,20), E(20,20), B(20,20), C(20,20)         00000600 R  0000
      DIMENSION V(20),AREA(21),XL(20),AK2(20),W1(21),DEOX(20,20)         00000700 R  0000
      DIMENSION W2(21),FLOW(21),D(21),U(21),H(21),C1(20,20)              00000800 R  0000
      DIMENSION C2(20,20)                                                00000900 R  0000
      DOSAT(T)=14.652-0.41022*T+0.007991*T**2.-0.000077774*T**3.                  R  0000
      READ(5,160) IRUN                                                            R  0015
      DO 999 KIK=1,IRUN                                                           R  0025
      READ(5,162) START, ALO, DO, ALL, DOL, TEMPU, TEMPL                          R  0030
  162 FORMAT(8E10.3)                                                     00001100 R  0053
      CU=DOSAT(TEMPU)                                                             R  0053
      CL=DOSAT(TEMPL)                                                             R  0055
      DEF=CU-DO                                                                   R  0057
      DEFL=CL-DOL                                                                 R  0058
C                                                                        00001200 R  0059
C       APPLY STREETER-PHELPS EQUATION IF FIRST INPUT IS ABOVE MP 10     00001300 R  0059
      IF (START. EQ. 0.) GO TO 21                                        00001400 R  0060
C                                                                        00001500 R  0061
  129 FORMAT(1H ,"MP= ",F5.2,2X,"BOD= ",F6.2,"DO DEF= ",F6.2,                     R  0063
     12X,"DO = ",F6.2)                                                            R  0063
      READ(5,160) INUMB                                                  00001800 R  0063
  160 FORMAT(I5)                                                         00001900 R  0073
      DO 20 KK=1, INUMB                                                  00002000 R  0073
      READ (5,162) ASTART, ASTOP, AR, QR, W,QW,AKW, AH                            R  0078
      IF(KK.EQ.1) PRINT 129, ASTART, ALO, DEF, DO                                 R  0102
      READ(5,162) RTEMP, WDO, WTEMP                                               R  0119
      CS=DOSAT(WTEMP)                                                             R  0132
      DEFCIT=CS-WDO                                                               R  0134
      WDEF=DEFCIT*QW*5.39                                                         R  0135
      EX=(ASTART-ASTOP)                                                  00002300 R  0139
      AU=((QR+QW)/AR)*15.36                                                       R  0141
      AKA=12.9*((QR/AR)**0.5)/AH**1.5                                             R  0144
      ALO=((W+ALO*QR*5.39)/((QR+QW)*0.646))*0.1199                       00002500 R  0155
      DEF=((WDEF+DEF*QR*5.39)/((QR+QW)*0.646))*0.1199                    00002600 R  0165
      DEF= (AKW/(AKA-AKW)*(EXP((-AKW/AU)*EX)-EXP((-AKA/AU)*EX)))*ALO     00002700 R  0175
     1      + DEF*EXP((-AKA/AU)*EX)                                      00002800 R  0181
      ALO=ALO*EXP((-AKW/AU)*EX)                                          00002900 R  0185
      CS=DOSAT(RTEMP)                                                             R  0188
      DO=CS-DEF                                                                   R  0190
      PRINT 129,ASTOP,ALO,DEF,DO                                         00003000 R  0191
   20 CONTINUE                                                           00003100 R  0208
   21 CONTINUE                                                           00003200 R  0209
C                                                                        00003300 R  0209
C        INITIALIZE ARRAYS FOR EACH SECTION                              00003400 R  0209
C                                                                        00003500 R  0209
      DO400I=1,20                                                        00003600 R  0209
      DO400J=1,20                                                        00003700 R  0214
      C1(I,J)=0.                                                         00003800 R  0220
      A(I,J)=0.                                                          00003900 R  0223
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      Q(I,J)=0.                                                         R  0226
      E(I,J)=0.                                                         R  0229
      B(I,J)=0.                                                         R  0231
      C(I,J)=0.                                                         R  0234
  400 DEOX(I,J)=0.                                                      R  0238
C                                                                       R  0240
C        READ IN (1) AVERAGE DEPTH IN FEET(H), (2) CROSS-SECTIONAL      R  0240
C        AREA IN SQUARE FEET(AREA), (3) FLOW IN CFS, (4) DISPERSION     R  0240
C        LBS PER DAY(W1), AND (6) BENTHAL DEMAND                        R  0240
C        ( IN GRAMS PER M**2 PER DAY(W2)                                R  0240
C                                                                       R  0240
      READ(5,50) (H(I), AREA(I),FLOW(I), D(I),W1(I),W2(I),AK1(I),TEMP   R  0241
     1(I),I=1,21)                                                       R  0268
   50 FORMAT(8E10.3)                                                    R  0280
      PRINT 777                                                         R  0280
  777 FORMAT("1",4X,"H",12X,"A",12X,"Q",12X,"D",12X,"W1",11X,"W2",11X   R  0284
     1"K1",9X,"TEMP",///)                                               R  0284
      PRINT 100, (H(I),AREA(I),FLOW(I),D(I),W1(I),W2(I),AK1(I),TEMP     R  0284
     1(I),I=1,21)                                                       R  0310
  100 FORMAT(8(3X,E10.3))                                               R  0322
C                                                                       R  0322
C                                                                       R  0322
C        CALCULATE VOLUME (V) FOR EACH SECTION(IN MILLIONS OF GALLONS)  R  0322
C                                                                       R  0322
      DO 3 I=1,20                                                       R  0322
      V(I)=((AREA(I)+AREA(I+1))/2.0)*0.0182                             R  0327
C                                                                       R  0334
C        CALCULATE AVERAGE VELOCITY(U) FOR EACH SECTION(IN FT PER SEC)  R  0334
C                                                                       R  0334
      U(I)=(FLOW(I)/AREA(I)+FLOW(I+1)/AREA(I+1))*0.5                    R  0336
C                                                                       R  0343
C        CALCULATE REAERATION COEFFICIENT(AK2) FOR EACH SECTION         R  0343
C                                                                       R  0343
    3 AK2(I)=12.9*U(I)**0.5/H(I)**1.5                                   R  0347
      DO 17 I=1,20                                                      R  0359
   17 W2(I)= (W2(I)/(H(I)*0.3048))*V(I)*8.34                            R  0365
C                                                                       R  0371
C        CALCULATE FLOW(IN MGD) AND BULK DISPERSION COEFFICIENTS(IN MGD) R  0371
C                                                                       R  0371
      DO 4 I=1,19                                                       R  0375
      Q(I,I+1) = FLOW(I+1)* 0.646                                       R  0380
    4 E(I,I+1)= D(I+1) *AREA(I+1)*0.1317                                R  0388
      Q01= FLOW(1)*0.646                                                R  0397
      Q2021= FLOW(21)*0.646                                             R  0400
      E01= D(1)*AREA (1)* 0.1317                                        R  0403
      E2021= D(21)*AREA(21)*0.1317                                      R  0407
C                                                                       R  0409
C        CALCULATE TRANSFER MATRICES FOR BOD(A) AND DO DEFICIT(B)       R  0409
C                                                                       R  0409
      DO 1 I=2,19                                                       R  0411
      A(I,I-1)=-0.5*Q(I-1,I)-E(I-1,I)                                   R  0417
      B(I,I-1)= A(I,I-1)                                                R  0428
      A(I,I)= 0.5*Q(I,I+1)-0.5*Q(I-1,I)+E(I-1,I)+E(I,I+1)+V(I)*AK1(I)   R  0433
      B(I,I)=0.5*Q(I,I+1)-0.5*Q(I-1,I)+E(I-1,I)+E(I,I+1)+V(I)*AK2(I)    R  0454
      A(I,I+1)= 0.5*Q(I,I+1)-E(I,I+1)                                   R  0475
    1 B(I,I+1)=A(I,I+1)                                                 R  0486
      A(1,1)=0.5*Q(1,2)-0.5*Q01+E01+E(1,2)+V(1)*AK1(1)                  R  0492
      B(1,1)=0.5*Q(1,2)-0.5*Q01+E01+E(1,2)+V(1)*AK2(1)                  R  0502
      A(1,2)= 0.5*Q(1,2)-E(1,2)                                         R  0512
      B(1,2)= A(1,2)                                                    R  0517
      A(20,19)=-0.5*Q(19,20) -E(19,20)                                  R  0518
      B(20,19)=A(20,19)                                                 R  0523
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      A(20,20)= 0.5*Q2021-0.5*Q(19,20)+E(19,20)+E2021+V(20)*AK1(20)      R  0524
      B(20,20)=0.5*Q2021-0.5*Q(19,20)+E(19,20)+E2021+V(20)*AK2(20)       R  0534
C                                                                        R  0542
C        CALCULATE DIAGONAL TRANSFER MATRIX FOR DEOXYGENATION(DEOX)      R  0542
C                                                                        R  0542
      DO 2 I=1,20                                                        R  0544
