A BARGAINING APPROACH FOR PROGRAMMING

LEAST-COST WASTE TREATMENT

ALONG A RIVER

by

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The work upon which this publication is based was supported in part by funds provided by the Office of Water Research and Technology, U. S. Department of the Interior, through the Water Resources Research Institute of The University of North Carolina as authorized under the Water Resources Act of 1964, as amended, and by the North Carolina Agricultural Experiment Station.

Project No. B-054-NC
Agreement No. 14-31-0001-3952

July 1975
ACKNOWLEDGMENTS

The authors want to express appreciation to Mr. Paul Wagner of the Environmental Protection Agency and to personnel in the Division of Environmental Management, N. C. Department of Natural and Economic Resources, for providing the data and constructive criticism of the results.
A model is developed for minimizing waste treatment costs to achieve a given stream standard. An optimum set of treatment levels is calculated using available information about the cost of waste treatment and the effects of waste in different reaches with an assumed procedure for bargaining among waste dischargers. Each discharger is assumed to be responsible for the quality of water in his reach. The optimum solution suggests an optimum set of discharge permits and charges. However, it does not favor any one administrative system or distribution of costs.

The model is run to find optimum or least-cost waste treatment levels for the Neuse River of North Carolina. The optimum solution has much less treatment than is currently being used. The costs of present waste treatment are estimated to be $3.7 million per year while the cost of the optimum set of treatment levels is only $1.09 million.
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SUMMARY AND CONCLUSIONS

The model developed in this study minimizes the cost of waste treatment to achieve certain dissolved oxygen standards. The model uses the idea of bargaining among waste dischargers and assumes that each is responsible for the oxygen level in his own reach. Through the bargaining process, each waste discharger tries to reduce his own treatment level by buying treatment levels from upstream users unless he finds it cheaper to treat himself. In this way, a set of treatment levels giving minimum costs is found.

The model also makes it possible to compare the costs of optimum and non-optimum systems. The model is applied to data from the Neuse River, North Carolina. It is assumed that treatment costs depend only upon the volume of wastewater treated and are the same for each waste discharger. Out of the 17 points of discharge where wastes are now being treated at a secondary level or higher, the optimum solution recommends primary treatment at one point, secondary treatment at four points, and tertiary treatment at two points. The difference in cost between present and optimum sets of treatment levels is 2.6 million per year in 1963 dollars. The model was run using data for 10-year low-flow conditions. Hence, it gives a conservative set of treatment levels that are needed to satisfy the dissolved oxygen requirements.

The optimum solution gives the marginal costs and treatment levels in each reach. Assuming that each waste discharger would remove all the wastes himself as long as his marginal cost was lower than a stream charge, then the marginal costs obtained from the model would also suggest an optimum set of charges. Similarly, results of this optimization model can be used to recommend a set of waste treatment levels (input specifications) or a set of effluent permits.

Government may adopt arbitrary rules such as requiring secondary treatment of all wastes because of lack of good data for calculating the effects of wastes and obtaining least-cost systems for managing rivers. However, with good data and a good optimization model, an administrator should be able to prescribe a variety of treatment levels and back-up his decisions. One might expect that further improvement of models of the type presented here will eventually result in legislation which permits more sophisticated systems of water quality management.
RECOMMENDATIONS

In the present model, many simplifying assumptions are made. This model can be refined in several ways to achieve better results:

a. Current stream standards have other dimensions besides dissolved oxygen; for example, coliform count, toxicity and turbidity. Including these other dimensions should lead to a more refined and acceptable set of recommended treatments.

b. Use of continuous cost curves and both long-run cost curves and short-range planning curves which assume existing facilities would make the results more useful and suggest a fairer set of charges and treatment levels.

c. Other factors affecting oxygen, such as benthal demand and photosynthesis, could be included to improve water prediction.

d. The effect of flow augmentation, reservoirs, falls, and in-stream aeration on water quality could be included in the model.

e. Optimum location of new waste treatment plants and the piping of treated wastes to points where waste assimilative capacities are higher could be included.

f. The model could be expanded to include calculation of how much more waste could be discharged into the river without violating the stream standards.
INTRODUCTION

The demand for higher stream standards is based upon increasing recreational needs and higher standards of living. Rapid industrial growth and increases in wage rates have resulted in many waste products of a complex nature. Ever higher levels of waste treatment seem to be needed to meet the higher stream standards. It is important to consider ways and means of minimizing waste treatment costs.

Recently, engineers and economists, including Johnson (1967) and Liebman and Lynn (1966), Macaulay (1970) and Thomann (1972) have become interested in the question of determining optimum stream standards. These occur where marginal costs of waste treatment are equal to the associated marginal benefits to downstream people of improved water quality. But, difficulties in measuring downstream benefits make it impractical to determine optimum stream standards. Also, high transactions costs among the many parties who are using a river render the determination of optimum levels through markets or bargaining unlikely. So, the most common alternative has been to accept stream standards developed by regulatory agencies and adopted after public hearings.

The purpose of this report is to report a model developed by Airan (1973) which can be used to find the least-cost combination of waste treatment levels in different plants along a river to achieve certain stream standards.

Various administrative systems have been suggested to meet predetermined stream standards. One system is to specify the inputs (treatment levels). These input requirements can be different for each user or uniform for everyone. Uniform input specifications have low administrative costs and may seem fair but, in reality, they are likely to be unfair to many and have high total costs.

Another administrative system is to grant permitted levels of specific effluents to each user. Typically, these permits are based on levels established in the past and are not transferable. However, users could be allowed to transfer these permits which would be valid for some defined period and some specified reach of the river. Initially, permits could be given to former users and, subsequently, permits could be sold by the state through competitive bidding. If transfers are not allowed, then effluent permits would need to be distributed on some efficiency grounds, taking into account the output, needs, and expansion of plants.
A third method of rationing the river's waste assimilative capacity is to charge for the waste discharged above permitted levels of effluents. These charges can be raised or lowered in order to achieve the required stream standards. If charges are the same for each reach, they will be unfair and have a higher total cost than is necessary. A fairer system would be to charge everyone according to the effect of their waste on the river. Johnson (1967) and Thomann (1972) consider charges to be an efficient and low-cost administrative system. Macaulay (1970) has favored charging downstream as well as upstream users because neither party is really to blame for the increased scarcity of the river's waste assimilative capacity.

Subsidies can also be used as an incentive for the users to reduce their wastes. According to Haskin (1970), subsidies would be less effective and more expensive than any other system. Here again, Macaulay (1970) suggests that if subsidies are given to downstream recipients, they should also be given to upstream users.

One more administrative system is to hold each user responsible for the water quality in his own reach. Mar (1971) has advocated such a system with the added feature that downstream users should be free to bargain with upstream users by paying them to adopt higher standards or to treat their wastes to a higher level.

A number of mathematical techniques have been used to solve the problem of obtaining least-cost sets of waste treatment systems. The decision process is of a sequential nature since the decision function in a downstream reach depends upon the output functions of the previous reach. Thomann (1972), Frankel (1965), and Johnson (1967) used linear programming to reach the optimum solution. They approximated a non-linear cost function by straight-line segments. To avoid the linear approximation of response and cost curves, Bayer (1972) solved this problem with a non-linear objective function and linear constraints, using a differential algorithm. Liebman and Lynn (1966) used dynamic programming and defined cost curves in tabular form.

**EXPLANATION OF THE MODEL**

The work presented here describes a mathematical technique similar to reactive programming Tramel, (1959) for solving this sequential problem using discrete cost curves in the objective function. The model uses the idea of bargaining (transfers) among users, each of whom is responsible for stream
standards in his own reach. Taking each reach in turn, the computer checks all the upstream reaches to find the one which has the minimum cost of increasing dissolved oxygen in that downstream reach. In contrast, the dynamic programming model used by Liebman and Lynn investigates the combinations of treatment levels in the previous reach only.

In reactive programming, a form of non-linear programming, one may go through many iterations to reach an approximate optimum point because a change in the decision function at any one location can change the prices at all other locations. But, in the model being presented, a decrease in treatment at any reach cannot cause a violation of standards upstream. Therefore, the computer routine reaches the optimum solution on the second iteration. The first iteration merely uses the present treatment levels as a starting solution and calculates the costs and dissolved oxygen levels.

The model cannot reach an optimum solution without being able to predict the effect on water quality downstream of any change in concentration of waste upstream. Organic wastes discharged in a river affect its water quality by depleting its dissolved oxygen, DO, content. The reduction in oxygen is caused mainly because of the exertion of carbonaceous biochemical oxygen demand, BOD, and nitrogenous biochemical oxygen demand, NOD. Natural reaeration from the atmosphere is the most important source of DO.

A dissolved oxygen profile of the river is predicted by using the relationship between pollutants and stream environment given by Streeter and Phelps (1925). They expressed the net change in DO deficit as

\[
\frac{dD}{dt} = K_1 L_a - K_2 D_a
\]

where \( D \) = dissolved oxygen saturation deficit \( (C_s - C) \) at any time in parts per million, ppm, 
\( C_s \) = dissolved oxygen saturation level in ppm, 
\( C \) = dissolved oxygen concentration in ppm, 
\( L_a \) = ultimate carbonaceous biochemical oxygen demand in ppm, 
\( D_a \) = dissolved oxygen deficit in the beginning of a reach, 
\( K_1 \) = deoxygenation coefficient to the base \( e \), day\(^{-1}\), and 
\( K_2 \) = reaeration coefficient to the base \( e \), day\(^{-1}\).

Equation (1), explained by Streeter and Phelps, does not include the NOD reaction term, \(-K N_a\). This term is added to equation (1) to get net rate of change in DO deficit as a sum of deoxygenation due to BOD and NOD and to reaeration.
Integrating equation (1) augmented and solving at the beginning of the reach where $t=0$, and at the end of the reach where $t=t$, one can obtain

$$D_b = \frac{K_1 L_a}{K_2 - K_1} (e^{-K_1 t} - e^{-K_2 t}) + \frac{K_3 N_a}{K_2 - K_3} (e^{-K_3 t} - e^{-K_2 t}) + D_a e^{-K_2 t},$$  

where $D_a$ = dissolved oxygen deficit in the beginning of the reach in ppm,

$D_b$ = dissolved oxygen deficit at the end of the reach in ppm,

$L_a$ = ultimate BOD concentration in the beginning of the reach in ppm,

$N_a$ = NOD concentration in the beginning of the reach in ppm,

$K_1$ = deoxygenation rate for carbonaceous biochemical oxygen demand to the base $e$ per day,

$K_2$ = reaeration coefficient to the base $e$ per day, and

$K_3$ = deoxygenation rate for nitrogenous biochemical oxygen demand to the base $e$ per day.

A typical DO sag curve is shown in Figure 1.

BOD and NOD at the end of each reach are calculated from the following integrated forms of rate of deoxygenation of BOD, i.e., $-K_1 L$, and rate of deoxygenation of NOD, $-K_3 N$:

$$L_b = L_a e^{-K_1 t}$$  

$$N_b = N_a e^{-K_3 t}$$

where $L_b$ = ultimate BOD concentration at the end of a reach in ppm, and

$N_b$ = NOD concentration at the end of a reach in ppm.

In the present model, equations (2), (3), and (4) are changed to the logarithmic base 10.

The river is divided into different reaches in such a way that waste is discharged only at the head of each reach. Users are prohibited from piping their wastes to the next reach. Each waste discharger is responsible for the water quality in his whole reach and has two alternative ways of doing it. He can change his own treatment level or ask (or bribe) some upstream discharger to increase his treatment level. In the 5th reach, for example, if the water quality constraint is not met, there will be an investigation so as to find which upstream reach has the minimum marginal cost of increasing the DO level in reach 5. To calculate this marginal cost, one needs to know the increase
Oxygen supplied by reaeration

Deficit and deoxygenation, ppm

Oxygen sag
Point of inflection

Oxygen required = initial deficit + BOD

Figure 1. The dissolved-oxygen sag and its components: deoxygenation and reaeration

\[ D_a = \text{initial deficit} \]
\[ D_c = \text{critical deficit} \]
\[ D_i = \text{inflection deficit} \]
\[ t_c = \text{critical time} \]
\[ t_i = \text{inflection time} \]
in total cost of that upstream reach associated with an increase in its treatment level, i.e.,

$$\frac{dS(L)}{d\text{Trt}(L)}$$

Where $S(L) =$ total cost to reach L, and

$\text{Trt}(L) =$ treatment level in reach L.

