AN EVALUATION OF AVAILABLE DISSOLVED OXYGEN SIMULATION APPROACHES TO A SIMPLE RIVER SYSTEM IN OKLAHOMA

By

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CHAPTER I

INTRODUCTION

The intent of this work was to test available steady-state dissolved oxygen models for wasteload allocations. The features, capabilities, limitations and applicability of a selected set of available models were evaluated by comparative application of the appropriate models to a hydraulically simple river system in Oklahoma. This work was designed to provide guidance on the advantages and disadvantages of some of the many available dissolved oxygen models.

The methods evaluated were readily available and ranged from simple nomographs which predate modern computers to computer modeling software packages originally designed for mainframe computers and subsequently modified to execute on microcomputers. All of the models and nomographs evaluated were based upon the coupled dissolved oxygen-biochemical oxygen demand equation, also known as the Streeter-Phelps approach (Appendix).

The following dissolved oxygen models were evaluated: the River Model for Dissolved Oxygen (Elliot and James, 1986), OSUDOX, which is based upon models written by Thomann (1972), the Steady-State, One-Dimensional River Network Model (Wu, 1986), McBride's Nomograph (McBride, 1982), and the Simplified Mathematical Modeling of Water Quality Nomograph (Hydroscience, Inc., 1971).

The River Model for Dissolved Oxygen, was unique in the utilization of a dispersion coefficient in the calculation of dissolved oxygen concentrations. Also, it was the only finite-difference simulation method evaluated. Finite-difference models use differential equations to calculate the dissolved oxygen concentrations predicted along the river system. This model was capable of handling biochemical oxygen demand (BOD) removal, addition and decay. Reaeration, photosynthetic/respiratory loads as well as benthic demands were incorporated in the final calculation of dissolved oxygen concentration. This model did not however, have the capability of simulating the effects of nitrification on stream dissolved oxygen (Elliot and James, 1986).

The second model, OSUDOX, was a steady-state model which was capable of dealing with many complex stream conditions, including multiple stream segments, branched river systems, as well as point and non-point source wasteloads. OSUDOX takes in to account the effects of benthic demands, photosynthetic/respiratory demands, altitude, carbonaceous biochemical oxygen demand (CBOD), removal and decay, as well as nitrogenous biochemical oxygen demand (NBOD), removal and decay in the calculation of dissolved oxygen concentration (Thomann, 1972).

The Steady-State, One-Dimensional River Network Model was similar to OSUDOX in the ability to handle complex stream parameters such as multiple segments and branched stream systems, along with point source and uniform load non-point source wasteloads. The River Network Model utilizes five day Biochemical Oxygen Demand (BOD_5) removal and decay, along with nitrification, benthic demands, and net photosynthetic/ respiratory loads in the calculation of dissolved oxygen concentration (Wu, 1986).

The first non-computer based method listed, the McBride's Nomograph, deals with steady-state, unsegmented and unbranched river systems which receive no external waste load inputs. This nomograph utilizes five day biochemical oxygen demand (BOD_5) decay, along with stream reareation and deoxygenation in the calculation of dissolved oxygen deficit. This method fails to address the effects of nitrification on stream dissolved oxygen concentration however (McBride, 1982)

The Simplified Mathematical Modeling of Water Quality Nomograph models steady-state unsegmented streams with a single wasteload input. In the calculation of dissolved oxygen deficit this method uses five day biochemical oxygen demand (BOD_5) decay, in addition to stream reareation and deoxygenation while failing to consider the effects of nitrification (Hydroscience, Inc., 1971).

CHAPTER II

SITE SELECTION

A simple, hydraulically uncontrolled and unbranched stream system with one upstream point source pollutant load was sought to test these various models. These types of conditions should lend themselves to the simplest of codes or nomographs, i.e. those which do not require stream segmentation for analysis. The criteria for selection of an appropriate stream system to simulate included: availability of data, simplicity of stream hydraulics and utility of the site to real world applications and subsequent analysis. The Oklahoma State Health Department was contacted to assist in the site selection process. At the Department's suggestion, a segment of Kingfisher Creek located in Sec 15 T16N R07W, Kingfisher County, Oklahoma was chosen for this effort. The relative position of the study area is illustrated in Figure 1 (Oklahoma State Health Department, 1985).

Previous to the current study, the Health Department collected data during an intensive survey conducted at this site. These data were judged appropriate for this effort and served to create input data for the three computer models and the two nomographs previously described (Tables I and II).