    2 DEOX(I,I)=V(I)*AK1(I)                                              R  0550
C        PRINT OUT THE (A) MATRIX                                        R  0553
C                                                                        R  0553
      PRINT 150                                                          R  0555
      PRINT 200                                                          R  0558
      DO5I=1,20                                                          R  0562
    5 PRINT 201, I,(A(I,J),J=1,10)                                       R  0568
      PRINT 202                                                          R  0588
      DO6I=1,20                                                          R  0592
    6 PRINT 201,I,(A(I,J),J=11,20)                                       R  0598
      PRINT 151                                                          R  0618
C                                                                        R  0618
C        PRINT OUT THE (B) MATRIX                                        R  0618
C                                                                        R  0618
      PRINT 200                                                          R  0622
      DO7I=1,20                                                          R  0625
    7 PRINT 201,I,(B(I,J),J=1,10)                                        R  0631
      PRINT 202                                                          R  0651
      DO 8I=1,20                                                         R  0655
    8 PRINT 201,I,(B(I,J),J=11,20)                                       R  0661
C                                                                        R  0677
C        PRINT OUT THE (DEOX) MATRIX                                     R  0677
C                                                                        R  0677
      PRINT 152                                                          R  0681
      PRINT 200                                                          R  0685
      DO9I=1,20                                                          R  0688
    9 PRINT 201,I,(DEOX(I,J),J=1,10)                                     R  0694
      PRINT 202                                                          R  0714
      DO10I=1,20                                                         R  0718
   10 PRINT 201,I,(DEOX(I,J),J=11,20)                                    R  0724
      NORDER=20                                                          R  0744
C                                                                        R  0744
C        INVERT THE (A) MATRIX                                           R  0744
C                                                                        R  0744
      CALL MIN(A,NORDER)                                                 R  0745
C                                                                        R  0746
C                                                                        R  0746
C        INVERT THE (B) MATRIX                                           R  0746
C                                                                        R  0746
      CALL MIN(B,NORDER)                                                 R  0747
C        PRINT OUT THE INVERSE (1/A)                                     R  0748
C                                                                        R  0748
      PRINT 153                                                          R  0748
      PRINT 200                                                          R  0752
C                                                                        R  0752
      DO11I=1,20                                                         R  0755
   11 PRINT 201,I,(A(I,J),J=1,10)                                        R  0762
      PRINT 202                                                          R  0782
      DO12I=1,20                                                         R  0786
   12 PRINT 201,I,(A(I,J),J=11,20)                                       R  0792
C                                                                        R  0808
C        PRINT OUT THE INVERSE (1/B)                                     R  0808
C                                                                        R  0808
      PRINT 156                                                          R  0812
      PRINT 200                                                          R  0816
      DO13I=1,20                                                         R  0819
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      PRINT 200                                                          00016200 R  0816
      DO13I=1,20                                                            ...00 R  0819

   13 PRINT 201,I,(B(I,J),J=1,10)                                        00016400 R  0825
      PRINT 202                                                          00016500 R  0845
      DO14I=1,20                                                         00016600 R  0849
   14 PRINT 201,I,(B(I,J),J=11,20)                                       00016700 R  0855
C                                                                        00016800 R  0871
C        BOUNDARY CORRECTION ROUTINE                                     00016900 R  0871
C                                                                        00017000 R  0871
      W1(1)= W1(1)+(0.5*Q01+E01)*ALD*8.345                               00017100 R  0875
      W2(1)= W2(1)+(0.5*Q01+E01)*DEF*8.345                               00017200 R  0884
      W1(20)=W1(20)+(-0.5*Q2021+E2021)*ALL*8.345                         00017300 R  0892
      W2(20)= W2(20)+(-0.5*Q2021+E2021)*DEFL*8.345                       00017400 R  0900
C                                                                        00017500 R  0904
C        CALCULATE THE COMPOUND STEADY STATE TRANSFER MATRIX (C)         00017600 R  0904
C                                                                        00017700 R  0904
      NCOLM=20                                                           00017800 R  0908
      CALL MMULT(A,B,C,NORDER,NORDER,NCOLM)                              00017900 R  0908
      CALL MMULT(C,DEOX,C1,NORDER,NORDER,NCOLM)                          00018000 R  0913
      PRINT 155                                                          00018100 R  0917
      PRINT 200                                                          00018200 R  0920
C                                                                        00018300 R  0920
C        TRANSFORM UNITS TO 10,000 LBS PER DAY INPUT/MG PER LITER OUTPUT00018400 R  0920
C                                                                        00018500 R  0920
      DO600I=1,20                                                        00018600 R  0924
      DO600J=1,20                                                        00018700 R  0929
  600 C2(I,J)=C1(I,J)*1199.                                              00018800 R  0936
C                                                                        00018900 R  0940
C        PRINT OUT (C)                                                   00019000 R  0940
C                                                                        00019100 R  0940
      DO15I=1,20                                                         00019200 R  0943
   15 PRINT 201,I,(C2(I,J),J=1,10)                                       00019300 R  0950
      PRINT 202                                                          00019400 R  0970
      DO16I=1,20                                                         00019500 R  0974
   16 PRINT 201,I,(C2(I,J),J=11,20)                                      00019600 R  0980
      NCOLM=1                                                            00019700 R  1000
C                                                                        00019800 R  1000
C        CALCULATE STEADY STATE BOD PROFILE(XL) IN UNITS OF MG/L         00019900 R  1000
C                                                                        00020000 R  1000
      CALL MMULT(A,W1,XL,NORDER,NORDER,NCOLM)                            00020100 R  1001
      DO410I=1,20                                                        00020200 R  1005
  410 XL(I)=XL(I)*0.1199                                                 00020300 R  1011
C                                                                        00020400 R  1013
C        CALCULATE STEADY STATE DO DEFICIT PROFILE (DOX)IN UNITS OF MG/L00020500 R  1013
C                                                                        00020600 R  1013
      CALL MMULT(C1,W1,W3,NORDER,NORDER,NCOLM)                           00020700 R  1016
      CALL MMULT(B,W2,W4,NORDER,NORDER,NCOLM)                            00020800 R  1020
                                                                         SEGMENT    1 IS 1023 LONG
                                                                  START OF SEGMENT **********   2
C                                                                        00020900 R  0002
C        PRINT OUT STEADY STATE PROFILES                                 00021000 R  0002
C                                                                        00021100 R  0002
      PRINT 154                                                          00021200 R  0002
      PRINT 203                                                          00021300 R  0006
      DO411I=1,20                                                        00021400 R  0009
      DOX=(W3(I)+W4(I))*0.1199                                           00021500 R  0015
      CS=14.652-0.41022*TEMP(I)+0.0079910*TEMP(I)**2.-0.000077774*       00021600 R  0020
     1TEMP(I)**3.                                                        00021700 R  0034
      CACT=CS-DOX                                                        00021800 R  0037