An increase in the treatment level would result in increase removal of NOD as well as ultimate BOD. DO sag computations are used to calculate the change in DO level in reach S with respect to per unit change in treatment level in the upstream reach, L, i.e.,

$$\frac{d\text{DOC}(S)}{d\text{Trt}(L)}$$

where $\text{DOC}(S) =$ dissolved oxygen concentration in reach S in ppm. The change in total cost in reach L with respect to per unit change in DO in reach S is calculated as:

$$\frac{dS(L)}{d\text{Trt}(L)} \times \frac{d\text{Trt}(L)}{d\text{DOC}(S)} = \frac{dS(L)}{d\text{DOC}(S)} .$$

The "bargaining approach" only means that reach S may ask an upstream reach to increase its treatment level perhaps for some mutually agreeable price. Presumably, this price will be less than his marginal cost of additional treatment in reach S.

Figure 2 provides a simplified flow chart of the computations. Among other things, the computer program results show how much each industry can discharge and what the marginal cost will be at the discharge point. Such facts can be used in the administration of systems of rights or charges. This bargaining approach to a least-cost solution may seem cumbersome compared to other types of programming, but it is actually rapid and economical. A river, with 20 potential treatment sites and 4 levels of treatment at each, has many possible combinations (80 things taken 20 at a time). The bargaining approach only checks a small fraction of this number of possible solutions. The only options allowed in the checking process are reductions of treatment levels in the Sth reach and increases in treatment at reach L = 1 . . . S. One pass through the reaches $S = 1 . . . N$ is sufficient. A detailed flow chart and listing of the computer program are presented in Appendices B and C.
Set $K = 2$
Set $S = 1$
Set $NBEST = 0$

Ask subroutine DO SAG II to calculate $DOC(S)$

Is $DOC(S)$ above required?

No

Ask DO SAG II to calculate change in $DOC(S)$ due to a change in treatment level in $L$

$= DDOC(L,S)$

Calculate marginal cost of increasing a treatment level to discharger in $L$

$= DMC(L)$

Calculate the marginal cost of increasing $DOC(S)$ by increasing a treatment level in $L$, i.e.,

$MCC(L,S) = DMC(L)/DDOC(L,S)$

Among $L$ to $S$, find reach with minimum $MCC(L,S) = NBEST$

Add one level of treatment in reach $NBEST$

$T(NBEST) = T(NBEST + 1)$

Is treatment level in $S$ already at zero level? Does $T(S) = 1$?

No

Is NBEST ≥ S?

Yes

No

Subtract one level of treatment in $S$: $T(S) = T(S) - 1$

Set $S = S + 1$

No

Is $S = N + 1$?

Yes

Print optimal set of treatment levels, oxygen levels at end of each reach, list of restrictive reaches, list $MCC(L)$ for restrictive reaches

Figure 2. Simplified flow chart of bargaining steps
Definitions of Variables in Flow Chart

There are \( N \) reaches, \( I = 1 \ldots N \). \( S \) is the number of the reach currently being checked, \( L = 1 \ldots S \).

\( \text{NBEST} \) = number of that reach for which marginal cost of added treatment is minimal.

\( K \) = iteration number, \( K = 1 \ldots 2 \).

\( \text{T(I)} = M \) = treatment level in reach \( I \). (There are four levels of treatment.)

\( \text{T(I,K)} \) = set of treatments at the end of the \( K \)th iteration.

Input data include the flows of incoming tributaries and discharges of waste treatment plants, their DO, BOD, and NOD concentrations, marginal costs per million gallons per day, mgd, for increasing treatment levels in each reach, existing treatment levels, dissolved oxygen concentrations allowed, velocity, area and width.

The dissolved oxygen sag routine, DO Sag II, calculates:

\( \text{DOC(S)} \) = dissolved oxygen concentration in reach \( S \).

\( \text{DDOC(L,S)} \) = change in the dissolved oxygen concentration of reach \( S \) due to a change in the treatment level in reach \( L \).

\( \text{DMC(L)} \) = marginal cost of increasing treatment level to discharger in \( L \).

\( \text{MGC(L,S)} \) = marginal cost of increasing \( \text{DOC(S)} \) by increasing treatment level in \( L \).

APPLICATION OF THE MODEL TO THE NEUSE RIVER

The optimization model developed and presented here has been applied to the Neuse River of North Carolina. The Neuse River is formed by the junction of the Eno and the Flat Rivers near Durham, North Carolina; it then flows towards the southeast to a point below New Bern, and then northeastward to Pamlico Sound and the Atlantic Ocean. The upper third of the river lies in the Piedmont Region of North Carolina where steeper terrain makes the river flow rapidly. The lower two-thirds, below Smithfield, flows through the Coastal Plains Region where the river becomes a sluggish coastal stream. A number of important agricultural areas, large cities, and big industries lie on or near the Neuse River. For example, the river receives domestic and industrial wastes from Durham, Smithfield, Burlington Industries, Raleigh, Goldsboro, and Kinston (North Carolina Stream Sanitation Committee, 1959).
Figure 3. Division of Neuse River into segments and reaches
Figure 4. Explanation of the structure of reaches
Data Analysis

Data for the upper two-third stretch of the river above Kinston have been used to run the model. Figure 3 shows that this 155-mile stretch of the river is divided into five main segments according to stream classification. As shown in Table 1 and Figure 3 each segment is divided further into small reaches so that there is a source of waste discharge and/or a tributary at the head of each reach. If there are more than one waste discharger in one reach, their wastes are taken as one waste load. The total flow in a reach is the flow from the tributary, the industry, and the previous reach, as shown in Figure 4. Waste matter from the sources located on long tributaries travels quite some distance before entering the river. As a result, it gets treated by reaeration from the atmosphere. Therefore, leftover BOD, NOD, and dissolved oxygen deficit, DO, are calculated for the wastes coming from Crabtree Creek and Little River which enter the river at the head of reaches 11 and 19, respectively. (See Figure 4.)

The model is run for severe drought conditions represented by the 7-day, 10-year low flow. Information about waste discharge of different sources in the upper Neuse River basin, expressed in population equivalents, was obtained from the North Carolina Department of Water and Air Resources for the years 1968 and 1972. According to an Environmental Protection Agency (1971) report, a typical municipal waste contains about 0.23 and 0.12 pounds per capita per day of ultimate carbonaceous and nitrogenous BOD, respectively. Therefore, the concentrations of BOD and NOD discharged by each source is calculated as:

\[
\text{BOD} = \text{PEW} \times \frac{0.23}{(\text{QW} \times C_1 \times C_2)}
\]
\[
\text{NOD} = \text{PEW} \times \frac{0.12}{(\text{QW} \times C_1 \times C_2)}
\]

where \( \text{PEW} \) = population equivalent,
\( \text{BOD} \) = ultimate BOD in ppm,
\( \text{NOD} \) = ultimate NOD in ppm,
\( \text{QW} \) = flow from waste source in cubic feet per seconds, cfs,
\( C_1 = 0.646 \) million gallons per day per cfs, and
\( C_2 = 8.34 \) pounds per million gallon per ppm.

It is assumed that each waste source is measuring its ultimate BOD.

Table 2 shows that some waste dischargers increased their wastes from 1968 to 1972 while others decreased theirs. It is assumed that 1.5 ppm BOD and no NOD come from the natural sources on tributaries and that there are no other
sinks or sources of dissolved oxygen in the river. Data about flow, area and other hydrological conditions were taken from different sources, which caused some inconsistency. Some adjustments were made in the data and these are explained in Appendix A.

Table 1. Identification of reaches

<table>
<thead>
<tr>
<th>Segment no.</th>
<th>Reach no.</th>
<th>Reach</th>
<th>Miles from Eno River</th>
<th>Is at a point just above:</th>
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<tr>
<td>I</td>
<td>1</td>
<td>Eno River</td>
<td>1.50</td>
<td>Knap of Reeds</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Knap of Reeds</td>
<td>3.00</td>
<td>Ellerbe Creek</td>
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<td></td>
<td>3</td>
<td>Ellerbe Creek</td>
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<tr>
<td>II</td>
<td>4</td>
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<td>14.63</td>
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<td></td>
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<td></td>
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<td>8</td>
<td>Burlington Industries</td>
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<td>BOD b (ppm)</td>
<td>Average daily flow (mgd)</td>
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<td>1</td>
<td>Durham's Eno River WTP d</td>
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</tr>
<tr>
<td>5</td>
<td>Creedmoor's WSL e</td>
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<td>106.58</td>
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<td>Beaverdam Creek</td>
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<td>7</td>
<td>Barton Creek</td>
<td>No waste</td>
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<tr>
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<tr>
<td>19</td>
<td>Oak Park Subdivision WTP</td>
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<td>0.03</td>
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*Note: a = Characteristics of raw wastes, b = BOD (Biochemical Oxygen Demand), c = Effluent NOD (Nutrients Oxygen Demand).*
Table 2. (continued).

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<th>Reach no.</th>
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<th>1972</th>
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<tr>
<td></td>
<td></td>
<td>Average daily flow (mgd)</td>
<td>BOD (ppm)</td>
<td>Average daily flow (mgd)</td>
<td>BOD (ppm)</td>
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<tr>
<td>Starmount Shopping Center WTP</td>
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<td>0</td>
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<td>City of Raleigh WTP</td>
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<td>16.00</td>
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<td></td>
<td>Bullock's Mobile Home Park WTP</td>
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<td>0.01</td>
<td>479.62</td>
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<td></td>
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<tr>
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<td>0</td>
<td>0.00</td>
<td>0</td>
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<td>239.81</td>
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<td>123.50</td>
<td>0.30</td>
<td>123.50</td>
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<td>112.71</td>
<td>0.002</td>
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<td>324.94</td>
<td>0.008</td>
<td>253.67</td>
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<td>19</td>
<td>Town of Wendell's WTP</td>
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<td>213.16</td>
<td>0.18</td>
<td>217.16</td>
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<tr>
<td>Nello L. Teer Quarry</td>
<td>0.00</td>
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<td>0.00</td>
<td>0</td>
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<tr>
<td>Solar-Basic Industries' WTP</td>
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<td>0.01</td>
<td>575.54</td>
<td>280.40</td>
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<td>1.00</td>
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<td>Kenly's WTP</td>
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<td>239.81</td>
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Table 2 (continued).

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<th>Reach no.</th>
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<td></td>
<td>1968</td>
<td>1972</td>
<td>1972</td>
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<tr>
<td></td>
<td></td>
<td>Average daily flow</td>
<td>BOD&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Average daily flow</td>
<td>BOD</td>
<td>Effluent NOD&lt;sup&gt;c&lt;/sup&gt;</td>
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<tr>
<td>20</td>
<td>Goldsboro's Waste Lagoons</td>
<td>5.20</td>
<td>190.70</td>
<td>5.24</td>
<td>284.66</td>
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<td>Walnut Cr., Estates Goldsboro's WTP</td>
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<td>0.15</td>
<td>203.04</td>
<td>297.10</td>
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<td></td>
<td>Gold Wayne Developing Co's WTP</td>
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<td>0.25</td>
<td>748.20</td>
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<td>21</td>
<td>Bear Cr.</td>
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<td></td>
<td>No waste</td>
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</tr>
<tr>
<td>22</td>
<td>Falling Cr.</td>
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<td></td>
<td></td>
<td>No waste</td>
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<td>23</td>
<td>Kinston's WTP</td>
<td>6.75</td>
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<td>3.55</td>
<td>302.09</td>
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<td></td>
<td>Airport's WTP</td>
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<td></td>
<td>Briery's WTP</td>
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<td>0</td>
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<td>199.84</td>
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</tbody>
</table>

<sup>a</sup>1.5 PPM is taken as background BOD.

<sup>b</sup>BOD stands for Biochemical Oxygen Demand.

<sup>c</sup>NOD stands for Nitrogenous Oxygen Demand.

<sup>d</sup>WTP stands for Waste Treatment Plant.

<sup>e</sup>WSL stands for Waste Stabilization Lagoons.

Sources: Department of Water and Air Resources. NOD values for 1972 are from a Report on the Neuse River by Wagner (1973).
DO Sag Computations

The model uses equations 10, 11 and 12 to calculate the DO profile along the river and BOD and NOD at the end of the reach. A simple mass balance is performed to find DO deficit, BOD and NOD in the beginning of each reach. Decoxygenation coefficients for biochemical oxygen demand, \( (k_1) \), and nitrogenous oxygen demand, \( (k_3) \), are taken from literature relating to similar river conditions where \( k_1 \) is assumed to be .14 and \( k_3 \) varies from 0.00 to 0.07.

Reaeration coefficients, \( (k_2) \), were calculated according to the formula given by Langbein and Durum (1967). The equation is:

\[
(k_2)_{20} = \frac{3.3V}{1.33H}
\]

where \( (k_2)_{20} \) = reaeration coefficient to the base 10 at 20° Centigrade, day\(^{-1}\),

\( V \) = velocity in feet per second, and

\( H \) = depth of the river in feet.