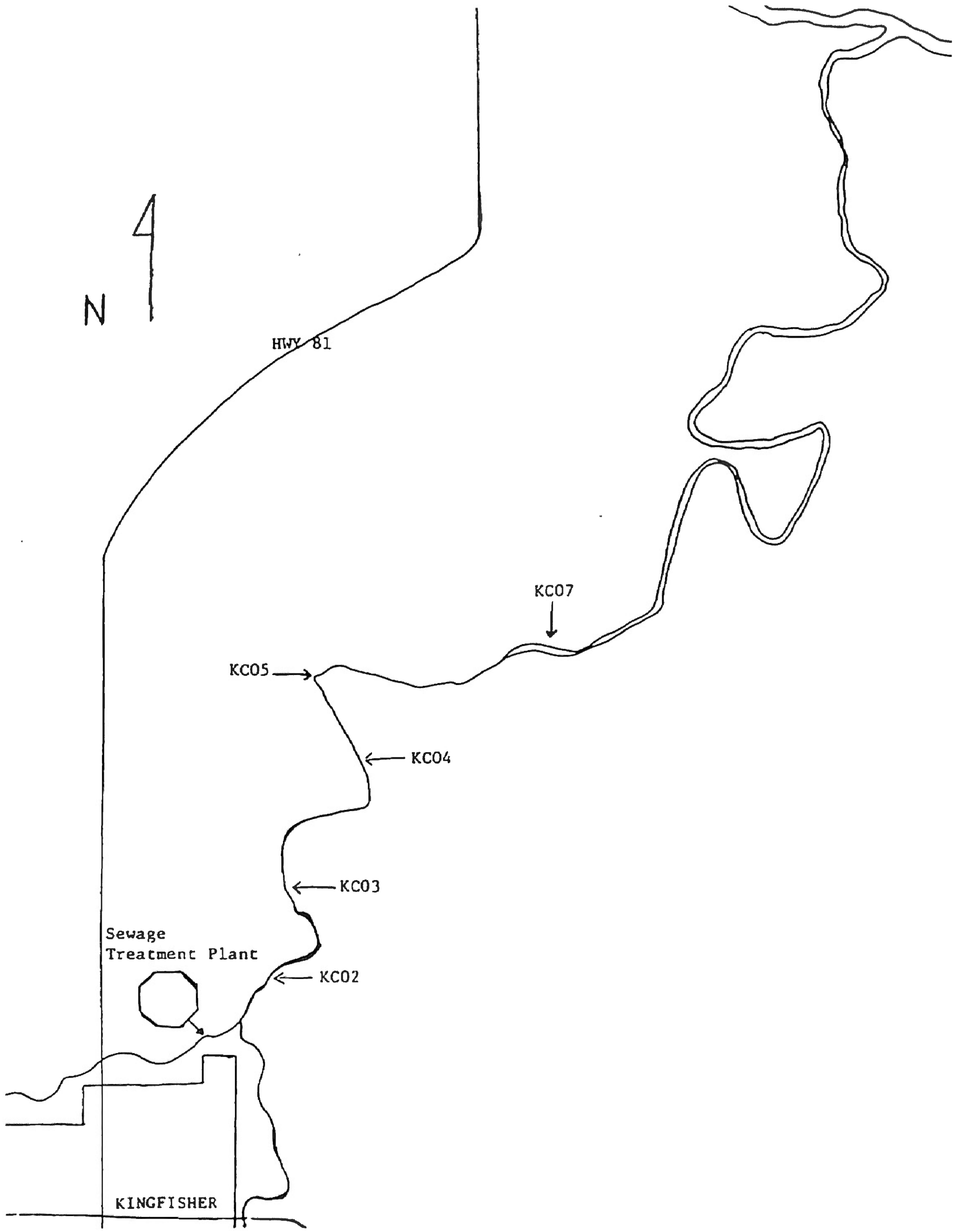

Figure 1. Kingfisher Creek Study Area
(Oklahoma State Health Department, 1985)

TABLE I

TIME OF TRAVEL STUDY: KINGFISHER CREEK

Site (start)	Site (end)	Distance (miles)	Velocity (ft/sec)	Time (days)
Confluence	KC07	3.0	0.63	0.29

(Oklahoma State Health Department, 1985)

TABLE II

WASTELOAD DATA: KINGFISHER CREEK

Site	Q (cfs)	D.O. (mg/l)	BOD_5 (mg/l)	$CBOD_L$ (mg/l)	$NBOD_L$ (mg/l)	CHLOR A (ug/l)	Pnet (mg/l/d)
KC02	5.4	5.6	6.3	6.3	4.7	29.5	--
KC03	5.4	5.6	5.4	6.6	4.1	20.5	--
KC04	--	5.6	--	--	--	--	0.46
KC05	5.6	5.8	5.1	7.3	3.7	26.5	--
KC07	5.6	6.0	6.4	7.4	4.4	51.0	0.75

(Oklahoma State Health Department, 1985)

A preliminary examination of these data together with the base map showing waste sources confirmed that it was an appropriate location for the current study. Kingfisher Creek, in this river reach, has one point source waste source and no tributary flow. This should favor the simplified nomographs while some non-point source flow and wasteload may require the segmented models to be employed.

CHAPTER III

RESULTS

More detailed analysis of the Health Department data showed that the non-point source wasteload was significant and appeared to enter the stream above Station KC05. This non-point source wasteload made it necessary to divide this river into at least two segments (Figure 2) in order to more accurately simulate observed conditions.

Since ease of use was one of the criteria used in the evaluation of the various methods, the segmentation of the system created a much more complex situation and served to complicate the application of the nomographs to the river system. Therefore, the segmentation and non-point source load input into the stream coupled with the failure of the method to address nitrification served to effectively eliminate the McBride's Nomograph as a viable dissolved oxygen model for use on this river system. The segmentation and failure of the method to address the effects of nitrification also forced the elimination of the Simplified Mathematical Modeling of Water Quality Nomograph from application on this river system. This left the three microcomputer codes with the potential to simulate this system. Of the remaining models, the first to be evaluated was the River Model for Dissolved Oxygen. This model was