      ADUT=(6.0-I*0.3)+0.15                                              00021900 R  0038
  411 PRINT 101,ADUT,XL(I),DOX,CACT                                      00022000 R  0047
  200 FORMAT(1H ,"SECTION",8X,"1",11X,"2",11X,"3",11X,"4",11X,"5",11X,   00022100 R  0064
     1"6",11X,"7",11X,"8",11X,"9",11X,"10",//)                           00022200 R  0064
                                                                         SEGMENT    3 IS   26 LONG
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    1"6",11X,"7",11X,"8",11X,"9",11X,"10",//)                               00022200 R  0064
                                                                           SEGMENT    3 IS   26 LONG

 201 FORMAT(1H ,I5,4X,10E12.3)                                              00022300 R  0064
                                                                           SEGMENT    4 IS    5 LONG
 202 FORMAT(1H ,//,1H ,"SECTION",8X,"11",10X,"12",10X,"13",10X,"14",9X,00022400 R  0064
    1"15",11X,"16",11X,"17",11X,"18",11X,"19",11X,"20",//)                 00022500 R  0064
                                                                           SEGMENT    5 IS   28 LONG
 203 FORMAT(1H ,"MILE PT",7X,"BOD(MG/L)",6X,"DO DEFICIT",7X,"DO",///       00022600 R  0064
    1)                                                                      00022700 R  0064
 101  FORMAT(" ",F5.2,5X,E10.3,5X,E10.3,5X,E10.3)                           00022800 R  0064
 150  FORMAT("1",10X,"THIS IS THE TRANSFER MATRIX FOR BOD(A).",///)        00022900 R  0064
                                                                           SEGMENT    6 IS   11 LONG
 151  FORMAT("1",10X,"THIS IS THE TRANSFER MATRIX FOR DO DEFICIT (B).  V00023000 R  0064
    1ALUES ARE EXPRESSED IN UNITS OF MG/DAY",///)                          00023100 R  0064
                                                                           SEGMENT    7 IS   17 LONG
 152  FORMAT("1",10X,"THIS IS THE DIAGONAL MATRIX FOR DEOXYGENATION COEF00023200 R  0064
    1FICIENTS (DEOX). VALUES ARE EXPRESSED IN UNITS OF MG/DAY",///)        00023300 R  0064
                                                                           SEGMENT    8 IS   19 LONG
 153  FORMAT("1",9X,"THIS IS THE INVERSE OF (A).  UNITS ARE DAYS/MG.",//00023400 R  0064
    1/)                                                                     00023500 R  0064
                                                                           SEGMENT    9 IS   12 LONG
 156  FORMAT("1",9X,"THIS IS THE INVERSE OF (B).  UNITS ARE DAYS/MG.",//00023600 R  0064
    1/)                                                                     00023700 R  0064
                                                                           SEGMENT   10 IS   12 LONG
 155  FORMAT("1","THIS IS THE COMPOUND STEADY STATE MATRIX (C)=(1/A)*(1/00023800 R  0064
    1B)*(DEOX) RELATING THE RESPONSE IN DO DEFICIT(D) FOR ANY SECTION O00023900 R  0064
    1F THE RIVER",/1H ,"TO A UNIT WASTE DISCHARGE INTO ANY SECTION.  W 00024000 R  0064
    1ASTE DISCHARGE IS EXPRESSED IN UNITS OF 10,000 LBS/DAY AND DO DEFI00024100 R  0064
    1CIT IN MG/L",///1H ,"D RESPONSE",40X,"WASTE INPUT OF 10,000 LBS/DA00024200 R  0064
    1Y INTO SECTION",/,1H ,"IN MG/L IN",/)                                 00024300 R  0064
                                                                           SEGMENT   11 IS   54 LONG
 154  FORMAT("1",30X,"STEADY STATE CONCENTRATIONS OF BOD AND D",///)       00024400 R  0064
 999  CONTINUE                                                                      R  0064
      STOP                                                                  00024500 R  0065
      END                                                                   00024600 R  0066
                                                                           SEGMENT    2 IS  127 LONG
                                                                  START OF SEGMENT **********   12
      SUBROUTINE MMULT(X,Y,Z,L1,L2,L3)                                      00024700 R  0000
      DIMENSION X(20,20),Y(20,20),Z(20,20)                                  00024800 R  0000
      DO 10 I=1,L1                                                          00024900 R  0000
      DO 10 J=1,L3                                                          00025000 R  0005
      Z(I,J) =0.                                                            00025100 R  0011
      DO 10 K=1,L2                                                          00025200 R  0015
 10   Z(I,J)=Z(I,J)+X(I,K)*Y(K,J)                                           00025300 R  0021
      RETURN                                                                00025400 R  0033
      END                                                                   00025500 R  0036
                                                                           SEGMENT   12 IS   51 LONG
                                                                  START OF SEGMENT **********   13
      SUBROUTINE MIN(X,N)                                                   00025600 R  0000
      DIMENSION X(20,20),II(20,20)                                          00025700 R  0000
      DO 10 J=1,N                                                           00025800 R  0000
 10   II(J,3)=0                                                             00025900 R  0006
      DO 70 I=1,N                                                           00026000 R  0008
      XM=0.                                                                 00026100 R  0013
      DO 30 J=1,N                                                           00026200 R  0014
      IF (II(J,3 )-1)12,30,12                                               00026300 R  0019
 12   DO 20 K=1,N                                                           00026400 R  0024
      IF (II(K,3 )-1) 13,20,13                                              00026500 R  0029
 13   IF(XM-ABS(X(J,K)))14,20,20                                            00026600 R  0034
 14   IR=J                                                                  00026700 R  0040
      IC=K                                                                  00026800 R  0040
      XM=ABS(X(J,K))                                                        00026900 R  0041
 20   CONTINUE                                                              00027000 R  0045
 30   CONTINUE                                                              00027100 R  0046
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      XM=ABS(X(J,K))                                        00026900 R   0041
   20 CONTINUE                                              00027000 R   0045
   30 CONTINUE                                              00027100 R   0046

      II(IC,3 )=II(IC,3 )+1                                 00027200 R   0046
      II(I,1)=IR                                            00027300 R   0049
      II(I,2)=IC                                            00027400 R   0051
      IF(IR-IC)32,42,32                                     00027500 R   0053
   32 DO 40 IJ=1,N                                          00027600 R   0056
      DUM=X(IR,IJ)                                          00027700 R   0061
      X(IR,IJ)=X(IC,IJ)                                     00027800 R   0064
   40 X(IC,IJ)=DUM                                          00027900 R   0071
   42 P=X(IC,IC)                                            00028000 R   0075
      X(IC,IC)=1                                            00028100 R   0078
      DO 50 IJ=1,N                                          00028200 R   0081
   50 X(IC,IJ)=X(IC,IJ)/P                                   00028300 R   0087
      DO 70 IK=1,N                                          00028400 R   0093
      IF (IK-IC)52,70,52                                    00028500 R   0098
   52 C=X(IK,IC)                                            00028600 R   0102
      X(IK,IC)=0.                                           00028700 R   0105
      DO60IJ=1,N                                            00028800 R   0108
   60 X(IK,IJ)=X(IK,IJ)-X(IC,IJ)*C                          00028900 R   0114
   70 CONTINUE                                              00029000 R   0124
      DO 90 I=1,N                                           00029100 R   0125
      K=N+1-I                                               00029200 R   0130
      IF(II(K,1)-II(K,2))75,90,75                           00029300 R   0132
   75 IR=II(K,1)                                            00029400 R   0137
      IC=II(K,2)                                            00029500 R   0138
      DO 80 IJ=1,N                                          00029600 R   0140
      DUM=X(IJ,IR)                                          00029700 R   0145
      X(IJ,IR)=X(IJ,IC)                                     00029800 R   0148
      X(IJ,IC)=DUM                                          00029900 R   0154
   80 CONTINUE                                              00030000 R   0158
   90 CONTINUE                                              00030050 R   0159
      RETURN                                                00030100 R   0159
      END                                                   00030200 R   0162
                                                           SEGMENT    13 IS   175 LONG
                                                           SEGMENT    14 IS    78 LONG
                                                           SEGMENT    15 IS    29 LONG
                                                           SEGMENT    16 IS   138 LONG
                                                   START OF SEGMENT **********   17
                                                           SEGMENT    17 IS    11 LONG

NUMBER OF SYNTAX ERRORS DETECTED = 0.