Increasing temperature causes an increase in reaeration coefficients. Coefficients are adjusted to varying temperatures according to the following formula:

\[
k_2 = (k_2)_{20}(1.047)^{(T-20)}
\]

where \( T \) stands for temperature in degrees Centigrade.

Reaeration coefficients calculated from this formula were very high. Therefore, coefficients calculated by the same equation are divided by a factor of 6 which makes the weighted average of the Lagbein and Durum \( k_2 \) values for the whole river approximately equal to the same weighted average of values calculated by Wagner (1973). These coefficients are compared with Langbein and Durum \( k_2 \) values; Langbein and Durum \( k_2 \) values, divided by two; and weighted averages of \( k_2 \) values given by Wagner\(^1\). These coefficients are shown in Table 3. In order to choose among the reaeration coefficients, dissolved oxygen predictions were compared with observed oxygen levels at 18 points on the river obtained from the North Carolina Department of Water

\(^1\)Wagner used the equation given by Tsivoglou and Wallace (1972) based upon channel slope, rather than velocity, to calculate reaeration coefficients for the Neuse River.
Table 3. Hydraulic characteristics of the river and comparison of reaeration coefficients calculated from 1, 2, 3, and 4.

<table>
<thead>
<tr>
<th>Segment no.</th>
<th>Points on river</th>
<th>Flow&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Area&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Width&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Depth&lt;sup&gt;d&lt;/sup&gt;</th>
<th>vel.&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Temp&lt;sup&gt;e&lt;/sup&gt;</th>
<th>k&lt;sub&gt;2&lt;/sub&gt;&lt;sup&gt;f&lt;/sup&gt;/ day based on</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>Northside</td>
<td>17.38</td>
<td>23.17</td>
<td>24</td>
<td>0.96</td>
<td>0.75</td>
<td>26.00</td>
<td>3.42 1.71 0.57 0.23</td>
</tr>
<tr>
<td>2</td>
<td>Falls</td>
<td>19.38</td>
<td>17.15</td>
<td>20</td>
<td>0.64</td>
<td>1.13</td>
<td>26.00</td>
<td>6.03 3.01 1.00 0.96</td>
</tr>
<tr>
<td>3</td>
<td>Neuse</td>
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<td>60.93</td>
<td>51</td>
<td>1.19</td>
<td>0.75</td>
<td>26.00</td>
<td>2.57 1.29 0.43 0.28</td>
</tr>
<tr>
<td>4</td>
<td>Clayton</td>
<td>84.25</td>
<td>135.89</td>
<td>107</td>
<td>1.27</td>
<td>0.62</td>
<td>26.00</td>
<td>1.96 0.98 0.33 1.02</td>
</tr>
<tr>
<td>4</td>
<td>Smithfield</td>
<td>84.84</td>
<td>110.18</td>
<td>84</td>
<td>1.31</td>
<td>0.77</td>
<td>26.00</td>
<td>2.33 1.17 0.39 0.64</td>
</tr>
<tr>
<td>4</td>
<td>Goldsboro</td>
<td>117.55</td>
<td>123.74</td>
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<td>0.95</td>
<td>26.00</td>
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<td>0.77</td>
<td>26.00</td>
<td>1.37 0.68 0.23 0.20</td>
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</tbody>
</table>

<sup>a</sup>See Appendix A Table 1.

<sup>b</sup>Area is calculated as flow/velocity.

<sup>c</sup>Data for width and velocity are taken from U. S. Geological Survey, corresponding to the flow data for year 1968 or 1970.

<sup>d</sup>Depth is calculated as area/width.

<sup>e</sup>Temperature is assumed to be 26°C all along the river.

<sup>f</sup>k<sub>2</sub> = Reaeration coefficient based upon

(1) equation given by Langbein and Durum (1967).
(2) equation given by Langbein and Durum (1967) divided by 2.
(3) equation given by Langbein and Durum (1967) divided by 6. A factor of one-sixth makes the weighted average value of the Langbein and Durum k<sub>2</sub> values for the whole river approximately equal to the same weighted average of Wagner (1973).
(4) weighted average of the reaeration coefficient given by Wagner (1973) for each segment.
and Air Resources. Observed DO levels were obtained for the period August 1970 to September 1970 because flows during that period were low and did not change drastically. Waste discharged by different sources also did not change much from 1968 to 1970. The results of comparison are given in Table 4. Column (2) in Table 4 shows that the DO levels predicted by reaeration coefficients which are given by Langbein and Durum's equation, reduced to half had the lowest average absolute percentage error of 17.79 percent. Therefore, these reaeration coefficients are used to calculate the DO levels along the river.

Values of DO deficit in each reach are calculated after a time interval of nearly an hour. The highest of these values gives the maximum deficit in that reach.

To compare different alternatives, the marginal costs of waste treatment are calculated from the total annual costs of BOD removal. Total annual costs, given by Frankel (1965) as continuous cost curves, are used to get stepped cost curves for discrete treatment levels. Marginal costs are calculated for these steps and these are listed in Table 5. Costs are expressed per million gallons of flow per day, mgd, for two sizes of plants. These costs are based on plants with a life expectancy of 25 years and a real interest rate of 4 percent. Costs are expressed in 1963 dollars and are based on an ENR construction cost index of 900.00. These total costs cover the total initial capital investment plus the annual operation and maintenance costs of the treatment plant. The primary treatment level involves a large initial investment. Increasing returns are realized in going to secondary treatment. Economics of size are also realized in going to a higher treatment. As costs per unit are higher for smaller plants than for larger plants, the present model might be expected to recommend high treatment levels at a few big plants rather than low treatment levels at many small plants. The discreteness of the treatments added might also contribute to such a result. The model could be modified to use a continuous cost curve and thereby get better results than those obtained with discrete steps.

RESULTS

The optimization model suggests treatment at only 7 of the 17 points where wastes are now being discharged and treated. (See Table 6) The results make it clear that some upstream reach might affect the water quality of a
Table 4. Comparison of observed DO levels with those predicted by using different reaeration coefficients

<table>
<thead>
<tr>
<th>Reach</th>
<th>DO observed&lt;sup&gt;a&lt;/sup&gt;</th>
<th>DO's predicted&lt;sup&gt;b&lt;/sup&gt;</th>
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<td></td>
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<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
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<tr>
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<td>na&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>4.89</td>
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<td>5.66</td>
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<td>--</td>
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<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>22</td>
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<td>7.63</td>
<td>7.09</td>
<td>5.29</td>
<td>5.11</td>
</tr>
</tbody>
</table>

Range of errors: 14-3.90, 16-3.46, 17-5.82, 19-3.35
Average of absolute percentage errors: 21.37%, 17.79%, 31.12%, 23.36%

<sup>a</sup>Dissolved oxygen concentrations observed by North Carolina State Department of Water and Air Resources for August-September, 1970.

<sup>b</sup>Dissolved oxygen concentration predicted by:

1. Reaeration coefficient calculated from the equation given by Langbein and Durum (1967).
2. Reaeration coefficient calculated from the equation given by Langbein and Durum (1967), reduced to half.
3. Reaeration coefficient calculated from the equation given by Langbein and Durum (1967), reduced to one-sixth.

<sup>c</sup>na = not available.
downstream reach more than its own waste. For example reach 4 asks reach 2 to go from primary to secondary treatment. No treatment would be necessary in reaches 2 and 3 if the stream standards did not increase at the beginning of reach 4. (See Figure 5.)

Table 5. Marginal cost of waste treatment per million gallons of wastewater for going to a higher level of treatment

<table>
<thead>
<tr>
<th>Size of plant (mgd)</th>
<th>No treatment to primary ($/mgd)</th>
<th>Primary treatment to secondary ($/mgd)</th>
<th>Secondary treatment to tertiary ($/mgd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 2.5</td>
<td>26,700.00</td>
<td>29,200.00</td>
<td>22,700.00</td>
</tr>
<tr>
<td>≤ 10</td>
<td>20,000.00</td>
<td>20,500.00</td>
<td>18,800.00</td>
</tr>
</tbody>
</table>

*a* All figures in 1963 dollars.

*b* Size given as average daily sewage flow.

*c* Primary treatment is assumed to result in the removal of 38 percent of BOD and 10 percent of NOD.

*d* Secondary treatment is assumed to result in additional removal of 52 percent of BOD and 40 percent of NOD or a total removal of 90 percent of BOD and 50 percent of NOD.

*e* Tertiary treatment is assumed to result in additional removal of 9 percent of BOD and 45 percent of NOD or a total removal of 99 percent of BOD and 95 percent of NOD.

Source: Frankel, R. J. (1965).
Identification of reaches and miles from the Eno River

Identification numbers of reaches and miles from the Eno River

Figure 5. Minimum allowed and predicted present and optimum DO levels along the Neuse River
Table 6. A comparison of present and least-cost treatment levels, costs and CO concentration at each reach along the Neuse River of North Carolina above Kinston, 1970 conditions

<table>
<thead>
<tr>
<th>Reach number</th>
<th>Treatment levels&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Costs of treatment (dollars per year)</th>
<th>Dissolved oxygen in stream (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present</td>
<td>Optimal</td>
<td>Required levels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Observed levels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Predicted levels</td>
</tr>
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<td>5.00</td>
</tr>
<tr>
<td>23</td>
<td>2</td>
<td>0</td>
<td>5.00</td>
</tr>
<tr>
<td>Total cost</td>
<td>3,712,644</td>
<td>1,097,448</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Treatment levels 0, 1, 2, and 3 refer to no treatment, primary, secondary, and tertiary, respectively.
Treatment in only 7 reaches, compared to 17 reaches, is now possible because the solution suggests discharge of untreated wastes at points where waste assimilative capacity of the river is high, such as at reaches 11 and 15-23. Reach 9 is affected more by waste from reach 8 than from its own waste. The results of the model show that with some act of treatment levels upstream, primary treatment at reach 8 and secondary treatment at reach 9, the change of DO level of reach 9 due to the increase in treatment level in reach 8 is 2.87 ppm. At the same time, an increase in the treatment level in reach 9 would only increase the DO level at the end of reach 9 by 0.03 ppm. The marginal costs of increasing DO by one ppm in reach 9 is $12,993 for reach 8 and $126,571 for reach 9.

The main difference between the present and the proposed optimum solutions is cost. (See Table 6). The present system costs approximately $3.7 million while an optimum system would cost only $1.09 million, according to the model.

APPLICATION OF RESULTS

The optimization model does not favor any one administrative system. Any one of several different systems could be used to attain given water quality standards. However, the model gives the marginal cost of treatment, allowable waste loads, and water quality levels for each reach.

Table 7 presents the implications of four alternative systems of water quality management, assuming that the 1968 waste loads before treatment are the maximum loads that the dischargers would want to discharge.

One administrative system consists of specifying a set of treatment levels for all the reaches. These treatment levels, or input requirements (column 2), satisfy the water quality constraint in each reach. This is the least costly set of treatment levels to maintain the water quality of the river.

Another suggested alternative system is to give effluent permits, as shown in column 3. As mentioned earlier, these are not the maximum discharge permits because the stream standards are overfulfilled at many places. In order to make full allocation of the river's waste assimilative capacity, more wastes can be discharged in the river. But, the effluent permits in column 3 at reaches 2, 3, 7, 8, 12, 18, and 20 are limiting and important to the attainment of downstream standards.

With respect to charges, it is assumed that each waste discharger would discharge untreated wastes to the river unless the charges per pound of BOD
Table 7. Different optimum administrative systems to achieve given stream standards

<table>
<thead>
<tr>
<th>Reaches</th>
<th>Treatment levels</th>
<th>Effluent permits BOD(ppm)</th>
<th>Effluent charges c/lb TOD</th>
<th>Stream standards and bargaining DO - ppm</th>
<th>Dissolved oxygen ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>231.75</td>
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<td>7.95</td>
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<tr>
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<td>2</td>
<td>44.67</td>
<td>3.00</td>
<td>3.00</td>
<td>6.00</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>36.94</td>
<td>2.50</td>
<td>3.00</td>
<td>4.84</td>
</tr>
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<td>0</td>
<td>192.90</td>
<td>0.00</td>
<td>5.00</td>
<td>6.24</td>
</tr>
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<td>0</td>
<td>4.27</td>
<td>0.00</td>
<td>5.00</td>
<td>6.76</td>
</tr>
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<td>0.00</td>
<td>5.00</td>
<td>6.99</td>
</tr>
<tr>
<td>7</td>
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<td>45.10</td>
<td>2.90</td>
<td>5.00</td>
<td>7.40</td>
</tr>
<tr>
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<td>12.94</td>
<td>1.80</td>
<td>3.00</td>
<td>6.86</td>
</tr>
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<tr>
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</tr>
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<td>3.00</td>
<td>5.50</td>
</tr>
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<td>0.00</td>
<td>5.00</td>
<td>6.35</td>
</tr>
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</tr>
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<td>6.47</td>
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<td>3.40</td>
<td>5.00</td>
<td>6.56</td>
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<td>6.68</td>
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<td>0.00</td>
<td>5.00</td>
<td>6.30</td>
</tr>
<tr>
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<td>230.64</td>
<td>0.00</td>
<td>5.00</td>
<td>5.25</td>
</tr>
</tbody>
</table>

a 0 = no treatment level.