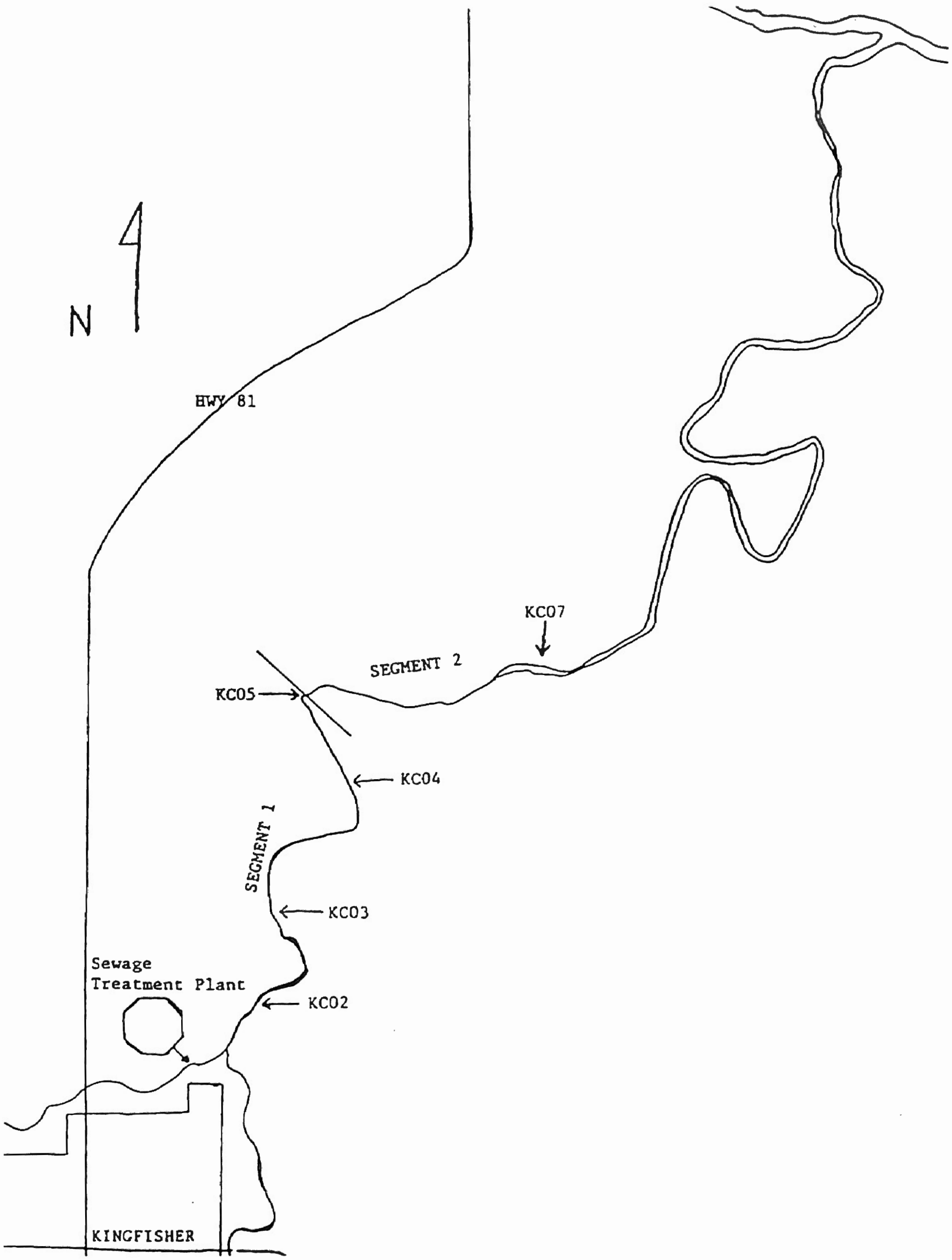

Figure 2. Kingfisher Creek Study Area: Segmented (Oklahoma State Health Department, 1985)

capable of simulating the effects of dispersion on stream dissolved oxygen concentration but was incapable of adequately modeling nitrification. Dresnack and Dobbins (1968) had previously shown the effects of various dispersion coefficients on dissolved oxygen concentration (Figure 3). An equation to calculate the dispersion coefficient is illustrated in the Appendix (Metcalf and Eddy, Inc., 1972). When this equation is applied to Kingfisher Creek, the resulting dispersion coefficient equals 0.36 square feet per second. This analysis shows that the advective component far exceeds dispersion in determining the hydrodynamic properties of these types of river systems.

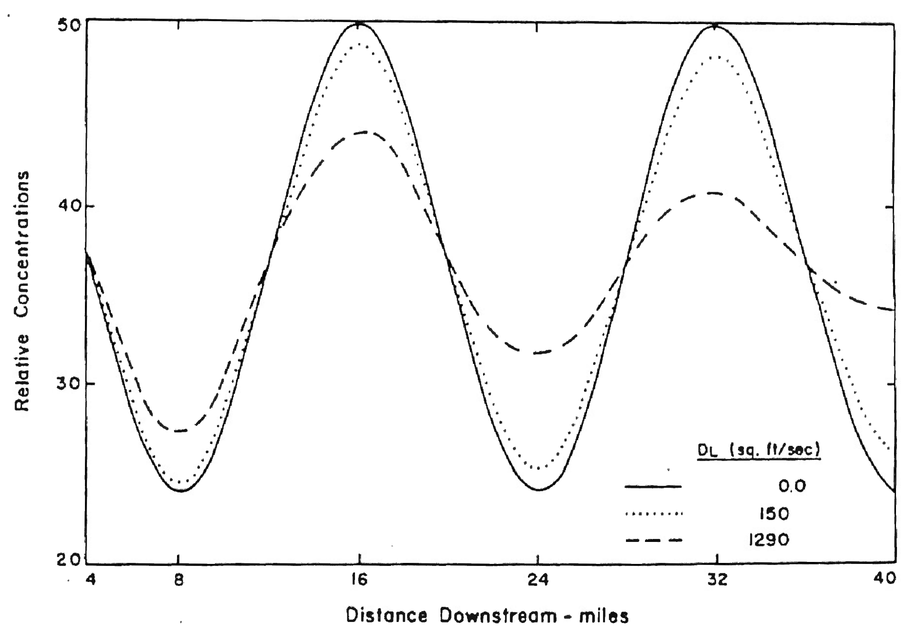

Figure 3. Effect of Dispersion on Dissolved Oxygen Concentration

(Dresnack and Dobbins, 1968)

As shown in Figure 3, in order for dispersion to have a significant impact on dissolved oxygen concentration, a coefficient of dispersion of much greater than 0.36 square feet per second must be present. Since the effects of dispersion are negligible in this river, this model was not utilized further. This decision was further reinforced by the models inability to simulate the effects of nitrification on dissolved oxygen concentration. This model proved to be overly sophisticated in its hydrodynamic properties while simultaneously being incomplete in its biochemical capabilities.

Of the remaining two models, given the significant non-point source wasteloads present in the stream and the resulting segmentation, both OSUDOX and the Steady-State, One-Dimensional River Network Model, were thought to be applicable to this river system.

The Health Department data were then reduced to appropriate input values for each code. Care was exercised to ensure that data accuracy was maintained during these manipulations and that the same data were applied to each code.

Table III illustrates the input data used in the River Network Model. Some of the important features of this data include segment temperature, five day biochemical oxygen demand (BOD_5), ammonia expressed as nitrogen (NH_3-N), kinetic coefficients calculated at segment temperatures, benthic demands, along with net photosynthetic/respiratory demands.