PRT SIZE = 88;  TOTAL SEGMENT SIZE = 1816 WORDS;  DISK SIZE = 74 SEGS;  NO. PRGM. SEGS = 41.

ESTIMATED CORE STORAGE REQUIREMENT = 8512 WORDS;  COMPILATION TIME = 46 SECS;  NO. CARDS = 319.

FORTRAN/LISTING OF FORTRAN/CLEVLND/AWAR    AT 11:21:54    MONDAY 08/25/75  PROC. TIME =      19:40 I/O TIME =       19:33
```

OUTPUT INTERPRETATION

OUTPUT INTERPRETATION

1. Page 131 contains the table of system parameters and forcings (labeled) for the navigation channel. This will be page one of the output.

2. The matrix equations to be solved are:

$$(L) = [A]^{-1} (W)$$

$$(D) = [C] (W) + [B]^{-1} (Sb)$$

$$[C] = [B]^{-1} (V K_1) [A]^{-1}$$

Where (L) = steady state CBOD concentrations

$[A]$ = transfer matrix for CBOD

(W) = waste load vector for CBOD

(D) = steady state DO deficit concentrations

$[B]$ = transfer matrix for DO deficit

(Sb) = benthic uptake vector

$(V K_1)$ = deoxygenation diagonal matrix

$[C]$ = compound transfer matrix

Each of the pages of output are identified by a title. The compound steady state transfer matrix on page 139 can be utilized as a table for waste load allocation purpose. Note from the table that a waste load into Section 5 (mile point 4.65) of 10,000 lbs./day will produce a minimum DO value of 1.52 mg/l in section 15. (Read down column 5 to row 15.)

Page 140 lists the steady state concentrations of CBOD and DO.

SYSTEM PARAMETERS FOR THE NAVIGATION CHANNEL

SECTION	DEPTH (ft.)	AREA (ft.^{2})	FLOW (CFS)	DISP (mi^2/day)	W1 (lbs/day)	W2 (gm/m^2/day)	K1 (day^{-1})	TEMP (°C)
1	0.200E+02	0.300E+04	0.305E+03	0.250E+00	0.0	0.500E+01	0.150E+00	0.286E+02
2	0.200E+02	0.350E+04	0.305E+03	0.220E+00	1440	0.500E+01	0.150E+00	0.295E+02
3	0.250E+02	0.420E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.305E+02
4	0.250E+02	0.440E+04	0.345E+03	0.220E+00	300	0.500E+01	0.150E+00	0.307E+02
5	0.250E+02	0.430E+04	0.345E+03	0.220E+00	5880	0.500E+01	0.150E+00	0.309E+02
6	0.250E+02	0.900E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.311E+02
7	0.250E+02	0.470E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.314E+02
8	0.250E+02	0.510E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.314E+02
9	0.250E+02	0.490E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.312E+02
10	0.250E+02	0.550E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.311E+02
11	0.250E+02	0.740E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.309E+02
12	0.250E+02	0.420E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.306E+02
13	0.250E+02	0.900E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.304E+02
14	0.250E+02	0.620E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.302E+02
15	0.250E+02	0.620E+04	0.345E+03	0.220E+00	0.0	0.500E+01	0.150E+00	0.302E+02
16	0.250E+02	0.650E+04	0.345E+03	0.400E+00	0.0	0.500E+01	0.150E+00	0.295E+02
17	0.250E+02	0.650E+04	0.345E+03	0.600E+00	0.0	0.500E+01	0.150E+00	0.289E+02
18	0.250E+02	0.450E+04	0.345E+03	0.800E+00	0.0	0.500E+01	0.150E+00	0.286E+02
19	0.250E+02	0.700E+04	0.345E+03	0.100E+01	0.0	0.500E+01	0.150E+00	0.283E+02
20	0.250E+02	0.450E+04	0.345E+03	0.100E+01	0.0	0.500E+01	0.150E+00	0.280E+02
21	0.0	0.820E+04	0.345E+03	0.120E+01	0.0	0.0	0.0	0.0

PROGRAM OUTPUT

H	A	Q	D	W1	W2	K1	TEMP
0.200E+02	0.325E+04	0.850E+03	0.700E+00	0.0	0.500E+01	0.150E+00	0.236E+02
0.200E+02	0.350E+04	0.850E+03	0.600E+00	0.144E+04	0.500E+01	0.150E+00	0.275E+02
0.250E+02	0.420E+04	0.875E+03	0.520E+00	0.0	0.500E+01	0.150E+00	0.305E+02
0.250E+02	0.440E+04	0.875E+03	0.490E+00	0.510E+03	0.500E+01	0.150E+00	0.307E+02
0.250E+02	0.430E+04	0.900E+03	0.520E+00	0.999E+04	0.500E+01	0.150E+00	0.309E+02
0.250E+02	0.900E+04	0.900E+03	0.400E+00	0.0	0.500E+01	0.150E+00	0.311E+02
0.250E+02	0.470E+04	0.900E+03	0.480E+00	0.0	0.500E+01	0.150E+00	0.314E+02
0.250E+02	0.510E+04	0.900E+03	0.450E+00	0.160E+04	0.500E+01	0.150E+00	0.313E+02
0.250E+02	0.490E+04	0.900E+03	0.460E+00	0.0	0.500E+01	0.150E+00	0.312E+02
0.250E+02	0.550E+04	0.900E+03	0.410E+00	0.0	0.500E+01	0.150E+00	0.311E+02
0.250E+02	0.740E+04	0.900E+03	0.400E+00	0.0	0.500E+01	0.150E+00	0.309E+02
0.250E+02	0.420E+04	0.900E+03	0.530E+00	0.0	0.500E+01	0.150E+00	0.306E+02
0.250E+02	0.900E+04	0.900E+03	0.400E+00	0.0	0.500E+01	0.150E+00	0.304E+02
0.250E+02	0.620E+04	0.900E+03	0.400E+00	0.0	0.500E+01	0.150E+00	0.302E+02
0.250E+02	0.620E+04	0.900E+03	0.400E+00	0.0	0.500E+01	0.150E+00	0.302E+02
0.250E+02	0.650E+04	0.900E+03	0.600E+00	0.0	0.500E+01	0.150E+00	0.295E+02
0.250E+02	0.650E+04	0.900E+03	0.800E+00	0.0	0.500E+01	0.150E+00	0.289E+02
0.250E+02	0.450E+04	0.900E+03	0.100E+01	0.0	0.500E+01	0.150E+00	0.286E+02
0.250E+02	0.700E+04	0.900E+03	0.140E+01	0.0	0.500E+01	0.150E+00	0.283E+02
0.250E+02	0.750E+04	0.900E+03	0.180E+01	0.0	0.500E+01	0.150E+00	0.280E+02
0.0	0.820E+04	0.900E+03	0.220E+01	0.0	0.0	0.0	0.0

THIS IS THE TRANSFER MATRIX FOR BOD(A).