1 = primary treatment level or 38 percent removal of BOD and 10 percent removal of NOD.

2 = secondary treatment level or 90 percent removal of BOD and 50 percent removal of NOD.

3 = tertiary treatment level or 99 percent removal of BOD and 95 percent removal of NOD.

b BOD = ultimate biochemical oxygen demand in ppm.

c TOD = total oxygen demand.
are such that it is cheaper to treat them. Therefore, the marginal cost for each reach would be the optimum set of charges. Charges are calculated for total oxygen demand, TOD, including both NOD and ultimate BOD because their treatment is accomplished jointly. Column 4 shows that these charges vary a great deal and this obviously suggests questions of equity.

Another possible system of water quality management would be to fix stream standards (column 5) and make the waste dischargers responsible for the stream standards in their own reach. Waste dischargers would be allowed to bargain among themselves in order to fulfill their water quality constraints. This would be the same as transferable rights as suggested by Mar (1971).

Thus, all of these systems could result in the same treatment costs but their administrative costs and income redistributions would be different, and these would be important factors in selecting among them.

The above suggestions are based on a DO sag relationship which has an average absolute error of 19.7% in DO prediction. This must be improved upon before there are any grounds for stating that these systems can be put into practice without fear of contravening the existing standards.

A note of caution that was sounded at the outset should be repeated here. Current stream standards have other dimensions besides dissolved oxygen; for example, coliform count, toxicity and turbidity. If and when it is possible to include these other dimensions in models such as the one developed here, then more acceptable recommendations will be obtained.
REFERENCES


Appendix A. Data Adjustment

Flow data used are the minimum 7-day discharges having a recurrence of 10 years (U. S. Department of the Interior, 1964). But these data are not given for all reaches so the remaining information about discharge is taken from the water quantity report by the U. S. Geological Survey for the years 1968 and 1970 (U. S. Department of the Interior, 1968-1970). Water withdrawals from the river are assumed to be zero as are inflows of water from other natural sources. Data for the flows from sources of waste are received from the Department of Water and Air Resources for the year 1968. Because of different sources of data, some inconsistency entered the data.

It is assumed that in the beginning of a reach, flow is entering from the previous reach, tributaries, and sources of waste. So total flow in the reach is the sum of the flows from the previous reach, sources of waste, and tributaries. In other words:

\[ Q\text{TOT}(N) = Q\text{IN}(N) + Q\text{W}(N) + Q\text{T}(N) \]

where

- \( Q\text{TOT}(N) \) = total flow in the reach,
- \( Q\text{IN}(N) \) = flow coming in Nth reach from (N-1) reach,
- \( Q\text{W}(N) \) = flow from the sources of waste, and
- \( Q\text{T}(N) \) = flow from the tributary.

This means that the following should be true:

\[ Q\text{TOT}(N) - Q\text{IN}(N) = Q\text{T}(N) + Q\text{W}(N). \]

But because of different sources of flow data, in some reaches the difference between total observed flow and the incoming flow \([Q\text{TOT}(N) - Q\text{IN}(N)]\) in the reach is less than the flow from sources of waste \([Q\text{W}(N)]\), as is clear from the Appendix A Table 1. So in those reaches, flow from tributaries is assumed to be zero and total flow is increased so that \(Q\text{TOT}(N) - Q\text{IN}(N)\) is equal to \(Q\text{W}(N)\). And in all other reaches, flow from the tributary is taken as residuals (i.e., the difference between total observed flow and the flows from sources of waste and previous reach):

\[ Q\text{T}(N) = Q\text{TOT}(N)^1 - [Q\text{W}(N) + Q\text{IN}(N)]. \]

\(^1\)Observed total flow,
Data about area, width, and velocity are available for only seven places on the river from the U. S. Geological Survey. They measure width and depth and calculate area as $\text{Area} = \text{Width} \times \text{Depth}$. They also calculate velocity and get the discharge as $\text{Discharge} = \text{Area} \times \text{Velocity}$.

The adjusted 10-year low flow data are matched with the U. S. Geological Survey data for recorded low flows in either 1968 or 1970, and then for that discharge the corresponding velocity and width are taken and the area and depth are calculated. For the whole segment, the same velocity, area, width, and depth are used except in the fourth segment, which is relatively large, so three values are taken for each variable. Temperature is assumed to be $26^\circ\text{C}$ all along the river.
Appendix A Table 1. Observed and adjusted flows

<table>
<thead>
<tr>
<th>Reach no.</th>
<th>Observed total at the head of reach (^a) (cfs)</th>
<th>Average flow from the previous reach (^b) (cfs)</th>
<th>Average flow from sources of waste (^c) (cfs)</th>
<th>Assumed flow from tributaries (^d) (cfs)</th>
<th>Calculated total at the head of reach (^a) (cfs)</th>
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<td>224.22</td>
<td>13.99</td>
<td>0.00</td>
<td>224.22</td>
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</table>

\(^a\) Minimum 7-day discharges having a recurrence of 10 years.

\(^b\) Total flow in the previous reach is incoming flow for the next reach.

\(^c\) Where difference between total observed flow and incoming flow in the reach is not equal to even the flow from sources of waste, flow from tributaries is assumed to be zero and at other places flow from the tributary is taken as the difference between total observed flow and the flows from sources of wastes and previous reach.

\(^d\) Calculated total flow is a sum of the flows from the previous reach, tributaries and sources of waste.

## Definitions of the Variables in the Program

<table>
<thead>
<tr>
<th>Variable name</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA</td>
<td>Cross-sectional area of the stream</td>
<td>square feet</td>
</tr>
<tr>
<td>BMCC</td>
<td>Best (minimum) marginal cost coefficient</td>
<td>-</td>
</tr>
<tr>
<td>BODA</td>
<td>Carbonaceous biochemical oxygen demand at head of a reach (ultimate)</td>
<td>ppm</td>
</tr>
<tr>
<td>BODB</td>
<td>Carbonaceous biochemical oxygen demand at end of a reach</td>
<td>ppm</td>
</tr>
<tr>
<td>BODEA</td>
<td>Carbonaceous biochemical oxygen demand in each (small) part of a reach</td>
<td>ppm</td>
</tr>
<tr>
<td>BODIN</td>
<td>Carbonaceous biochemical oxygen demand in incoming flow to a reach</td>
<td>ppm</td>
</tr>
<tr>
<td>BODL</td>
<td>Carbonaceous biochemical oxygen demand of waste in loading units</td>
<td>lbs./day</td>
</tr>
<tr>
<td>BODN</td>
<td>Carbonaceous biochemical oxygen demand from natural sources in reach</td>
<td>ppm</td>
</tr>
<tr>
<td>BODT</td>
<td>Carbonaceous biochemical oxygen demand from tributary at head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>BODW</td>
<td>Carbonaceous biochemical oxygen demand in waste at head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>CA</td>
<td>Coefficient of reaeration to the base 10</td>
<td>-</td>
</tr>
<tr>
<td>CA20</td>
<td>Coefficient of reaeration at 20 degrees Centigrade</td>
<td>-</td>
</tr>
<tr>
<td>CDIST</td>
<td>Cumulative distance up to the end of a reach</td>
<td>miles</td>
</tr>
<tr>
<td>COMPU</td>
<td>Computes reaeration coefficients and BOD and NOD for different levels of treatment for given data</td>
<td>-</td>
</tr>
<tr>
<td>CN</td>
<td>Coefficient of deoxygenation for NOD to the base 10</td>
<td>-</td>
</tr>
<tr>
<td>CD</td>
<td>Coefficient of deoxygenation for BOD to the base 10</td>
<td>-</td>
</tr>
<tr>
<td>COST</td>
<td>The annual cost of treatment for the reach specified</td>
<td>$/year</td>
</tr>
<tr>
<td>CTIME</td>
<td>Cumulative time up to the end of a reach</td>
<td>days</td>
</tr>
<tr>
<td>DDODT</td>
<td>Decrease in dissolved oxygen deficit in the last reach with a higher level of treatment in given reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DEPTH</td>
<td>Depth of the stream</td>
<td>feet</td>
</tr>
<tr>
<td>Variable name</td>
<td>Definition</td>
<td>Units</td>
</tr>
<tr>
<td>---------------</td>
<td>------------</td>
<td>-------</td>
</tr>
<tr>
<td>DIST</td>
<td>Distance of travel in reach (length of reach)</td>
<td>miles</td>
</tr>
<tr>
<td>DMC</td>
<td>Total increase in marginal cost per year with a higher level of treatment for a source of waste</td>
<td>$/year</td>
</tr>
<tr>
<td>DMCQ</td>
<td>Increase in marginal cost with a higher level of treatment per million gallons of waste water</td>
<td>$/MGD</td>
</tr>
<tr>
<td>DOCA</td>
<td>Dissolved oxygen concentration at the head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DOCB</td>
<td>Dissolved oxygen concentration at the end of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DOCIN</td>
<td>Dissolved oxygen concentration in incoming flow to a reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DOCM</td>
<td>Dissolved oxygen concentration minimum in the reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DOCMA</td>
<td>Dissolved oxygen concentration minimum allowed in a reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DOCS</td>
<td>Dissolved oxygen concentration saturation value</td>
<td>ppm</td>
</tr>
<tr>
<td>DOCT</td>
<td>Dissolved oxygen concentration from tributary at head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DOCW</td>
<td>Dissolved oxygen concentration in waste at head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DODA</td>
<td>Dissolved oxygen deficit at the head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DODB</td>
<td>Dissolved oxygen deficit at the end of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DOD</td>
<td>Dissolved oxygen deficit</td>
<td>ppm</td>
</tr>
<tr>
<td>DODEA</td>
<td>Dissolved oxygen deficit in each part of a reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DODIN</td>
<td>Dissolved oxygen deficit in incoming flow to a reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DODM</td>
<td>Dissolved oxygen deficit maximum value in reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DODMA</td>
<td>Dissolved oxygen deficit maximum allowed in reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DODMO</td>
<td>Dissolved oxygen deficit maximum old value, that is, before treatment is increased in any upstream reach</td>
<td>ppm</td>
</tr>
<tr>
<td>Variable name</td>
<td>Definition</td>
<td>Units</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>DODT</td>
<td>Dissolved oxygen deficit from tributary at head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DODW</td>
<td>Dissolved oxygen deficit in waste at head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>DOSAG</td>
<td>The array of treatment levels in any round of computations</td>
<td></td>
</tr>
<tr>
<td>FLOW</td>
<td>Representative discharge in a segment of river covering a number of reaches as defined in the program</td>
<td>cfs</td>
</tr>
<tr>
<td>K</td>
<td>Iteration number</td>
<td></td>
</tr>
<tr>
<td>MCC</td>
<td>Marginal cost coefficient for source of waste (DMC/DDODT)</td>
<td>$/year/ppm</td>
</tr>
<tr>
<td>N</td>
<td>Stands for number of reach on Neuse River or tributary</td>
<td></td>
</tr>
<tr>
<td>NBEST</td>
<td>Number of reach where there is minimum marginal cost</td>
<td></td>
</tr>
<tr>
<td>NODA</td>
<td>Nitrogenous oxygen demand at the head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>NODB</td>
<td>Nitrogenous oxygen demand at the end of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>NODEA</td>
<td>Nitrogenous oxygen demand in each part of the reach</td>
<td>ppm</td>
</tr>
<tr>
<td>NODIN</td>
<td>Nitrogenous oxygen demand in incoming flow to a reach</td>
<td>ppm</td>
</tr>
<tr>
<td>NODL</td>
<td>Nitrogenous oxygen demand in waste at head of reach in loading units</td>
<td>lbs./day</td>
</tr>
<tr>
<td>NODN</td>
<td>Nitrogenous oxygen demand from natural sources in a reach</td>
<td>ppm</td>
</tr>
<tr>
<td>NODT</td>
<td>Nitrogenous oxygen demand from tributary at head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>NODW</td>
<td>Nitrogenous oxygen demand in waste at head of reach</td>
<td>ppm</td>
</tr>
<tr>
<td>PEW</td>
<td>Population equivalent of raw-waste from sources of the waste</td>
<td></td>
</tr>
<tr>
<td>QIN</td>
<td>Incoming flow from previous reach</td>
<td>cfs</td>
</tr>
<tr>
<td>QT</td>
<td>Incoming flow from tributary at head of reach</td>
<td>cfs</td>
</tr>
<tr>
<td>QTOT</td>
<td>Total flow in a reach</td>
<td>cfs</td>
</tr>
<tr>
<td>QW</td>
<td>Volume of waste at head of reach</td>
<td>cfs</td>
</tr>
<tr>
<td>Variable name</td>
<td>Definition</td>
<td>Units</td>
</tr>
<tr>
<td>---------------</td>
<td>------------</td>
<td>-------</td>
</tr>
<tr>
<td>SAGI</td>
<td>Computes DO profile for the tributaries</td>
<td>-</td>
</tr>
<tr>
<td>SAGII</td>
<td>Computes DO profile along the river</td>
<td>-</td>
</tr>
<tr>
<td>SAGIP</td>
<td>Computes and points DO profile for the river</td>
<td>-</td>
</tr>
<tr>
<td>T</td>
<td>Stands for the level of treatment, subscripts 1, 2, 3, 4 are for no treatment, primary, secondary and tertiary treatment</td>
<td>-</td>
</tr>
<tr>
<td>TC</td>
<td>Total cost of waste treatment for all reaches of Neuse River</td>
<td>$</td>
</tr>
<tr>
<td>TCOST</td>
<td>Computes the total cost to individual waste sources and total cost of the whole system</td>
<td>$</td>
</tr>
<tr>
<td>TEMP</td>
<td>Temperature in the stream in degrees Centigrade</td>
<td>degrees</td>
</tr>
<tr>
<td>TIMA</td>
<td>Time of travel in each part of a reach</td>
<td>days</td>
</tr>
<tr>
<td>TIME</td>
<td>Time of travel in reach</td>
<td>days</td>
</tr>
<tr>
<td>V</td>
<td>Velocity of river</td>
<td>fps</td>
</tr>
<tr>
<td>VEL</td>
<td>Velocity of river in miles per day</td>
<td>miles/day</td>
</tr>
<tr>
<td>WIDTH</td>
<td>Surface width of the stream</td>
<td>feet</td>
</tr>
</tbody>
</table>
Flow Chart