TABLE III

INPUT DATA: STEADY-STATE, ONE-DIMENSIONAL RIVER NETWORK MODEL

Parameter	Reach 1	Reach 2
Reach Labels	0,3	1,0
BOD_5 (mg/l)	5.80	5.75
NH_3-N (mg/l)	0.32	0.31
DO Deficit (mg/l)	2.28	--
Waste Input Code	1	3
Number of Segments	18	13
Temp. of Reach (C°)	24	25.5
Length of Reach (mi)	1.6	1.1
Flow (cfs)	5.4	5.6
Velocity (mi/d)	10.3	10.3
BOD Decay K (d^{-1}) @ T	0.134	0.149
Reareation K (d^{-1}) @ T	4.199	4.319
BOD Removal K (d^{-1}) @ T	2.248	2.155
Nitrification K (d^{-1}) @ T	0.195	0.226
Benthic Demand (mg/l/d)	4.5	4.5
Pnet (mg/l/d)	0.463	0.750

(Oklahoma State Health Department, 1985 and Roberts, Personal Calculations, 1987)

The input data for OSUDOX is shown in Table IV. Some important features to note are the reference temperature used for the calculation of all kinetic coefficients, segment temperatures for internal kinetic coefficient adjustment and dissolved oxygen saturation concentration calculations, wasteload data expressed as ultimate carbonaceous biochemical oxygen demand ($CBOD_L$), and ultimate nitrogenous biochemical oxygen demand ($NBOD_L$). Benthic demands as well as photosynthetic/respiratory loads were also utilized in the calculations. The altitude adjustment factor though unimportant in this study, does provide the model greater versatility in other locations.

TABLE IV

INPUT DATA: OSUDOX

Parameter	Segment 1	Segment 2
Reference Temp. (C°)	20	--
Additional Stream Flow (cfs)	5.4	0.0
CBOD in Additional Stream Flow (mg/l)	6.45	0.0
NBOD in Additional Stream Flow (mg/l)	4.36	0.0
DO in Additional Stream Flow (mg/l)	5.6	0.0
Additional Waste Flow (cfs)	0.0	0.2
CBOD in Additional Waste Flow (mg/l)	0.0	100.0
NBOD in Additional Waste Flow (mg/l)	0.0	0.0
DO in Additional Waste Flow (mg/l)	0.0	0.0
CBOD Removal K at 20 C° (d^{-1})	1.94	1.76
CBOD Deoxygenation K at 20 C° (d^{-1})	0.1	0.1
NBOD Removal K at 20 C° (d^{-1})	0.13	0.13
NBOD Deoxygenation K at 20 C° (d^{-1})	0.13	0.13
Reaeration K at 20 C° (d^{-1})	3.76	3.71
Temperature (C°)	24	25.5
Benthic Demand (g/m^3)	0.5	0.5
Pnet (mg/l/d)	0.463	0.75
Velocity (ft/s)	0.63	0.63
Depth (ft)	0.36	0.71
Ending Distance (ft)	8450	14250
Elevation (msl)	1400	1380

(Oklahoma State Health Department, 1985 and Roberts, Personal Calculations, 1987)

The remaining two models were calibrated using the Health Department data. Since benthic demand input values were not readily available, chlorophyll Ȧ data was used to estimate the values. These estimated benthic demand values were then used as a "fitting parameter" and adjusted slightly in order to bring the simulation results in line with the observed data (Grimsrud, Finnemore and Owen, 1976). All other input values were taken directly from or derived from the Health Department Study.

After the models were calibrated and the simulations conducted, the dissolved oxygen concentration values calculated by the two models were plotted along with the dissolved oxygen data from the Oklahoma State Health Department intensive study (Figure 4). The uppermost line on the graph represents the results from the River Network Model the next line represents the output from OSUDOX, the symbols represent the actual dissolved oxygen concentrations measured in the field. The lowest line indicates the Oklahoma State dissolved oxygen standard for this river system, 5.0 parts per million (Oklahoma Water Resources Board, 1982).

Although there appears to be a large discrepancy in the dissolved oxygen concentrations between the actual values and those of the River Network Model. The maximum difference between the values is less than 0.7 parts per million. A variation between the simulated dissolved oxygen concentration and the actual dissolved oxygen concentration of plus or minus 1.0 parts per million was considered to be acceptable in this effort.