SECTION	1	2	3	4	5	6	7	8	9	10
1	.585E 03	-.165E 03	.0	.0	.0	.0	.0	.0	.0	.0
2	-.388E 03	.575E 03	-.176E 03	.0	.0	.0	.0	.0	.0	.0
3	.0	-.399E 03	.583E 03	-.173E 03	.0	.0	.0	.0	.0	.0
4	.0	.0	-.395E 03	.590E 03	-.183E 03	.0	.0	.0	.0	.0
5	.0	.0	.0	-.406E 03	.787E 03	-.363E 03	.0	.0	.0	.0
6	.0	.0	.0	.0	-.586E 03	.790E 03	-.186E 03	.0	.0	.0
7	.0	.0	.0	.0	.0	-.409E 03	.613E 03	-.191E 03	.0	.0
8	.0	.0	.0	.0	.0	.0	-.414E 03	.613E 03	-.185E 03	.0
9	.0	.0	.0	.0	.0	.0	.0	-.408E 03	.608E 03	-.186E 03
10	.0	.0	.0	.0	.0	.0	.0	.0	-.408E 03	.704E 03
11	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.501E 03
12	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
13	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
14	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
15	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
16	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
17	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
18	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
19	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
20	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0

SECTION	11	12	13	14	15	16	17	18	19	20
1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
2	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
3	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
4	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
6	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
7	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
8	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
9	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
10	-.278E 03	.0	.0	.0	.0	.0	.0	.0	.0	.0
11	.699E 03	-.182E 03	.0	.0	.0	.0	.0	.0	.0	.0
12	-.405E 03	.785E 03	-.363E 03	.0	.0	.0	.0	.0	.0	.0
13	.0	-.586E 03	.821E 03	-.215E 03	.0	.0	.0	.0	.0	.0
14	.0	.0	-.438E 03	.670E 03	-.215E 03	.0	.0	.0	.0	.0
15	.0	.0	.0	-.438E 03	.858E 03	-.402E 03	.0	.0	.0	.0
16	.0	.0	.0	.0	-.625E 03	.122E 04	-.573E 03	.0	.0	.0
17	.0	.0	.0	.0	.0	-.796E 03	.129E 04	-.481E 03	.0	.0
18	.0	.0	.0	.0	.0	.0	-.704E 03	.190E 04	-.118E 04	.0
19	.0	.0	.0	.0	.0	.0	.0	-.140E 04	.309E 04	-.167E 04
20	.0	.0	.0	.0	.0	.0	.0	.0	-.189E 04	.418E 04

THIS IS THE TRANSFER MATRIX FOR DO DEFICIT (B). VALUES ARE EXPRESSED IN UNITS OF MG/DAY

SECTION	1	2	3	4	5	6	7	8	9	10
1	.579E 03	-.165E 03	.0	.0	.0	.0	.0	.0	.0	.0
2	-.388E 03	.567E 03	-.176E 03	.0	.0	.0	.0	.0	.0	.0
3	.0	-.390E 03	.574E 03	-.173E 03	.0	.0	.0	.0	.0	.0
4	.0	.0	-.395E 03	.581E 03	-.183E 03	.0	.0	.0	.0	.0
5	.0	.0	.0	-.406E 03	.772E 03	-.363E 03	.0	.0	.0	.0
6	.0	.0	.0	.0	-.586E 03	.774E 03	-.186E 03	.0	.0	.0
7	.0	.0	.0	.0	.0	-.409E 03	.602E 03	-.191E 03	.0	.0
8	.0	.0	.0	.0	.0	.0	-.414E 03	.602E 03	-.185E 03	.0
9	.0	.0	.0	.0	.0	.0	.0	-.408E 03	.596E 03	-.186E 03
10	.0	.0	.0	.0	.0	.0	.0	.0	-.408E 03	.690E 03
11	.0	.0	.0	.0	.0	.0	.0	.0	.0	-.501E 03
12	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
13	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
14	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
15	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
16	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
17	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
18	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
19	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
20	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0

SECTION	11	12	13	14	15	16	17	18	19	20
1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
2	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
3	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
4	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
6	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
7	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
8	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
9	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
10	-.278E 03	.0	.0	.0	.0	.0	.0	.0	.0	.0
11	.686E 03	-.182E 03	.0	.0	.0	.0	.0	.0	.0	.0
12	-.405E 03	.770E 03	-.363E 03	.0	.0	.0	.0	.0	.0	.0
13	.0	-.586E 03	.804E 03	-.215E 03	.0	.0	.0	.0	.0	.0
14	.0	.0	-.438E 03	.654E 03	-.215E 03	.0	.0	.0	.0	.0
15	.0	.0	.0	-.438E 03	.843E 03	-.402E 03	.0	.0	.0	.0
16	.0	.0	.0	.0	-.625E 03	.120E 04	-.573E 03	.0	.0	.0
17	.0	.0	.0	.0	.0	-.796E 03	.128E 04	-.481E 03	.0	.0
18	.0	.0	.0	.0	.0	.0	-.704E 03	.189E 04	-.118E 04	.0
19	.0	.0	.0	.0	.0	.0	.0	-.140E 04	.307E 04	-.167E 04
20	.0	.0	.0	.0	.0	.0	.0	.0	-.189E 04	.416E 04

THIS IS THE DIAGONAL MATRIX FOR DEOXYGENATION COEFFICIENTS (DEOX). VALUES ARE EXPRESSED IN UNITS OF MG/DAY

SECTION	1	2	3	4	5	6	7	8	9	10
1	.921E 01	.0	.0	.0	.0	.0	.0	.0	.0	.0
2	.0	.105E 02	.0	.0	.0	.0	.0	.0	.0	.0
3	.0	.0	.117E 02	.0	.0	.0	.0	.0	.0	.0
4	.0	.0	.0	.119E 02	.0	.0	.0	.0	.0	.0
5	.0	.0	.0	.0	.182E 02	.0	.0	.0	.0	.0
6	.0	.0	.0	.0	.0	.187E 02	.0	.0	.0	.0
7	.0	.0	.0	.0	.0	.0	.134E 02	.0	.0	.0
8	.0	.0	.0	.0	.0	.0	.0	.137E 02	.0	.0
9	.0	.0	.0	.0	.0	.0	.0	.0	.142E 02	.0
10	.0	.0	.0	.0	.0	.0	.0	.0	.0	.176E 02
11	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
12	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
13	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
14	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
15	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
16	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
17	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
18	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
19	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
20	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0

SECTION	11	12	13	14	15	16	17	18	19	20
1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
2	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
3	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
4	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
6	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
7	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
8	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
9	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
10	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
11	.158E 02	.0	.0	.0	.0	.0	.0	.0	.0	.0
12	.0	.180E 02	.0	.0	.0	.0	.0	.0	.0	.0
13	.0	.0	.207E 02	.0	.0	.0	.0	.0	.0	.0
14	.0	.0	.0	.169E 02	.0	.0	.0	.0	.0	.0
15	.0	.0	.0	.0	.173E 02	.0	.0	.0	.0	.0
16	.0	.0	.0	.0	.0	.177E 02	.0	.0	.0	.0
17	.0	.0	.0	.0	.0	.0	.150E 02	.0	.0	.0
18	.0	.0	.0	.0	.0	.0	.0	.157E 02	.0	.0
19	.0	.0	.0	.0	.0	.0	.0	.0	.198E 02	.0
20	.0	.0	.0	.0	.0	.0	.0	.0	.0	.214E 02

THIS IS THE INVERSE OF (A). UNITS ARE DAYS/MG.