The Bargaining Approach for Programming
Least-Cost Waste Treatment Levels along the Neuse River

START


A

DO SAG Analysis for Neuse River Tributaries

A

No. of tributaries are the first reaches
N = 1 to 2

Input data about the flow in the tributary and from industries and creeks
[PEW(N), QW(N), DOCW(N), T(N), QT(N), BODT(N), DOCT(N), FLOW(N), WIDTH(N), TEMP(N), QIN(N), V(N), DIST(N), BODIN(N), NODIN(N), DOCIN(N), NODT(M,M)]

Set reach no. N=1 and treatment level M=1

Call subroutine COMPU(N) to calculate (1) reaeration coefficients (2) BOD and NOD at different treatment levels

Set treatment level (M)=1

Call subroutine SAGI(N)
Compute DOD levels at end of reach

B

36
Data for DO Sag Analysis in Neuse River

Input data about the flow in the river and from industries and tributaries:

\[ \{ \text{PEW(I), QW(I), DOCW(I), DMCQ(M, I), T(I), CN(I), QT(I), NODT(M, I),} \]
\[ \text{BODT(M, I), DOCT(M, I): BODIN(3),} \]
\[ \text{NODIN(3), DOCIN(3), QIN(3):} \]
\[ \text{DCOS(I), DOCMA(I), V(I), DIST(I),} \]
\[ \text{TEMP(I), FLOW(I), WIDTH(I)} \]

Put BODT(I), DOCT(I) = 0 except where these values are calculated on the tributaries.

Deoxygenation rate for BOD = 0.14

Call subroutine COMPU(I).
Calculate (1) reaeration coefficient
(2) BOD and NOD at different treatment levels.

Calculate DO deficit of waste, incoming flow to the reach and maximum allowed, i.e.:
\[ \text{DODW(I), DODMA(I), DODIN(3).} \]

Compute VEL(I), TIME(I), CTIME(I), CDIST(I).

Compute total marginal cost of going to a higher treatment level
\[ \text{DMC(M, I) = DMCQ(M, I) x Q(W)} \]

Write all the input and output data.
DO Sag Analysis in the Neuse River for Existing Treatment Levels

D

Iteration $K = 1$

$N = 3$

Call subroutine SAGIP$(N)$.
Calculate DO Sag curve.

Call subroutine TCOST$(N)$.
Calculate cost for each source of waste and total cost of the system.

Write the array of treatment levels.

Write all the input and output data.

E
The Bargaining Approach

E

Iteration no. k = 2
Take reach S = 3

Call subroutine SAGII(S)
Calculate DO Sag curve.

Compare maximum DO
deficit and maximumallowed DO deficit in
the reach.
Is DODM(M,S) >
DODM(S)?

To begin, assign a very high
number as minimum cost
and the reach with that cost as 0,
i.e., BMCC = 975, NBEST = 0.

Assign DO maximum deficit in reach S
as old value of DO maximum deficit,
i.e., the value before an increase
in treatment level.
DODM(S) = DODM(M,S)

Take first upstream reach as L
or L = 3

Increase the treatment level in L by 1
T(L) = T(L) + 1.

F
Calculate DO sag curve.

Is there a source of waste on this reach? Is DMC > 0.0001?

Yes

Call subroutine SAGII(S).
Calculate DO sag curve.

Calculate change in DOD maximum in reach S as a result of an increase in treatment level in upstream reach L, i.e., compute

\[ DDODT(L) = DODMO(S) - DODM(M,S). \]

Is this change in DOD maximum in reach S more than 0.0001, i.e.,

Is \[ DDODT(L) > 0.0001? \]

Yes

Compute the marginal cost of increasing DO concentration in reach S by increasing a treatment level in L, i.e.,

\[ MCC(L) = DMC(M,L)/DDODT(L). \]

Is \( MCC(L) \) higher than BMCC?

Yes

Reduce treatment level in L by 1.

\[ T(L) = T(L) - 1. \]

No

Put \( DDODT(L) = 0.0001 \).

581

Put BMCC = MCC(L)

NEST = L

Reduce treatment level in L by 1.

\[ T(L) = T(L) - 1. \]

Go to next reach

\[ L = L + 1. \]

Go to 581

No
Go to 573

Is L > S?

Yes

Is NBEST > 0?

No

Yes

Increase the treatment level by 1 in the reach where MC is minimum, i.e.,
\[ T(\text{NBEST}) = T(\text{NBEST}) + 1 \]

Call subroutine \text{SAGII(S)}.
Calculate DO sag curve.

Compare DOD maximum and maximum allowed DOD after increasing a treatment level in NBEST.
Is \[ \text{DODM}(M,S) > \text{DODMA}(S) \]?

No

Go to 570

Yes

610

Is \( T(S) = 1 \)?

No

Reduce a treatment level in S by 1.
\[ T(S) = T(S) - 1 \]

Go to 550

Yes

Go to next reach
\[ S = S + 1 \]

Is \( S > N \)?

No

Go to 550

Yes

Call subroutine \text{TCOST(N)} to calculate total cost.

Call subroutine \text{SAGIP(N)} to calculate DO sag curve

Write all the output

Call \text{EXIT}

END

Write: The waste load in reach S is so high that even after maximum possible treatment in reach S and all upstream reaches, the DO constraint is not met.
SUBROUTINE COMPU(N)

Specify common variables, real and integers

Calculate reaeration coefficient, i.e.,
   Area(N), Depth(N)
   CA20(N), CA(N)

Calculate BOD in lbs
for different reaches, i.e.,
   BODL(M,N) = FEW(N) x 0.23

Calculate BOD in ppm for different levels of treatments for different reaches, i.e.,
   BODW(M,N)
   BODW(M+1,N), BODW(M+2,N)
   BODW(M+3,N)

Calculate NOD in lbs
for different reaches, i.e.,
   NODL(M,N) = FEW(N) x 0.12

Calculate NOD in ppm
for different levels of treatment
for different reaches, i.e.,
   NODW(M,N), NODW(M+1,N)
   NODW(M+2,N), NODW(M+3,N)

Take background BOD as 1.5 ppm
and NOD as 0.0 ppm or put
   BODN(N) = 1.50
   NODN(N) = 0.00

Return

End
SUBROUTINE SAGI(N)

Specify real, integer and common variables

Put CD = 0.14

Compute DO deficit, BOD and NOD at the head of the reach and at the end of the reach or compute DODW(M,N), DODT(M,N), DODIN(N), VEL(N), TIME(N), BODA(M,N), NODA(M,N), DODA(M,N), DODB(M,N), BODB(M,N), NODB(M,N)

RETURN

END
SUBROUTINES SAGI(N) and SAGII(N)*

Specify real, integer and common variables

Take reach no. I = 3

M = T(I)

Compute (I) total flow,
(2) BOD, NOD, DOD at the
head of the reach, i.e., compute
QUOT(I), BODA(M,I) DODA(M,I),
NODA(M,I).

To calculate DOD at equal intervals,
start with a new variable, TIMA = 0.00
and put DO deficit in the beginning
of the reach as maximum deficit up to now.
Put TIMA = 0.00
DODM(M,I) = DODA(M,I)

TIMA = TIMA + 0.04

Is increased
TIMA more than actual time
of travel in that reach?
Is TIMA ≥ TIME(I)?

No

Compute BOD, DOD and NOD
in every small part of the reach,
i.e., compute
E1(I), E2(I), E3(I), DODEA(M,I),
BODEA(M,I), NODEA(M,I).

Yes

TIMA = TIME(I)

Write
I, M, TIMA, TIME(I), DODEA(M,I),
BODEA(M,I), NODEA(M,I), T(I).

H
def f:

to now more than deficit in the present part of the reach?
Is DODM(M,I) ≥ DODEA(M,I)?

Yes

Check if time of travel in the present reach has already been used.
Is TIMA = TIME(I)?

Yes

Assign DOD, BOD, NOD and total flow at the end of the reach as incoming flow for the next reach, i.e., put
BODB(M,I) = DODEA(M,I)
NODB(M,I) = NODEA(M,I)
BODIN(I+1) = BODB(I)
NODIN(I+1) = NODB(M,I)
QIN(I+1) = QTOT(I)
DODIN(I+1) = DODB(M,I)

Go to next reach
I = I + 1

No

Go to 780

Call the deficit in this part the maximum deficit in the reach.

Put
DODM(M,I) = DODEA(M,I)

No

Go to 775

Is I > N?

Yes

RETURN

END
SUBROUTINE TCOST(N)

Specify real, integer and common variables

Take reach no. \( I = 3 \)

Calculate total cost to individual source of waste

Take \( M = T(I) \)
\( \text{COST} = 0.00 \)

Is \( M = 1? \)

\( I = I + 1 \)

No

\( J = 2 \)

Compute
\( \text{COST}(J) = \text{COST}(I) + \text{DMC}(J,I) \)

\( J = J + 1 \)

Yes

Is \( J > M? \)

No

Calculate total cost of all the sources of waste

\( \text{TC}(K) = 0.00 \)

\( I = 3 \)

Is \( I > N? \)

Yes

RETURN

END
Appendix C. Computer Program Listing of the Model

REAL MCC,NODA,NODIN,NODW,NODN,NODT,NODB,NODEA,NODEL
INTEGER R,S,T,DOSAG

DEFINITIONS OF VARIABLES

N STANDS FOR NUMBER OF REACH ON NEUSE RIVER OR TRIBUTARY
DOCA = DISSOLVED OXYGEN CONCENTRATION AT THE HEAD OF REACH, PPM
WHERE PPM STANDS FOR PARTS PER MILLION OR MILLIGRAMS PER LITER
DOCB = DISSOLVED OXYGEN CONCENTRATION AT THE END OF REACH, PPM
DOCS = DISSOLVED OXYGEN CONCENTRATION, SATURATION VALUE IN PPM
DOCW = DISSOLVED OXYGEN CONCENTRATION IN WASTE AT HEAD OF REACH, PPM
DOCt = DISSOLVED OXYGEN CONCENTRATION FROM TRIBUTARY AT HEAD OF REACH
DOCIN = DISSOLVED OXYGEN CONCENTRATION IN INCOMING FLOW TO A REACH, PPM
DOCMA = DISSOLVED OXYGEN CONCENTRATION, MINIMUM ALLOWED IN REACH, PPM
DODA = DISSOLVED OXYGEN DEFICIT AT THE HEAD OF REACH, PPM
DODB = DISSOLVED OXYGEN DEFICIT AT THE END OF REACH, PPM
DODM = DISSOLVED OXYGEN DEFICIT, MAXIMUM VALUE IN REACH, PPM
DODW = DISSOLVED OXYGEN DEFICIT IN WASTE AT HEAD OF REACH, PPM
DODT = DISSOLVED OXYGEN DEFICIT FROM TRIBUTARY AT HEAD OF REACH, PPM
DODIN = DISSOLVED OXYGEN DEFICIT IN INCOMING FLOW TO A REACH, PPM
DODMA = DISSOLVED OXYGEN DEFICIT, MAXIMUM ALLOWED IN REACH, PPM
DOCEA = DISSOLVED OXYGEN DEFICIT IN EACH SEGMENT OF A REACH, PPM
WHERE A SEGMENT IS OF A MILE OR LESS DISTANCE
BODA = ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND AT HEAD OF A REACH, PPM
BODB = ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND AT END OF A REACH, PPM
BODL = ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND OF WASTE IN LOADING
UNITS, LBS/Day
BODW = ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND IN WASTE AT HEAD OF
REACH, PPM
BODT = ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND FROM TRIBUTARY AT HEAD
OF REACH, PPM
BODN = ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND FROM NATURAL SOURCES
IN REACH, PPM
BODIN = ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND IN INCOMING FLOW TO A
REACH, PPM
BODEA = ULTIMATE CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND IN EACH SEGMENT OF A REACH, PPM