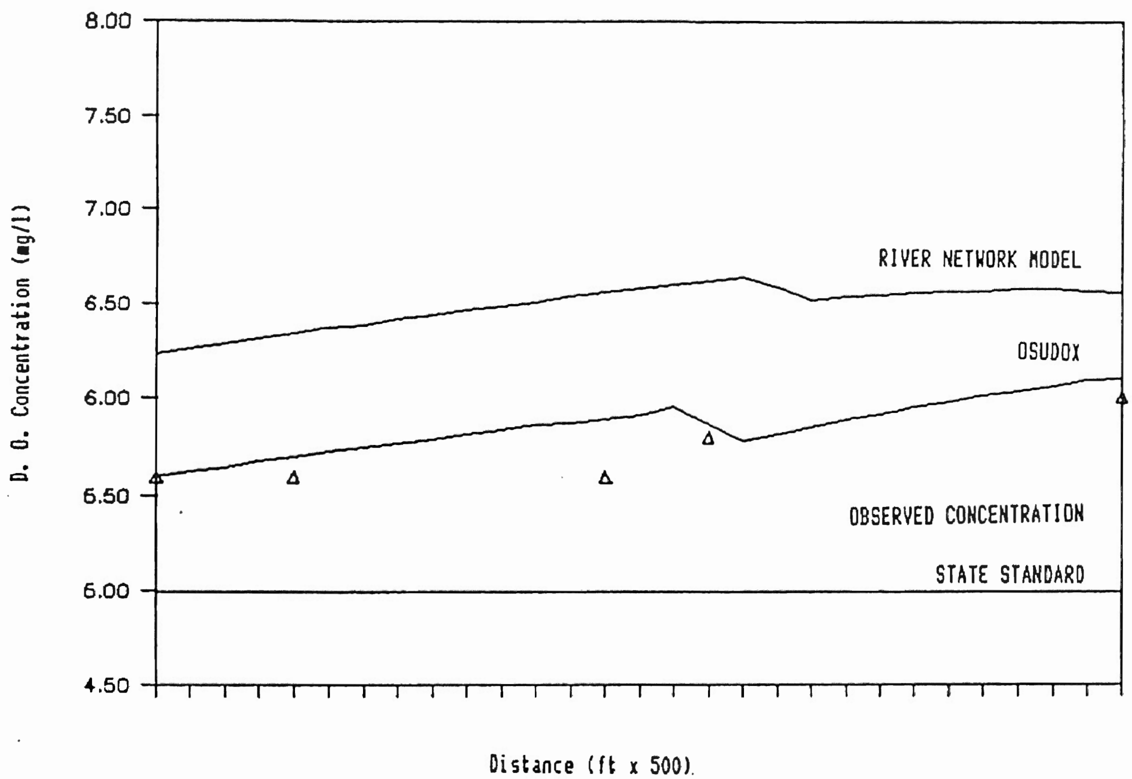

Figure 4. Simulated vs. Observed Dissolved Oxygen Concentrations: Kingfisher Creek

CHAPTER IV

DISCUSSION

Applicability of the Simulation Methods

Given a river system which would allow the application of any of the simulation methods discussed, the decision of which of the models to use would then be based upon several factors. The first factor considered would be the intended use of the simulation results and the format of the output data required from the simulation method. Second, the amount, format and type of data available for the simulation input would have to be considered. A third consideration is ease of use. Simple nomographs are able to produce rapid results with little data, whereas, computer simulations require much more data and are often clumsy and time consuming in their execution. Another consideration involves the accuracy of the results obtained. Nomographs provide fast, simplified answers of moderate accuracy, whereas computer models require more complex data but their outputs may be more accurate. Finally, the applicability of the simulation method to the stream system in question is probably the most important consideration in the selection of a simulation method. As was shown earlier, what first appears to be a straight forward and relatively simple river system can, upon closer examination, turn out to be a quite complex system. This complexity, therefore, serves to limit the choices available to the planner in choosing a model.

Features, Capabilities, and Utility of the Simulation Methods

The River Model for Dissolved Oxygen is a steady-state model utilized for the calculation of dissolved oxygen concentration in a river. The program is coded in Basic. This model was unique in that it utilized a coefficient of dispersion and a finite-difference approach in the calculation of dissolved oxygen concentrations. Although inapplicable in this river system, due in part to the limited impact of dispersion on this system, Figure 3 on Page 10, illustrates the marked effect dispersion can have on dissolved oxygen concentrations in rivers (Dresnack and Dobbins, 1968). This model could be improved if the effects of wastes containing nitrogenous biochemical oxygen demand (NBOD) were addressed. The River Model for Dissolved Oxygen would be more appropriate for application on larger, slower moving river systems where the effects of dispersion are greater. BOD_5 and dissolved oxygen concentrations make up the output data. Table V summarizes the features of this model.

TABLE V

MODEL CHARACTERISTICS: RIVER MODEL FOR DISSOLVED OXYGEN

Features/ Capabilities	Utility	Drawbacks	Reasons for Rejection
Based on dispersion CBOD removal and decay Point source loads	Large streams Multiple segments Point source discharges	Must calculate dispersion coefficient. Must input D.O. saturation concentration. Fails to address nitrification.	Dispersion effects are negligible in this river system. Significant nitrogenous load.

(Elliot and James, 1986)

OSUDOX is a computer model which is coded in Fortran. This model allows the user to calculate kinetic coefficients at a user specified reference temperature, thereby eliminating the tedious calculations required to correct for stream segment temperature variations. This simulation method easily handles additional stream flows as well as additional waste flows within one segment. OSUDOX takes both nitrogenous biochemical oxygen demand removal and decay as well as carbonaceous biochemical oxygen demand removal and decay into account in the calculations. Altitude correction factors are also built in. This feature is not as important as are some of the other features for applications in

Oklahoma, but altitude plays an important role in dissolved oxygen solubility in areas outside of Oklahoma. OSUDOX applies equally well to simple unbranched river systems as it does to more complex river systems with multiple branches and wasteloads. The output data from OSUDOX consist of distance, dissolved oxygen concentration, dissolved oxygen deficit, $NBOD_L$, $CBOD_L$, as well as temperature corrected kinetic values. Table VI, Page 20, summarizes some of the features of OSUDOX.

The Steady-State, One-Dimensional River Network Model is computer model which is coded in Basic. The River Network Model utilizes BOD decay and removal as well as the effects of nitrification on dissolved oxygen concentration. A quite convenient feature of this model is the option of inputing the wasteload data values in either pounds per day or milligrams per liter, thereby eliminating the need to reformat existing data with unit conversions. The user is required to construct a diagram of the river system under study and assign segment and wasteload descriptors to the various parts of the river system. This ensures thorough familiarity with the river system and enhances stream reach characterization. This model works equally well on complex streams as it does on simple streams. The output data from this model consist of dissolved oxygen concentration, BOD_5, and ammonia expressed as nitrogen (NH_3-N). Some of the features of this method are illustrated in Table VII on Page 21.

TABLE VI

MODEL CHARACTERISTICS: OSUDOX

Features/ Capabilities	Utility	Drawbacks	Reason for Rejection
Temperature corrected kinetics	Branched or unbranched rivers	No input re-editing feature.	None
CBOD removal and decay	Multiple segments		
NBOD removal and decay			
Benthic demand			
Net photosynthetic/ respiratory demand			
Altitude correction			
Multiple segments			
Point and non-point source inputs			
Calculates NBOD, CBOD, and DO deficit			

(Thomann, 1972)

TABLE VII

MODEL CHARACTERISTICS: STEADY-STATE, ONE-DIMENSIONAL RIVER NETWORK MODEL

Features/ Capabilities	Utility	Drawbacks	Reasons for Rejection
Benthic demand Photosynthetic/ respiratory load Nitrification coefficient CBOD removal and decay Multiple segments Point and non-point source inputs Calculates D.O., BOD_5 and NH_3-N Wasteloads in lb/d or mg/l	Branched or unbranched rivers Multiple segments	Must calculate kinetic coefficient at segment temperature. Must calculate D.O. deficit.	None

(Wu, 1986)

The McBride's Nomograph is useful in emergency situations where a rapid determination of maximum dissolved oxygen deficit and the location of the deficit is important (Nemerow, 1985). This method requires very little data and is limited in application to unsegmented streams with negligible nitrogenous demands and which are not receiving wasteload inputs. The output data from this method are the critical dissolved oxygen deficit, the location of the critical deficit, and the assimilative capacity of the stream. Table VIII shows the features of this nomograph.