SECTION	1	2	3	4	5	6	7	8	9	10
1	.233E-02	.945E-03	.395E-03	.161E-03	.670E-04	.395E-04	.169E-04	.735E-05	.312E-05	.130E-05
2	.222E-02	.335E-02	.140E-02	.572E-03	.237E-03	.140E-03	.600E-04	.261E-04	.111E-04	.462E-05
3	.210E-02	.317E-02	.370E-02	.151E-02	.627E-03	.370E-03	.159E-03	.688E-04	.292E-04	.122E-04
4	.197E-02	.297E-02	.346E-02	.379E-02	.157E-02	.926E-03	.397E-03	.172E-03	.731E-04	.306E-04
5	.181E-02	.273E-02	.319E-02	.348E-02	.371E-02	.219E-02	.938E-03	.407E-03	.173E-03	.723E-04
6	.172E-02	.260E-02	.303E-02	.332E-02	.353E-02	.371E-02	.159E-02	.691E-03	.293E-03	.123E-03
7	.163E-02	.245E-02	.286E-02	.313E-02	.333E-02	.350E-02	.381E-02	.165E-02	.701E-03	.293E-03
8	.153E-02	.231E-02	.269E-02	.294E-02	.314E-02	.329E-02	.358E-02	.383E-02	.162E-02	.680E-03
9	.143E-02	.216E-02	.252E-02	.275E-02	.293E-02	.308E-02	.335E-02	.358E-02	.381E-02	.159E-02
10	.132E-02	.199E-02	.232E-02	.253E-02	.270E-02	.283E-02	.308E-02	.330E-02	.350E-02	.372E-02
11	.123E-02	.186E-02	.217E-02	.237E-02	.253E-02	.266E-02	.289E-02	.309E-02	.329E-02	.349E-02
12	.111E-02	.168E-02	.196E-02	.214E-02	.228E-02	.240E-02	.261E-02	.279E-02	.297E-02	.315E-02
13	.104E-02	.156E-02	.182E-02	.199E-02	.212E-02	.223E-02	.243E-02	.259E-02	.276E-02	.293E-02
14	.923E-03	.139E-02	.162E-02	.178E-02	.189E-02	.199E-02	.216E-02	.231E-02	.246E-02	.261E-02
15	.766E-03	.116E-02	.135E-02	.147E-02	.157E-02	.165E-02	.179E-02	.192E-02	.204E-02	.216E-02
16	.627E-03	.946E-03	.110E-02	.121E-02	.128E-02	.135E-02	.147E-02	.157E-02	.167E-02	.177E-02
17	.495E-03	.748E-03	.872E-03	.953E-03	.102E-02	.107E-02	.116E-02	.124E-02	.132E-02	.140E-02
18	.293E-03	.442E-03	.515E-03	.563E-03	.600E-03	.630E-03	.686E-03	.733E-03	.780E-03	.828E-03
19	.176E-03	.266E-03	.310E-03	.338E-03	.361E-03	.379E-03	.412E-03	.440E-03	.468E-03	.497E-03
20	.796E-04	.120E-03	.140E-03	.153E-03	.163E-03	.171E-03	.186E-03	.199E-03	.212E-03	.225E-03

SECTION	11	12	13	14	15	16	17	18	19	20
1	.679E-06	.275E-06	.159E-06	.694E-07	.283E-07	.149E-07	.848E-08	.343E-08	.173E-08	.691E-09
2	.241E-05	.976E-06	.562E-06	.246E-06	.100E-06	.528E-07	.301E-07	.121E-07	.614E-08	.245E-08
3	.636E-05	.258E-05	.148E-05	.650E-06	.265E-06	.140E-06	.794E-07	.321E-07	.162E-07	.647E-08
4	.159E-04	.646E-05	.372E-05	.163E-05	.663E-06	.349E-06	.199E-06	.804E-07	.406E-07	.162E-07
5	.376E-04	.153E-04	.879E-05	.385E-05	.157E-05	.826E-06	.470E-06	.190E-06	.959E-07	.383E-07
6	.638E-04	.259E-04	.149E-04	.652E-05	.266E-05	.140E-05	.796E-06	.322E-06	.163E-06	.649E-07
7	.153E-03	.620E-04	.357E-04	.156E-04	.636E-05	.335E-05	.191E-05	.771E-06	.389E-06	.155E-06
8	.354E-03	.144E-03	.827E-04	.362E-04	.147E-04	.777E-05	.442E-05	.179E-05	.902E-06	.360E-06
9	.829E-03	.336E-03	.194E-03	.847E-04	.345E-04	.182E-04	.103E-04	.418E-05	.211E-05	.843E-06
10	.194E-02	.786E-03	.453E-03	.198E-03	.807E-04	.425E-04	.242E-04	.977E-05	.494E-05	.197E-05
11	.369E-02	.150E-02	.861E-03	.377E-03	.153E-03	.809E-04	.460E-04	.186E-04	.939E-05	.375E-05
12	.333E-02	.358E-02	.206E-02	.903E-03	.368E-03	.194E-03	.110E-03	.446E-04	.225E-04	.898E-05
13	.309E-02	.333E-02	.351E-02	.153E-02	.625E-03	.329E-03	.187E-03	.757E-04	.383E-04	.153E-04
14	.276E-02	.297E-02	.312E-02	.340E-02	.139E-02	.730E-03	.415E-03	.168E-03	.848E-04	.338E-04
15	.229E-02	.246E-02	.259E-02	.282E-02	.304E-02	.160E-02	.912E-03	.369E-03	.186E-03	.743E-04
16	.187E-02	.202E-02	.212E-02	.231E-02	.249E-02	.262E-02	.149E-02	.603E-03	.305E-03	.122E-03
17	.148E-02	.159E-02	.168E-02	.182E-02	.197E-02	.207E-02	.217E-02	.877E-03	.443E-03	.177E-03
18	.875E-03	.941E-03	.991E-03	.108E-02	.116E-02	.123E-02	.128E-02	.136E-02	.686E-03	.274E-03
19	.525E-03	.565E-03	.595E-03	.648E-03	.699E-03	.736E-03	.771E-03	.816E-03	.841E-03	.336E-03
20	.238E-03	.256E-03	.260E-03	.293E-03	.316E-03	.333E-03	.349E-03	.360E-03	.380E-03	.391E-03

THIS IS THE INVERSE OF (B). UNITS ARE DAYS/MG.