DIMENSION DDMO(25), DDIST(25), CTIME(25), DDM(25), DOSAG(25, 2)

NODEA = NITROGENOUS OXYGEN DEMAND IN EACH SEGMENT OF A REACH, PPM

NOD = NITROGENOUS OXYGEN DEMAND AT HEAD OF A REACH, PPM

NODL = NITROGENOUS OXYGEN DEMAND IN WASTE IN LOADING UNITS, LBS/DAY

NODW = NITROGENOUS OXYGEN DEMAND IN WASTE AT HEAD OF A REACH, PPM

NOD = NITROGENOUS OXYGEN DEMAND FROM TRIBUTARY AT HEAD OF A REACH, PPM

NODN = NITROGENOUS OXYGEN DEMAND FROM NATURAL SOURCES IN A REACH, PPM

NODIN = NITROGENOUS OXYGEN DEMAND IN INCOMING FLOW TO A REACH, PPM

NODEA = NITROGENOUS OXYGEN DEMAND IN EACH SEGMENT OF A REACH, PPM

PEW = POPULATION EQUIVALENT OF RAW WASTE, INDUSTRY AT HEAD OF REACH

QIN = INCOMING FLOW FROM LAST REACH, CFS

QW = VOLUME OF WASTE AT HEAD OF REACH, CFS

QT = INCOMING FLOW FROM TRIBUTARY AT HEAD OF REACH, CFS

QTOT = TOTAL FLOW IN A REACH, CFS

FLOW = REPRESENTATIVE DISCHARGE IN A SEGMENT OF RIVER COVERING A NUMBER OF REACHES AS DEFINED IN THIS PROGRAM.

T STANDS FOR THE LEVEL OF TREATMENT. SUBSCRIPTS 1, 2, 3, 4 ARE FOR NO TREATMENT, PRIMARY, SECONDARY AND TERTIARY TREATMENT RESPECTIVELY.

AREA = CROSS-SECTIONAL AREA OF THE STREAM, SQ. FEET.

WIDTH = SURFACE WIDTH OF THE STREAM, FEET

DEATH = DEPTH OF THE STREAM, FEET

V = VELOCITY OF RIVER IN FEET PER SECOND (FPS)

VEL = VELOCITY OF RIVER IN MILES PER DAY

TEMP = TEMPERATURE IN THE STREAM IN DEGREES CENIGRADE

CD = COEFFICIENT OF DEOXEGENATION FOR BOD TO THE BASE 10

CN = COEFFICIENT OF DEOXEGENATION FOR NOD TO THE BASE 10

CA = COEFFICIENT OF REAERATION TO THE BASE 10

CA20 = COEFFICIENT OF REAERATION AT 20 DEGREES CENIGRADE.

COMMON T(25), PEW(25), BOD(4, 25), BODN(25), BODT(4, 25), BODA(4, 25),

1BOD(4, 25), QIN(25), QW(25), QT(25), QTOT(25), DD (25), BODN(25),


5K(25), DOC(25), TEM(25), AREA(25), WIDTH(25), CA20(25), DEATH(25),

6FLOW(25), NODA(4, 25), NODIN(25), NODL(4, 25), NODT(4, 25),

7NODN(4, 25), NODEA(4, 25), NODL(4, 25), E3(25), TIMA, CN(25), DODEA(4, 25),

8BODEA(4, 25)

TIMA = TIME IN EACH SEGMENT OF A REACH, DAYS

TIME = TIME OF TRAVEL IN REACH IN DAYS

DIST = DISTANCE OF TRAVEL IN REACH (LENGTH OF REACH), MILES

CDIST = CUMULATIVE DISTANCE UPTO THE END OF REACH, MILES

DMCQ = INCREASE IN MARGINAL COST WITH A HIGHER LEVEL OF TREATMENT PER MILLION GALLONS OF WASTE, $/MG

DMC = TOTAL INCREASE IN MARGINAL COST PER DAY WITH A HIGHER LEVEL OF
TREATMENT FOR AN INDUSTRY, \$/T/DAY

\( \text{MCC} = \text{MARGINAL COST COEFFICIENT FOR AN INDUSTRY, } \text{DMC/DDDT} \)

\( \text{BMCC} = \text{BEST MARGINAL COST COEFFICIENT} \)

\( \text{NBEST} = \text{NUMBER OF REACH WHERE THERE IS MINIMUM MARGINAL COST} \)

\( \text{DDDOD} = \text{DISSOLVED OXYGEN DEFICIT, MAXIMUM, OLD VALUE, THAT IS, BEFORE} \)

\( \text{CALL TREATMENT IS INCREASED IN ANY UPSTREAM REACH} \)

\( \text{DDDOD} = \text{DECREASE IN DISSOLVE OXYGEN DEFICIT IN THE LAST REACH WITH A} \)

\( \text{HIGHER LEVEL OF TREATMENT IN GIVEN REACH, DDDOD/T} \)

\( \text{COST} = \text{THE COST OF TREATMENT PER DAY FOR THE REACH SPECIFIED, } \$ \)

\( \text{TCD} = \text{TOTAL COST OF WASTE TREATMENT FOR ALL REACHES OF NEUSE RIVER, } \$ \)

\( \text{DOCSD} = \text{THE ARRAY OF TREATMENT LEVELS IN ANY ROUND OF COMPUTATIONS} \)

---

************ DO SAG ANALYSIS FOR NEUSE RIVER TRIBUTARIES ************

*** END ***

READ(1,10)PEW(N),QW(N),DOCW(N),BODIN(N),QIN(N),DOCIN(N),
IV(N),DISTIN(QTIN),DOCIS(N),TEMP(N),QTOT(N),WIDTH(N),
2FLOW(N),CNIN(N),NODIN(N),TIN(N),N=1,2)

10 FORMAT(8F10.2/8F10.2/12)

READ(1,140) (BODT(M,N),DOCT(M,N),M=1,4),N=1,2)

READ(1,140) (NODT(M,N),M=1,4),N=1,2)

ANALYSIS FOR CRABTREE CREEK BEGINS.

N=1

M=1

12 CALL COMPUN(N)

14 DO 15 M=1,4

15 END

12 CALL COMPUN(N)

14 DO 15 M=1,4

15 END

WRITE(3,20)

20 FORMAT(50X,'DATA FOR CRABTREE CREEK')

WRITE(3,25)

25 FORMAT(9X,'N',6X,'T(N)',5X,'QW(N)',5X,'QIN(N)',3X,'QTOT(N)',5X,'TEMP(N)',3X,'DIST(N)',
23X,'TIME(N)'/)

WRITE(3,30) N,TIN(QW(N),QTIN),QIN(N),QTOT(N),TEMP(N),AREA(N),WIDTH(N),TIME(N)

30 FORMAT(210,10F10.2)

WRITE(3,35)

35 FORMAT(4X,'N',4X,'PEW(N)',1X,'BODL(N)',3X,'BODIN(N)',3X,'DOCW(N)',
1X,'QW(N)',3X,'QIN(N)',3X,'QTOT(N)',3X,'TEMP(N)',3X,
2'AREA(N)',2X,'WIDTH(N)',2X,'DEPTH(N)',3X,'FLOW(N)'/)

WRITE(3,40) N,PEW(N),BODL(N),BODIN(N),DOCW(N),BODIN(N),DOCIN(N),
100CS(N),TEMP(N),AREA(N),WIDTH(N),DEPTH(N),FLOW(N)

40 FORMAT(/15,12F10.2)

50
ANALYSIS FOR LITTLE RIVER BEGINS.

N=2
M=1
CALL COMPU(N)
DO 70 M=1,4
CALL SAG1(N)
BODT(M,21)=BODB(M,N)
NODT(M,21)=NODB(N,N)
QT(21)=QTOT(N)
70 CDDT(M,21)=DODB(M,N)
WRITE (3,75)
75 FORMAT(/50X,'DATA FOR LITTLE RIVER'/)
WRITE(3,25)
WRITE(3,30) N,T(N),QW(N),QT(N),QW(N),QTOT(N),CA(N),CD,V(N),VEL(N)
1, DIST(N),TIME(N)
WRITE(3,35)
WRITE(3,40) PEW(N),BOD1(N),BODIN(N),DOCW(N),BODIN(N),BODIN(N),
1,DCS(N),TEMP(N),AREA(N),WIDTH(N),DEPTH(N),FLOW(N)
WRITE(3,45)
WRITE(3,40) M,BODW(M,N),DODB(M,N),BODT(M,N),NODT(M,N),DODT(M,N),
1,BODA(M,N),BODB(M,N),NODA(M,N),NODB(M,N),DDCA(M,N),DDDB(M)
2,N);M=1,4)
WRITE(3,55)
WRITE(3,60) N,NODIN(N),NODN(N),CN(N)
C C
C DATA FOR DO SAG ANALYSIS IN NEUSE RIVER
C C
C
N=25
READ(1,140) (PEW(I),I=3,N)
READ(1,140) (QW(I),I=3,N)
READ(1,140) (QT(I),I=3,12)
READ(1,112) (QT(I),I=14,20)
READ(1,112) (QT(I),I=22,4)
111 FORMAT (7F10.2)
112 FORMAT (4F10.2)
DO 115 I=3,12
DO 115 M=1,4
NODT(M, I)=0.0
CODT(M, I)=0.0
115 BOOT(M, I)=0.0
DO 116 I=14,20
DO 116 M=1,4
NODT(M, I)=0.0
CODT(M, I)=0.0
116 BOOT(M, I)=0.0
DO 117 I=22,4
DO 117 M=1,4
NODT(M, I)=0.0
CODT(M, I)=0.0
117 BOOT(M, I)=0.0
READ(1, 140) (CN(I), I=3,N)
READ(1, 140) (FLOW(I), I=3,N)
READ(1, 140) (QTOT(I), I=3,N)
READ(1, 140) (TEMP(I), I=3,N)
READ(1, 140) (WIDTH(I), I=3,N)
READ(1, 140) (DOCS(I), I=3,N)
READ(1, 140) (DOCW(I), I=3,N)
READ(1, 140) (V(I), I=3,N)
READ(1, 140) (DIST(I), I=3,N)
READ(1, 140) (DOCMA(I), I=3,N)
DO 120 I=3,N
M=1
CALL COMPU(I)
120 CONTINUE
READ(1, 130) (T(I), I=3,N)
130 FORMAT (23I2)
READ(1, 141) (DMCQ(M, I), I=3,N, M=2,4)
140 FORMAT (8F10.2)
141 FORMAT (8F10.2/8F10.2/7F10.2)
I=3
READ(1, 150) BODIN(I), QIN(I), DOCIN(I), NODIN(I)
150 FORMAT (4F10.2)
BODIN(I)=DOCS(I)-DOCIN(I)
CD=0.14
DO 170 I=3,N
DO 170 M=1,4
170 DOW(M, I)=DOCS(I)-DOCW(I)
DO 260 I=3,N
DOCMA(I)=DOCS(I)-DOCMA(I)
VEL(I)=V(I)/0.0611
C 1 MILE PER DAY=0.0611 FEET PER SECOND
260 TIME(I)=DIST(I)/VEL(I)
CDIST(3)=DIST(3)
CTIME(3)=TIME(3)
DO 270 I=4,N
CTIME(I)=CTIME(I-1)+TIME(I)
CCIST(I)=CDIST(I-1)+DIST(I)