TABLE VIII

MODEL CHARACTERISTICS: MCBRIDE'S NOMOGRAPH

Features/ Capabilities	Utility	Drawbacks	Reasons for Rejection
Predict maximum D.O. sag and location Predict assimilative capacity	Unsegmented & unbranched rivers	No wasteload inputs. No multiple segments. No branches. Does not consider nitrification.	Not applic-able to segmented river with waste flow. Significant nitrogenous load.

(McBride, 1982)

The Simplified Mathematical Modeling of Water Quality Nomograph is somewhat more flexible than is the McBride's Nomograph in that it allows for some wasteload input. As with the McBride's Nomograph, this model allows for rapid determination of the critical dissolved oxygen deficit and its location. The applicability of this method is also limited to unsegmented streams but does allow for carbonaceous wasteloads while failing to consider nitrification. The output data from this method are the critical dissolved oxygen deficit, the location of the critical deficit, and the assimilative capacity of the stream. Table IX summarizes the features of this nomograph.

TABLE IX

MODEL CHARACTERISTICS: SIMPLIFIED MATHEMATICAL MODELING OF WATER QUALITY

Features/ Capabilities	Utility	Drawbacks	Reasons for Rejection
Predict maximum D.O. sag and location	Unbranched rivers	No nitrification effects.	Significant NBOD load in this system.
Predict assimilative capacity			

(Hydroscience, Inc., 1971)

CHAPTER V

MANAGEMENT APPLICATIONS

Both OSUDOX and the River Network Model can be applied to Kingfisher Creek in order to aid in the evaluation of water quality management practices. Additional simulations were initiated in order to show some of the uses these models can have in water quality planning and management. Figure 5 shows the effect on stream dissolved oxygen concentration of increasing the efficiency of the sewage treatment plant. The biochemical oxygen demand concentration in the stream below the sewage treatment plant has been reduced by one-half, while the non-point source concentration remains constant. Figure 6, Page 26, illustrates the effects on stream dissolved oxygen concentration when the efficiency of the sewage treatment plant is reduced. The biochemical oxygen demand concentration in the stream below the sewage treatment plant has been doubled while the non-point source load is kept constant.

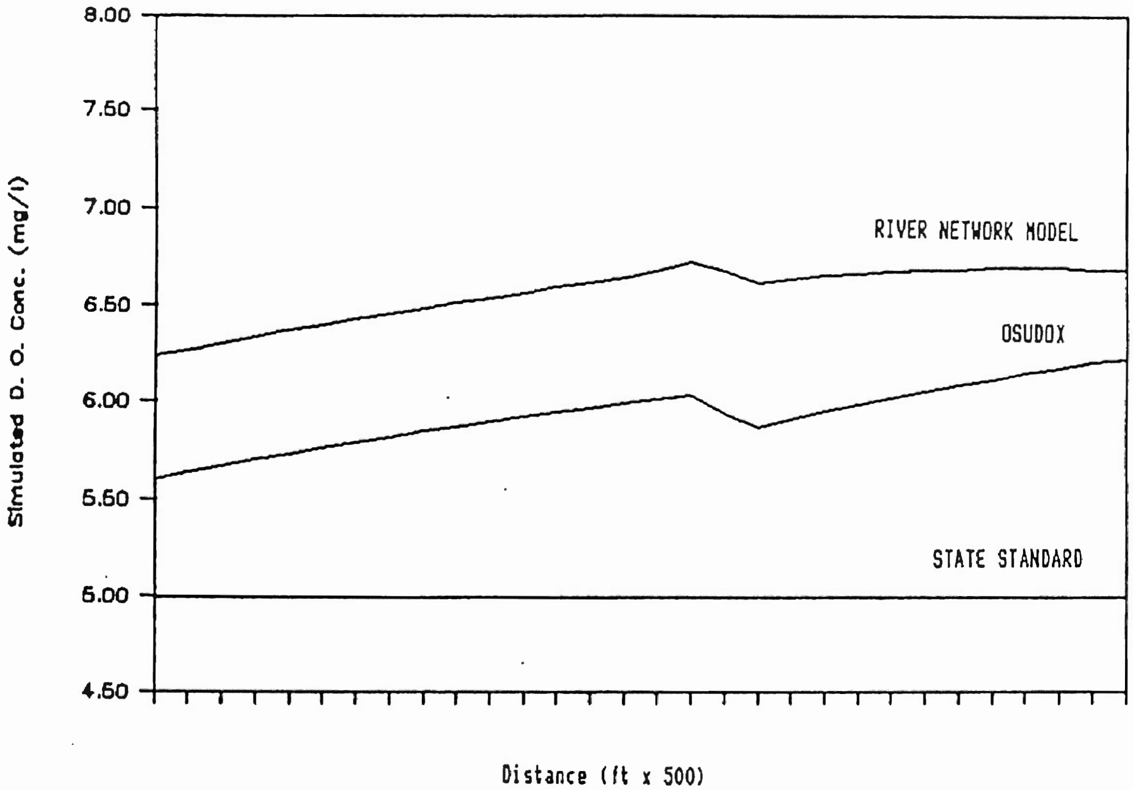

Figure 5. Predicted Effects of Decreasing Stream BOD Concentration by 50% on Dissolved Oxygen Concentration