SECTION	1	2	3	4	5	6	7	8	9	10
1	.240E-02	.101E-02	.441E-03	.190E-03	.844E-04	.518E-04	.233E-04	.106E-04	.475E-05	.212E-05
2	.237E-02	.354E-02	.155E-02	.666E-03	.296E-03	.182E-03	.816E-04	.372E-04	.166E-04	.743E-05
3	.235E-02	.350E-02	.401E-02	.173E-02	.767E-03	.471E-03	.211E-03	.964E-04	.431E-04	.192E-04
4	.232E-02	.346E-02	.396E-02	.420E-02	.187E-02	.115E-02	.515E-03	.235E-03	.105E-03	.468E-04
5	.228E-02	.341E-02	.390E-02	.414E-02	.426E-02	.262E-02	.118E-02	.536E-03	.240E-03	.107E-03
6	.226E-02	.338E-02	.386E-02	.410E-02	.423E-02	.429E-02	.193E-02	.878E-03	.393E-03	.175E-03
7	.224E-02	.334E-02	.382E-02	.405E-02	.418E-02	.424E-02	.432E-02	.197E-02	.882E-03	.393E-03
8	.221E-02	.330E-02	.377E-02	.401E-02	.413E-02	.419E-02	.427E-02	.433E-02	.194E-02	.866E-03
9	.218E-02	.325E-02	.372E-02	.395E-02	.407E-02	.413E-02	.421E-02	.427E-02	.433E-02	.193E-02
10	.214E-02	.319E-02	.365E-02	.388E-02	.400E-02	.405E-02	.413E-02	.420E-02	.425E-02	.430E-02
11	.210E-02	.314E-02	.359E-02	.381E-02	.393E-02	.398E-02	.406E-02	.412E-02	.418E-02	.423E-02
12	.204E-02	.304E-02	.347E-02	.369E-02	.380E-02	.386E-02	.393E-02	.399E-02	.404E-02	.409E-02
13	.198E-02	.295E-02	.338E-02	.358E-02	.369E-02	.375E-02	.382E-02	.388E-02	.393E-02	.398E-02
14	.185E-02	.276E-02	.315E-02	.335E-02	.345E-02	.350E-02	.357E-02	.362E-02	.367E-02	.371E-02
15	.161E-02	.240E-02	.274E-02	.291E-02	.300E-02	.305E-02	.311E-02	.315E-02	.319E-02	.323E-02
16	.136E-02	.202E-02	.232E-02	.246E-02	.253E-02	.257E-02	.262E-02	.266E-02	.270E-02	.273E-02
17	.109E-02	.163E-02	.186E-02	.198E-02	.204E-02	.207E-02	.211E-02	.214E-02	.217E-02	.219E-02
18	.655E-03	.978E-03	.112E-02	.119E-02	.122E-02	.124E-02	.127E-02	.129E-02	.130E-02	.132E-02
19	.397E-03	.592E-03	.678E-03	.720E-03	.742E-03	.752E-03	.767E-03	.779E-03	.789E-03	.798E-03
20	.180E-03	.269E-03	.308E-03	.327E-03	.337E-03	.342E-03	.349E-03	.354E-03	.358E-03	.363E-03

SECTION	11	12	13	14	15	16	17	18	19	20
1	.116E-05	.503E-06	.303E-06	.139E-06	.593E-07	.322E-07	.187E-07	.766E-08	.390E-08	.157E-08
2	.406E-05	.176E-05	.106E-05	.487E-06	.208E-06	.113E-06	.654E-07	.269E-07	.137E-07	.549E-08
3	.105E-04	.457E-05	.275E-05	.126E-05	.539E-06	.293E-06	.169E-06	.696E-07	.355E-07	.142E-07
4	.256E-04	.111E-04	.669E-05	.307E-05	.131E-05	.713E-06	.412E-06	.169E-06	.863E-07	.346E-07
5	.584E-04	.254E-04	.153E-04	.702E-05	.300E-05	.163E-05	.943E-06	.387E-06	.197E-06	.791E-07
6	.957E-04	.416E-04	.250E-04	.115E-04	.491E-05	.267E-05	.154E-05	.634E-06	.323E-06	.130E-06
7	.215E-03	.934E-04	.562E-04	.258E-04	.110E-04	.590E-05	.346E-05	.142E-05	.725E-06	.291E-06
8	.473E-03	.205E-03	.124E-03	.568E-04	.243E-04	.132E-04	.762E-05	.313E-05	.160E-05	.640E-06
9	.105E-02	.458E-03	.276E-03	.127E-03	.541E-04	.294E-04	.170E-04	.698E-05	.356E-05	.143E-05
10	.235E-02	.102E-02	.614E-03	.282E-03	.120E-03	.654E-04	.379E-04	.156E-04	.793E-05	.318E-05
11	.427E-02	.186E-02	.112E-02	.513E-03	.219E-03	.119E-03	.689E-04	.283E-04	.144E-04	.578E-05
12	.413E-02	.419E-02	.252E-02	.116E-02	.494E-03	.269E-03	.155E-03	.638E-04	.325E-04	.130E-04
13	.401E-02	.407E-02	.411E-02	.189E-02	.806E-03	.438E-03	.253E-03	.104E-03	.530E-04	.213E-04
14	.375E-02	.380E-02	.384E-02	.390E-02	.166E-02	.904E-03	.523E-03	.215E-03	.110E-03	.439E-04
15	.326E-02	.331E-02	.334E-02	.339E-02	.343E-02	.187E-02	.108E-02	.443E-03	.226E-03	.906E-04
16	.275E-02	.279E-02	.282E-02	.286E-02	.290E-02	.292E-02	.169E-02	.695E-03	.354E-03	.142E-03
17	.221E-02	.224E-02	.227E-02	.230E-02	.233E-02	.235E-02	.237E-02	.973E-03	.496E-03	.199E-03
18	.133E-02	.135E-02	.136E-02	.138E-02	.140E-02	.141E-02	.142E-02	.144E-02	.733E-03	.294E-03
19	.806E-03	.817E-03	.825E-03	.837E-03	.848E-03	.856E-03	.863E-03	.872E-03	.876E-03	.351E-03
20	.366E-03	.371E-03	.375E-03	.380E-03	.386E-03	.389E-03	.392E-03	.396E-03	.398E-03	.400E-03

THIS IS THE COMPOUND STEADY STATE MATRIX (C)=(1/A)*(1/B)*(DEOX) RELATING THE RESPONSE IN DO DEFICIT(D) FOR ANY SECTION OF THE RIVER TO A UNIT WASTE DISCHARGE INTO ANY SECTION. WASTE DISCHARGE IS EXPRESSED IN UNITS OF 10,000 LBS/DAY AND DO DEFICIT IN MG/L

D RESPONSE IN MG/L IN	WASTE INPUT OF 10,000 LBS/DAY INTO SECTION									
SECTION	1	2	3	4	5	6	7	8	9	10
1	0.328E-01	0.265E-03	0.385E-05	0.116E-07	0.145E-09	0.406E-10	0.364E-12	0.812E-14	0.979E-16	0.143E-17
2	0.634E-01	0.388E-01	0.745E-03	0.251E-05	0.339E-07	0.974E-08	0.898E-10	0.204E-11	0.250E-13	0.371E-15
3	0.936E-01	0.756E-01	0.433E-01	0.193E-03	0.297E-05	0.894E-06	0.858E-08	0.201E-09	0.251E-11	0.379E-13
4	0.119E+00	0.108E+00	0.618E-01	0.414E-01	0.881E-03	0.289E-03	0.296E-05	0.723E-07	0.929E-09	0.144E-10
5	0.150E+00	0.147E+00	0.127E+00	0.888E-01	0.761E-01	0.301E-01	0.347E-03	0.904E-05	0.121E-06	0.193E-08
6	0.169E+00	0.170E+00	0.154E+00	0.118E+00	0.122E+00	0.786E-01	0.110E-02	0.310E-04	0.435E-06	0.716E-08
7	0.194E+00	0.201E+00	0.190E+00	0.155E+00	0.181E+00	0.141E+00	0.475E-01	0.182E-02	0.292E-04	0.522E-06
8	0.218E+00	0.231E+00	0.224E+00	0.191E+00	0.237E+00	0.201E+00	0.917E-01	0.483E-01	0.102E-02	0.207E-04
9	0.242E+00	0.260E+00	0.258E+00	0.226E+00	0.292E+00	0.259E+00	0.135E+00	0.938E-01	0.499E-01	0.136E-02
10	0.266E+00	0.290E+00	0.292E+00	0.262E+00	0.350E+00	0.320E+00	0.181E+00	0.142E+00	0.102E+00	0.690E-01
11	0.284E+00	0.312E+00	0.318E+00	0.289E+00	0.393E+00	0.366E+00	0.215E+00	0.179E+00	0.141E+00	0.119E+00
12	0.307E+00	0.341E+00	0.352E+00	0.325E+00	0.450E+00	0.426E+00	0.261E+00	0.227E+00	0.194E+00	0.187E+00
13	0.320E+00	0.358E+00	0.372E+00	0.347E+00	0.485E+00	0.463E+00	0.289E+00	0.257E+00	0.227E+00	0.229E+00