DO 280 I=3,12
DO 280 M=2,4
280 DMC(M,I)=DMCQ(M,I)*QW(I)*.646
DO 281 I=1,4
DO 281 M=2,4
281 DMC(M,13)=DMCQ(M,13)*(QW(13)+QT(13))*.646
DO 282 I=1,4
DO 282 M=2,4
282 DMC(M,21)=DMCQ(M,21)*(QW(21)+QT(21))*.646
DO 284 I=22,25
DO 284 M=2,4
284 DMC(M,I)=DMCQ(M,I)*QW(I)*.646

C
1 CUBIC FEET PER SECOND (CFS) = .646 MILLION GALLON PER DAY (MGD)
WRITE(3,290)
290 FORMAT(40X,'DATA FOR DO SAG ANALYSIS IN NEUSE RIVER')
WRITE(3,300)
300 FORMAT(8X,'5X,T(I)',4X,'QW(I)',4X,'QT(I)',4X,'CA(I)',5X,
1X,'VEL(I)',2X,'DIST(I)',2X,'TIME(I)',1X,'DIST(I)',1X,
2X,'TIME(I)',1X,'DOCMA(I)',1X,'DODMA(I)')/
WRITE(3,310) (T(I),QW(I),QT(I),CA(I),VEL(I),DIST(I),TIME(I),
1CDIST(I),CTIME(I),DOCMA(I),DODMA(I),I=3,N)
310 FORMAT(219,11F9.2)
320 FORMAT(4X,'9X,PETW(I)',1X,'BODL(1,I)',1X,'BODW(1,I)',1X,
1X,'BODW(2,I)',1X,'BODW(3,I)',1X,'BODW(4,I)',3X,'DDCMW(I)',1X,'DODW(1,I),
21)',1X,'DODW(2,I)',1X,'DODW(3,I)',1X,'DODW(4,I)'/)
WRITE(3,330) (PETW(I),BODL(1,I),BODW(1,I),BODW(2,I),BODW(3,I),
1BODW(4,I),DDCMW(I),DODW(1,I),DODW(2,I),DODW(3,I),DODW(4,I),I=3,N)
330 FORMAT(15,F15.2,10F10.2)
340 FORMAT(9X,'9X,BODT(1,I)',1X,'BODW(2,I)',1X,'BODT(3,I)',1X,
1X,'BODT(4,I)',3X,'DODT(1,I)',1X,'DODT(2,I)',1X,'DODT(3,I)',1X,
2X,'DODT(4,I)',3X,'BODN(I)')/
WRITE(3,350) (BODT(1,I),BODT(2,I),BODT(3,I),BODT(4,I),DODT(1,I),
1DODT(2,I),DODT(3,I),DODT(4,I),BODN(I),I=3,N)
350 FORMAT(110,9F10.2)
WRITE(3,360)
360 FORMAT(9X,'9X,BODCQ(2,I)',1X,'BODCQ(3,I)',1X,'BODCQ(4,I)',2X,
1X,'BODCQ(2,I)',1X,'BODCQ(3,I)',1X,'BODCQ(4,I)',3X,'DDCQSI(I)',3X,'TEMP(I)',
23X,'AREA(I)',2X,'WIDTH(I)',3X,'FLOW(I)'/)
WRITE(3,370) (BODCQ(2,I),BODCQ(3,I),BODCQ(4,I),BDMC(2,I),BDMC(3,I),
1BDMC(4,I),DDCQSI(I),TEMP(I),AREA(I),WIDTH(I),FLOW(I),I=3,N)
370 FORMAT(110,11F10.2)
WRITE(3,380)
380 FORMAT(12X,'BODIN(3)',4X,'QIN(3)',2X,'DODIN(3)',2X,'DODIN(3)',
18X,'CD',2X,'BODIN(3)')/
WRITE(3,389) BODIN(3),QIN(3),DOCIN(3),DODIN(3),CD,NODIN(3)
385 FORMAT(10X, 6F10.2/)
WRITE(3,386)
386 FORMAT( /4X,'I',5X,'CN(I)',3X,'NODN(I)',1X,'NODL(I)',1X,'NODW(I)',1X,'NODM(2, I)',1X,'NODW(3, I)',1X,'NODW(4, I)',1X,'NODT(1, I)',1X,'NODT(2, I)',1X,'NODT(3, I)',1X,'NODT(4, I)'/)
WRITE(3,387) I, CN(I), NODN(I), NODL(I), NODM(2, I), NODW(3, I), NODW(4, I), NODT(1, I), NODT(2, I), NODT(3, I), NODT(4, I), I=3, N)
387 FORMAT(15,1F10.2/)

C-------------------------------------------------------------------------
C CO SAG ANALYSIS IN NEUSE RIVER DUE TO EXISTING TREATMENT LEVELS
C-------------------------------------------------------------------------

K=1
N=25
CALL SAG1P(N)

390 FORMAT(10X,'RESULTS OF CO SAG ANALYSIS IN NEUSE RIVER DUE TO EXISTING TREATMENT LEVELS.
* ITERATION, K=1'/'
WRITE(3,390)

400 FORMAT( /9X,'I',9X,'M',6X,'T(I)',3X,'QTOT(I)',1X,'BODA(M)',1X,'BODM(2, M)',1X,'BODW(3, M)',1X,'BODW(4, M)',1X,'BODT(1, M)',1X,'BODT(2, M)',1X,'BODT(3, M)',1X,'BODT(4, M)',1X,'QIN(I)',1X,'QODN(I)',1X,'QODM(I)',1X,'QODW(I)',1X,'QODT(I)',1X,'QODT(2, I)',1X,'QODT(3, I)',1X,'QODT(4, I)',1X,'M=I(I)'/)
WRITE(3,400) I, M, T(I), QTOT(I), BODA(M), BODM(2, M), BODW(3, M), BODW(4, M), BODT(1, M), BODT(2, M), BODT(3, M), BODT(4, M), QIN(I), QODN(I), QODM(I), QODW(I), QODT(I), M=I(I)

410 FORMAT(15,10F10.2/)
415 CONTINUE
WRITE(3,420)

420 FORMAT( /4X,'I',4X,'M',3X,'TIME(I)',1X,'QODM(M)',2X,'BODIN(I)',1X,'QODIN(I)',2X,'BODIN(I)',1X,'QODIN(I)',2X,'BODIN(I)',1X,'QODIN(I)',2X,'BODIN(I)',1X,'QODIN(I)',2X,'BODIN(I)',1X,'QODIN(I)',2X,'BODIN(I)',1X,'QODIN(I)',2X,'BODIN(I)',1X,'QODIN(I)',2X,'BODIN(I)',1X,'QODIN(I)',2X,'BODIN(I)',1X,'QODIN(I)',2X,'BODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)',1X,'QODIN(I)'...
C

THE "BARGAINING APPROACH" SOLUTION FOR LEAST-COST WASTE TREATMENT LEVELS ALONG NEUSE RIVER AND CORRESPONDING DO SAG ANALYSIS

C

N=25

WRITE(3,530)
530 FORMAT(//,5X,'INTERIM RESULTS OF THE BARGAINING APPROACH'/)

K=K+1
WRITE(3,545)K
545 FORMAT(/,5X,'THIS IS THE START OF ITERATION, K=',I5/)

S=3
WRITE(3,550)
550 CALL SAGII(S)
WRITE(3,555)S,M,DODM(M,S),DODMA(S)
555 FORMAT(//,15X,'CURRENT REACH UPTO WHICH ANALYSIS HAS PROGRESSED, S=',I5/)

CALL SAGII(S)
WRITE(3,560)
560 FORMAT(/,10X,'THIS IS THE START OF ITERATION, K=',I5/)

S=M
WRITE(3,565)
565 FORMAT(/,10X,'LET US SEE IN WHICH REACH FROM 3 TO S WE SHOULD INCREASE TREATMENT IN ORDER TO SATISFY OXYGEN CONSTRAINT IN REACH S'/)

BMCC=0.9*(10.0**7.50)

WRITE(3,570)
570 FORMAT(/,10X,'INITIAL VALUES: BMCC=',E15.8,10X,'NBEST=',I5,10X,'DODM(S)=',F10.7/)

CALL SAGII(S)
WRITE(3,571)
571 FORMAT(/,10X,'PROCEDURE TO FIND NBEST, ITS MCC AND DODM FOLLOWS'/)

IF(T(L)*NE.4.0) GO TO 5747
WRITE(3,572)L
572 FORMAT(/,10X,'TREATMENT IN REACH L=',I2,1X,'CANNOT BE INCREASED ANY MORE AS IT IS ALREADY=4'/'

GO TO 581

T(L)=T(L)+1
M=T(L)
IF(DMC(M,L),GT.0.0001) GO TO 5747
WRITE(3,573)M
573 FORMAT(/,10X,'TREATMENT LEVEL IN REACH L=',I2,1X,'CANNOT BE INCREASED AS THERE IS NO WASTE IN THE REACH'/)

GO TO 578
5747 WRITE(3,5748) L
5748 FORMAT(*X,'REACH WHERE TREATMENT LEVEL HAS BEEN TEMPORARILY INCREASED')
      CALL SAG1(L)
      WRITE(3,5760)L,T(S),M,DODM(M,S),DODMA(S)
5760 FORMAT(I0X,'S=',I5,10X,'T(S)=',I5,10X,'M=',I5,10X,'DODM(M,S)=',I5,10X,'DODMA(S)=',F10.7)
      IF(DODDT(L).GT.0.0) GO TO 5761
      DODDT(L)=0.0001
5761 M=T(L)
      MCC(L)=DMC(M,L)/DODDT(L)
      IF(MCC(L).GE.BMCC) GO TO 5762
5762 WRITE(3,5777)L,T(L),M,DODDT(L),DMC(L,M),MCC(L),BMCC
5777 FORMAT(/I0X,'L=',I5,10X,'T(L)=',I5,10X,'M=',I5,9X,'DODM(L)=',F10.7)
5778 T(L)=T(L)-1
581 CONTINUE
584 FORMAT(*X,'PROCEDURE TO FIND NBEST ETC. FINISHES')
585 WRITE(3,585)BMCC,NBEST
585 FORMAT(/I0X,'BMCC=',E15.8,I0X,'NBEST=',I10)
590 FORMAT(*X,'THE WASTE LOAD DUE TO INDUSTRY IN REACH S=',I2,1X,
      1'CALL SAG1(S) THAT EVEN AFTER MAXIMUM POSSIBLE TREATMENT AND BUYING AT FULL CAPACITY, TREATMENTS FROM UPSTREAM REACHES, THE D.C. CONSTRAINT IS NOT SATISFIED. THE INDUSTRY HAS TO REDUCE ITS WASTE BY IN-LINE CHANGES, OR LOWER ITS PRODUCTION LEVEL OR MUST BE FORCED TO GO OUT OF BUSINESS')
591 GO TO 800
600 NBEST=NBEST+1
      CALL SAG1(S)
      WRITE(3,606)S,M,DODM(M,S),DODMA(S)
606 FORMAT(*X,'AFTER INCREASING T(NBEST) BY 1, S=',I5,10X,'M=',I5,10X,'DODM(M,S)=',I5,10X,'DODMA(S)=',F10.7)
      IF(DODM(M,S).GT.DODMA(S)) Go TO 560
      IF(NBEST.EQ.S) GO TO 620
      IF(NBEST.EQ.I1) GO TO 620
610 IF(T(S).EQ.0) GO TO 620
      T(S)=T(S)-1
581 CONTINUE
614 FORMAT(*X,'BARGAINING STEP, INDUSTRY IN REACH S TRIES TO DECREASE ITS TREATMENT BY BUYING IT FROM THOSE UPSTREAM')
      CALL SAG1(S)
      WRITE(3,616)S,M,DODM(M,S),DODMA(S)
616 FORMAT(*X,'AFTER DECREASING T(S) BY 1, S=',I5,10X,'M=',I5,10X,
      1'DODM(M,S)=',F10.7,I0X,'DODMA(S)=',F10.7)
      IF(DODM(M,S)-DODMA(S)) .GT. 0.0 GO TO 610
550 GO TO 800
560 CONTINUE
561 WRITE(3,561)BMCC,NBEST
561 FORMAT(/I0X,'BMCC=',E15.8,I0X,'NBEST=',I10)
      IF(NBEST.GT.0) GO TO 600
      WRITE(3,590)S
      WRITE(3,591)S
      WRITE(3,592)S
      WRITE(3,593)S
      WRITE(3,594)S
620 S=S+1
IF (S.GT.N) GO TO 630
GO TO 546