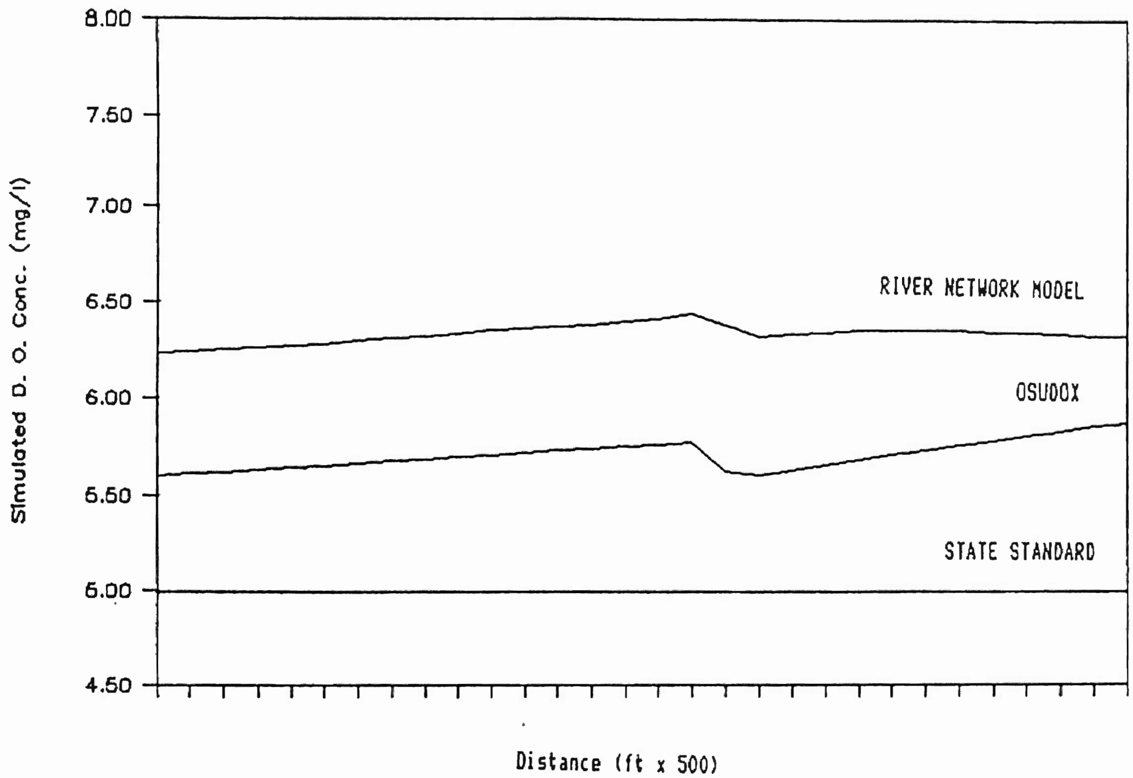

Figure 6. Predicted Effects of Doubling Stream BOD Concentration on Dissolved Oxygen Concentration

Figure 7 demonstrates the predicted effects on stream dissolved oxygen concentration of increasing the non-point source load by a factor of two while the upstream wasteload remains constant at current levels. Figure 8, Page 28, shows the effects of a fifty percent decrease in non-point source loading while upstream wasteloading remains constant.

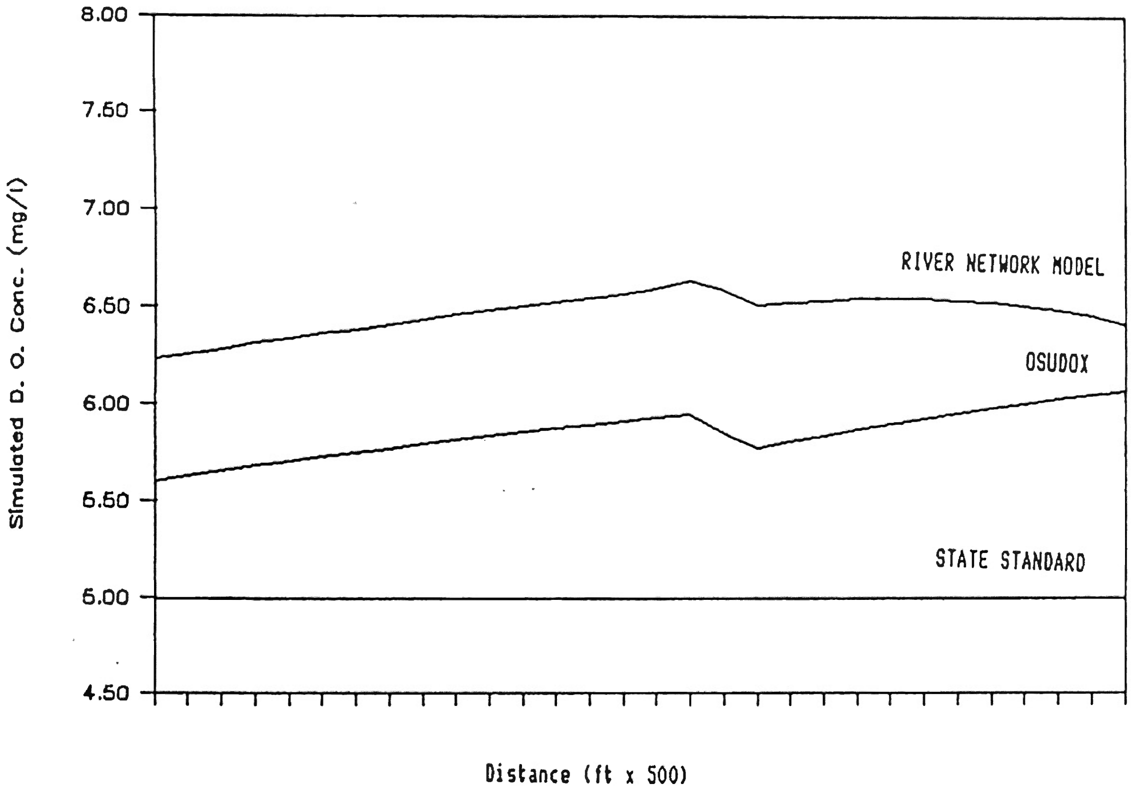

Figure 7. Predicted Effects of Doubling NPS BOD Load on Dissolved Oxygen Concentration