14	0.339E+00	0.381E+00	0.399E+00	0.375E+00	0.529E+00	0.510E+00	0.324E+00	0.295E+00	0.267E+00	0.281E+00
15	0.355E+00	0.402E+00	0.424E+00	0.402E+00	0.574E+00	0.559E+00	0.361E+00	0.335E+00	0.311E+00	0.339E+00
16	0.358E+00	0.407E+00	0.432E+00	0.412E+00	0.591E+00	0.579E+00	0.379E+00	0.355E+00	0.334E+00	0.371E+00
17	0.341E+00	0.369E+00	0.414E+00	0.396E+00	0.571E+00	0.561E+00	0.369E+00	0.348E+00	0.331E+00	0.371E+00
18	0.257E+00	0.294E+00	0.313E+00	0.300E+00	0.435E+00	0.428E+00	0.284E+00	0.269E+00	0.258E+00	0.291E+00
19	0.176E+00	0.202E+00	0.215E+00	0.207E+00	0.300E+00	0.296E+00	0.196E+00	0.187E+00	0.179E+00	0.203E+00
20	0.882E-01	0.101E+00	0.108E+00	0.104E+00	0.150E+00	0.148E+00	0.986E-01	0.938E-01	0.902E-01	0.102E+00

SECTION	11	12	13	14	15	16	17	18	19	20
1	0.201E-18	0.165E-20	0.304E-21	0.152E-22	0.955E-24	0.273E-24	0.889E-25	0.239E-25	0.131E-25	0.511E-26
2	0.524E-16	0.276E-18	0.805E-19	0.407E-20	0.256E-21	0.736E-22	0.240E-22	0.648E-23	0.355E-23	0.138E-23
3	0.541E-14	0.289E-16	0.847E-17	0.431E-18	0.273E-19	0.789E-20	0.258E-20	0.698E-21	0.383E-21	0.150E-21
4	0.208E-11	0.113E-13	0.333E-14	0.171E-15	0.109E-16	0.318E-17	0.104E-17	0.283E-18	0.155E-18	0.607E-19
5	0.284E-09	0.157E-11	0.469E-12	0.243E-13	0.157E-14	0.459E-15	0.151E-15	0.412E-16	0.227E-16	0.885E-17
6	0.107E-08	0.503E-11	0.162E-11	0.950E-13	0.620E-14	0.182E-14	0.603E-15	0.164E-15	0.907E-16	0.354E-16
7	0.813E-07	0.475E-09	0.146E-09	0.777E-11	0.516E-12	0.153E-12	0.510E-13	0.140E-13	0.774E-14	0.303E-14
8	0.339E-05	0.208E-07	0.652E-08	0.354E-09	0.240E-10	0.720E-11	0.241E-11	0.666E-12	0.369E-12	0.144E-12
9	0.246E-03	0.163E-05	0.526E-06	0.294E-07	0.204E-08	0.621E-09	0.210E-09	0.583E-10	0.324E-10	0.127E-10
10	0.156E-01	0.118E-03	0.400E-04	0.232E-05	0.167E-06	0.517E-07	0.177E-07	0.495E-08	0.276E-08	0.108E-08
11	0.619E-01	0.603E-03	0.219E-03	0.134E-04	0.100E-05	0.318E-06	0.110E-06	0.311E-07	0.174E-07	0.684E-08
12	0.125E+00	0.760E-01	0.341E-01	0.236E-02	0.191E-03	0.632E-04	0.223E-04	0.640E-05	0.360E-05	0.142E-05
13	0.165E+00	0.123E+00	0.901E-01	0.749E-02	0.666E-03	0.229E-03	0.822E-04	0.239E-04	0.136E-04	0.536E-05
14	0.213E+00	0.181E+00	0.158E+00	0.656E-01	0.792E-02	0.301E-02	0.113E-02	0.340E-03	0.194E-03	0.773E-04
15	0.267E+00	0.246E+00	0.236E+00	0.133E+00	0.803E-01	0.370E-01	0.149E-01	0.468E-02	0.272E-02	0.109E-02
16	0.299E+00	0.286E+00	0.286E+00	0.178E+00	0.130E+00	0.914E-01	0.408E-01	0.136E-01	0.805E-02	0.325E-02
17	0.303E+00	0.295E+00	0.301E+00	0.196E+00	0.154E+00	0.119E+00	0.680E-01	0.252E-01	0.154E-01	0.630E-02
18	0.239E+00	0.238E+00	0.246E+00	0.165E+00	0.135E+00	0.111E+00	0.704E-01	0.407E-01	0.275E-01	0.116E-01
19	0.168E+00	0.168E+00	0.174E+00	0.118E+00	0.985E-01	0.826E-01	0.540E-01	0.344E-01	0.273E-01	0.122E-01
20	0.847E-01	0.848E-01	0.884E-01	0.603E-01	0.506E-01	0.428E-01	0.283E-01	0.187E-01	0.157E-01	0.834E-02

STEADY STATE CONCENTRATIONS OF BOD AND D

MILE PT	BOD(MG/L)	DO DEFICIT	DO
5.85	0.886E+01	0.430E+01	0.410E+01
5.55	0.875E+01	0.438E+01	0.341E+01
5.25	0.857E+01	0.458E+01	0.279E+01
4.95	0.828E+01	0.465E+01	0.269E+01
4.65	0.995E+01	0.499E+01	0.232E+01
4.35	0.971E+01	0.520E+01	0.208E+01
4.05	0.949E+01	0.545E+01	0.179E+01
3.75	0.959E+01	0.569E+01	0.156E+01
3.45	0.936E+01	0.594E+01	0.133E+01
3.15	0.906E+01	0.622E+01	0.107E+01
2.85	0.885E+01	0.642E+01	0.890E+00
2.55	0.851E+01	0.672E+01	0.638E+00
2.25	0.828E+01	0.691E+01	0.474E+00
1.95	0.804E+01	0.713E+01	0.280E+00
1.65	0.772E+01	0.735E+01	0.640E-01
1.35	0.743E+01	0.738E+01	0.132E+00
1.05	0.718E+01	0.712E+01	0.474E+00
0.75	0.671E+01	0.588E+01	0.175E+01
0.45	0.641E+01	0.465E+01	0.303E+01
0.15	0.617E+01	0.323E+01	0.450E+01

R E S T R I C T I O N S

R E S T R I C T I O N S

The major restriction placed upon this model is that for every section interface the relationship

$$0.5\,Q - E' < 0$$

must hold true, where E' = D *AREA* 0.1317. Where this restriction is not true, results will not be valid.

Computer time for one simulation on an IBM-360/70 is approximately 30 seconds. This includes compilation and run time.

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(Please read Instructions on the reverse before completing)

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16. ABSTRACT A computer model is developed to rapidly simulate dissolved oxygen content in the Cuyahoga River under varying conditions of flow and biochemical oxygen demand. It is composed of three separate models: Model I is based upon Streeter-Phelps equations (Streeter and Phelps, 1925); Model II is a revised and expanded version of the Delaware Estuary finite difference model (Thomann, 1972); and Model III is a time-variant model. These models, which have been used to simulate present and projected dissolved oxygen levels for the entire length of the Cuyahoga River, show that the municipal and industrial treatment programs to be implemented by 1978 will result in improved dissolved oxygen conditions in the Cuyahoga River. However, run-off and benthic oxygen demand will still result in a severe oxygen sag in the navigation channel during summer low flows.

Programming is in FORTRAN IV (level G) language and is compatible with the IBM 360/70 system. The program requires 20 K storage. A flow chart and explanations for the model's routines and detailed in Appendix C.

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17. KEY WORDS AND DOCUMENT ANALYSIS

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	Lake Erie	
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Water Quality, Models	Great Lakes	8H
	Chemical Parameters	

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