630 CALL TCOST(N)
DO 640 I=3,N
640 DOSAG(K,I)=T(I)
WRITE(3,670)

670 FORMAT(/50X,'OUTPUT DATA FOR BARGAINING APPROACH SOLUTION*/)
CALL SAGIP(N)
680 WRITE(3,400)
DO 695 I=3,N

695 CONTINUE
WRITE(3,420)
DO 715 I=3,N
M=T(I)
WRITE(3,430) I,M,TIME(I),DODM(M,I),BODINI(I),QIN(I),DODIN(I),INODIN(I)
715 CONTINUE
WRITE(3,720)

720 FORMAT(/9X,'I',9X,'M',6X,'T(I)',3X,'COST(I)',2X,'DMC(2,I)',2X,'DSG(3,I)',2X,'DMC(4,I)')
DO 735 I=3,N

735 CONTINUE
WRITE(3,740)

740 FORMAT(/4X,'K',10X,'TC(I)',6X,'T(3)',14X,'T(4)',14X,'T(5)',14X,'T(6)',14X,'T(7)',14X,'T(8)',14X,'T(9)',14X,'T(10)',14X,'T(11)',14X,'T(12)',14X,'T(13)',14X,'T(14)',14X,'T(15)',14X,'T(16)',14X,'T(17)',14X,'T(18)',14X,'T(19)',14X,'T(20)',14X,'T(21)',14X,'T(22)',14X,'T(23)',14X,'T(24)',14X,'T(25)',14X)
WRITE(3,750) (R,TC(R),DOSAG(R,3),DOSAG(R,5),DOSAG(R,6),DOSAG(R,7),DOSAG(R,8),DOSAG(R,9),DOSAG(R,10),DOSAG(R,11),DOSAG(R,12),DOSAG(R,13),DOSAG(R,14),DOSAG(R,15),DOSAG(R,16),DOSAG(R,17),DOSAG(R,18),DOSAG(R,19),DOSAG(R,20),DOSAG(R,21),DOSAG(R,22),DOSAG(R,23),DOSAG(R,24),DOSAG(R,25),R=1,K)

750 FORMAT(/15,E15.8,6X,2341/)

760 FORMAT(10X,THE PROGRAM IS SATISFACIOTRILY COMPLETED*/)
800 CALL EXIT
DEBUG SUBCHK
END

SUBROUTINE COMPUTE(N)
C
SUBROUTINE COMPUTE(N) CALCULATES CA(N) AND BODM(N,N) FOR GIVEN DATA
C
REAL MC,CA,NOA,NOB,NODA,NODB,NOO,NOON,NOOL,NOOOL,NOOON,NOOONL
COMMON T(25),PAW(28),BODM(4,25),BODIN(25),BODT(4,25),BODA(4,25),
180DB(4,25),QIN(25),QN(25),QT(25),QTOT(25),DOCW(25),BODN(25),
ISUBROUTINE SAGI(N)

AREA(N) = FLOW(N) / V(N)
DEPTH(N) = AREA(N) / WIDTH(N)
CA20(N) = 1.65 * (V(N) / DEPTH(N)) ** (4. / 3.1)
CA(N) = CA20(N) * (1.047 * (TEMP(N) - 20))

BDNL(M,N) = 10.239 * PEW(N)

BDW(M,N) = BDNL(M,N) / (QW(N) * 0.646 ** 8.36)

1 CUBIC FEET PER SECOND (CFS) = 0.646 MILLION GALLON PER DAY (MGD)

1 P.P.M. = 8.36 POUNDS PER MILLION GALLONS

BDW(M+1,N) = (1 - 0.38) * BDW(M,N)

BDW(M+2,N) = (1 - 0.90) * BDW(M,N)

BDW(M+3,N) = (1 - 0.99) * BDW(M,N)

BDW(M,N) = (1 - 0.12) * PEW(N)

BDW(M,N) = BDW(M,N) / (QW(N) * 0.646 ** 8.34)

NODW(M+1,N) = (1 - 0.10) * NODW(M,N)

NODW(M+2,N) = (1 - 0.50) * NODW(M,N)

NODW(M+3,N) = (1 - 0.95) * NODW(M,N)

BDW(N) = 1.5

NODW(N) = 0.0

RETURN

END

SUBROUTINE SAGI(N)

SUBROUTINE SAGI COMPUTES DO PROFILE FOR NEUSE RIVER TRIBUTRIES

REAL MCQ, NODA, NODIN, NODW, NODN, NODT, NODB, NODEA, NODL
3CA(25), COV(25), VEL(25), TIME(25), DIST(25), COST(25), TC(25),
SKM(25), DOCS(25), TEMP(25), AREA(25), WIDTH(25), CA20(25), DEPTH(25),
6FLOW(25), NODA(4, 25), NODIN(25), NODW(4, 25), NODN(25), NODT(4, 25),
7NODB(4, 25), NODEA(4, 25), NODL(4, 25), E3(25), TIMA, CN(25), BDDEA(4, 25),
8BDDEA(4, 25)

DDW(M,N) = DOCS(N) - DOCW(N)

DDOT(M,N) = DOCS(N) - DOC(T,M,N)

DDIN(N) = DOCS(N) - DOC(N)

CD = 0.14

VEL(N) = V(N) / 0.0611

58
C

1 MILE PER DAY = 0.0611 FEET PER SECOND
TIME(N)=DIST(N)/VEL(N)
BDOM(N,K)=BDIN(N)*QIN(N)+BDW(N)*QW(N)+BDT(N)*QT(N)+BON(N)
1+QW(N)+QT(N))/QTOT(N)
NODA(N,K)=NODIN(N)*QIN(N)+NODW(N)*QW(N)+NODT(N)*QT(N)+NODN(N)
1+QW(N)+QT(N))/QTOT(N)
DODA(N,K)=((BDIN(N)*QIN(N)+BDW(N)*QW(N)+BDT(N)*QT(N))/QTOT(N)
1(N)
E1(N)=10.0**(-CD*T(N))
E2(N)=10.0**(-CA(N)*T(N))
E3(N)=10.0**(-CN(N)*T(N))
DODA(N,K)=((CD*BDA(N,K)))/(CA(N)-CD))**(E1(N)-E2(N))**((CN(N)
1+NODA(N,K))/(CA(N)-CN(N))**(E3(N)-E2(N))+DODA(N,K)*E2(N)
BDA(N,K)=BDIN(N,K)*E1(N))
NODA(N,K)=NOD(N,K)*E3(N)
RETURN
END

SUBROUTINE SAGII(N)

C

SUBROUTINE SAGII COMPUTES DO PROFILE FOR REACHES OF NEUSE RIVER

REAL MCC,NDDA,NDDIN,NDDW,NDDN,NDDT,NDDB,NODEA,NDDL
INTEGER R,S,T,DDAG
COMMON T(25),PEN(25),BDOW(4,25),BDIN(26),BDOT(4,25),BODA(4,25),
1BDW(4,25),QIN(26),QW(25),QT(25),QTOT(26),DCW(25),BODN(25),
3CA(25),CDV(25),VEL(25),TIME(25),DIST(25),GOST(25),TC(25),
5DCIN(26),5K,M,DOCS(25),H(25),AREA(25),WIDTH(25),CA(20,25),DEPP(25),
6BDOW(25),NODD(4,25),NOD(25),NODW(4,25),NODN(25),NODT(4,25),
7NODB(4,25),NODEA(4,25),NODL(4,25),E3(25),TIMA,CN,NDDA(4,25),
8BDDEA(4,25)

C

DO 820 I=3,N
785

M=N(I)

BDOMA(N,K)=BDIN(N)*QIN(N)+BDW(N,M)*QW(N)+BDT(N)*QT(N)+BON(N)
1+QW(N)+QT(N))/QTOT(N)
NODA(N,K)=NODIN(N)*QIN(N)+NODW(N,M)*QW(N)+NODT(N)*QT(N)+NODN(N)
1+QW(N)+QT(N))/QTOT(N)
DODA(N,K)=((BDIN(N)*QIN(N)+BDW(N,M)*QW(N)+BDT(N)*QT(N))/QTOT(N)
1(N)
TIMA=0.00
DODM(N,K)=DODA(N,K)
780 TIMA=TIMA+0.04
IF(TIMA.GE.TIME(I)) GO TO 790
GO TO 792
790 TIMA=TIME(I)
792 E1(I)=10.0**(-CD*TIMA)
E2(I)=10.0**(-CA(I)*TIMA)

59
SUBROUTINE SAGIP(N)

GIVES DO PROFILE FOR REACHES OF NEUSE RIVER

REAL MCC, NODA, NODIN, NODW, NODN, NODT, NODB, NODEA, NCDL
INTEGER R, S, T, DOSAG
1 BODB(4, 25), QIN(26), QW(25), QT(26), QTOT(26), DCW(25), RODN(25),
4 NOD(4, 25), NOD(25), NOD(25), NOD(25), NCDL(1, 1), TC(25),
5 MC(25), E(25), T(25), BODL(4, 25), OCDM(25), DLC(25), DCIN(25),
6 SQ(25), DCCT(25), AREA(25), W(25), CW(25), DEPTH(25),
7 FL(25), NODA(4, 25), NODIN(25), NODW(4, 25), NOD(25), NCDL(4, 25),
8 BODL(4, 25), NODE(4, 25), NODE(25), NODE(25), NODE(25),
9 NCDL(1, 1), TC(25), E(25), T(25), TIMA, MC(25), BODA(4, 25),

WRITE (3, 775)


GO TO 820

1 = 3, N

785 M= M+ 1

TQ= TQ+ QT

NODA(1)= NODA(1)+ NOD(1)+ NOD(1)+ NOD(1)+ NOD(1)

1= (QW+ QT)/QT

NODA(1)= NODA(1)+ NOD(1)+ NOD(1)+ NOD(1)+ NOD(1)

1= QW+ QT

NODA(1)= NODA(1)+ NOD(1)+ NOD(1)+ NOD(1)+ NOD(1)

1= (QW+ QT)/QT

TIMA= 0.00

780 TIMA= TIMA+ 0.04

END
IF(TIMA.GE.TIME(I)) GO TO 790
GO TO 792
790 TIMA=TIME(I)
792 E1(I)=10.0*1(-CD*TIMA)
E2(I)=10.0*1(-CA(I)*TIMA)
E3(I)=10.0*1(-CN(I)*TIMA)
CODEA(M,I)=(CD*BODA(M,I))/((CA(I)-CD))+(E1(I)-E2(I))+(CN(I))
*NODEA(M,I)+((CA(I)-CN(I))*E3(I)+2*CODEA(M,I)*CODEA(M,I))
BODEA(M,I)=BODEA(M,I)+(E1(I))
NODEA(M,I)=NODEA(M,I)+E3(I)
WRITE (3,794) I,TIME(I),TIME(I),CODEA(M,I),BODEA(M,I),NODEA(M,I),
E3(I)
794 FORMAT ('**',2110,5F12.2,110)
IF(TIMA.GE.TIME(I)) GO TO 795
CODM(M,I)=CODEA(M,I)
GO TO 780
795 IF(TIMA.GE.TIME(I)) GO TO 810
GO TO 780
810 CODB(M,I)=CODEA(M,I)
BODEB(M,I)=BODEA(M,I)
NODEB(M,I)=NODEA(M,I)
815 MODI(I)=MODB(I)
QIN(I+1)=QTOT(I)
NODIY(I+1)=NOOB(M,I)
820 CODB(I+1)=MODB(I)
RETURN
END

SUBROUTINE TCOST(N)

SUBROUTINE TCOST COMPUTES THE TOTAL COST OF WATER QUALITY MANAGEMENT DUE TO DIFFERENT LEVELS OF TREATMENT IN ALL THE REACHES OF 2NEUSE RIVER

INTEGER R,S,T,DOSAG
REAL MCG,NODA,NODN,NOBN,NODR,NODEA,NCOL
CODMON T(25),PEW(25),BODW(4,25),BODIN(26),BODT(4,25),BODA(4,25),
1BODB(4,25),QIN(26),QW(25),QT(26),QTOT(26),DCOM(25),BDON(25),
2CODIN(26),DCOW(4,25),DCOT(4,25),DCOA(4,25),NOOB(4,25),DCOM(4,25),
3CA(25),CQ,V(25),V(25),Q(25),Q(25),TIME(25),DIST(25),COST(25),TC(25),
7NODR(4,25),NODEA(4,25),NODN(4,25),E3(25),TIMA,CN(25),CODEA(4,25),
8BODEA(4,25)

DO 905 I=1,N
M=T(I)
COST(I)=0.0
IF (M.EQ.1) GO TO 905

905 CONTINUE
DO 900 J=2,M
900  COST(I)=COST(I)+DMC(J,I)
905 CONTINUE
TC(K)=0.0
CD 910 I=3,N
910  TC(K)=TC(K)+COST(I)
RETURN
END