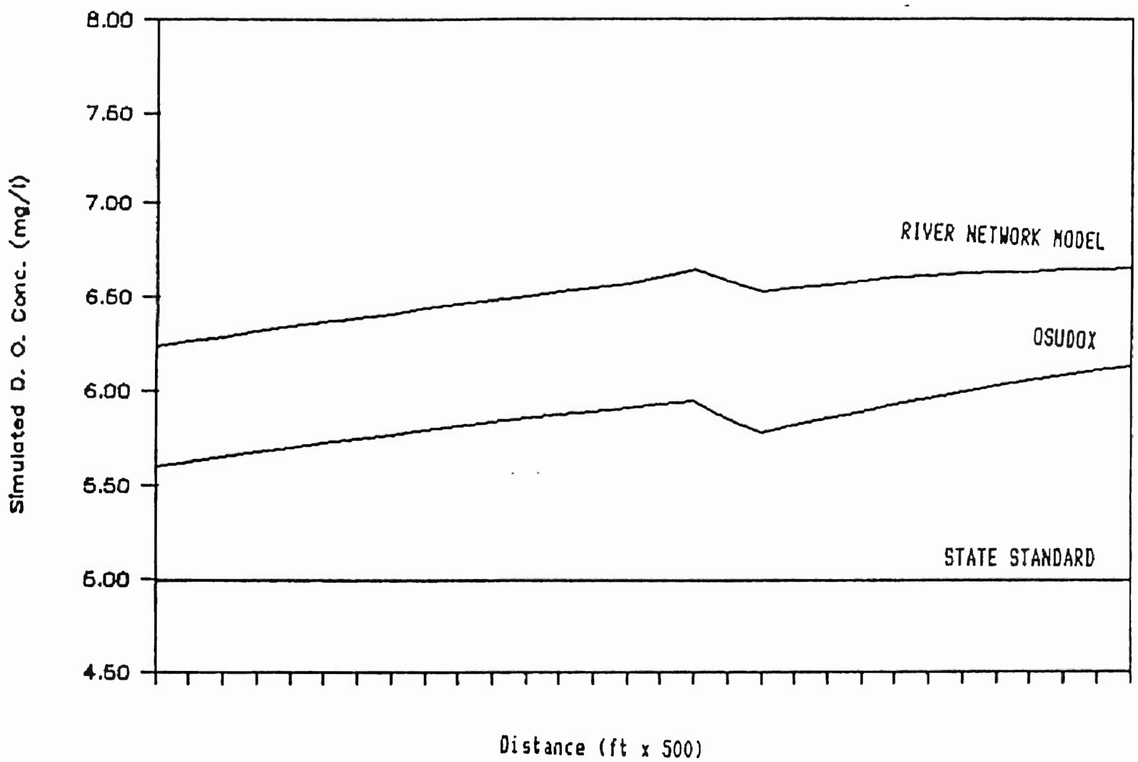

Figure 8. Predicted Effects of Decreasing NPS BOD Load by 50% on Dissolved Oxygen Concentration

Figure 9, demonstrates the predicted effects of doubling both the upstream wasteload concentration and the non-point source wasteload. Figure 10, Page 30, shows the predicted dissolved oxygen concentration encountered along the river with both the upstream and non-point source wasteloads concentrations decreased by one-half.

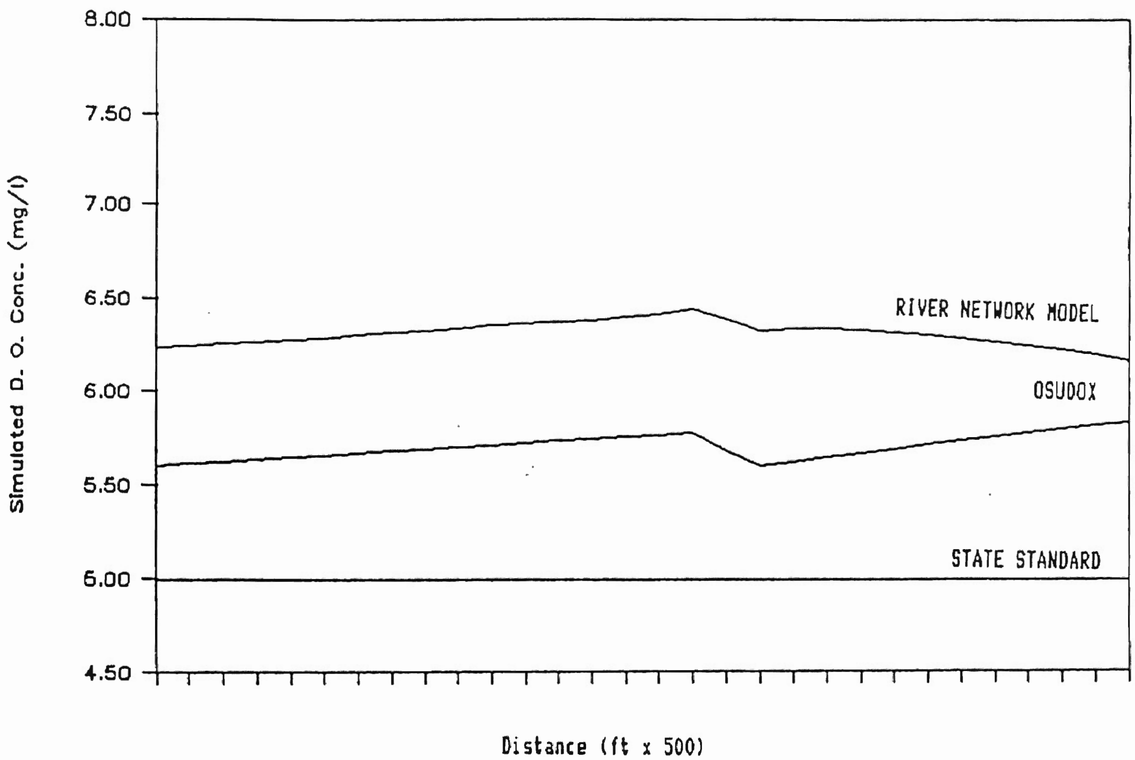

Figure 9. Predicted Effects of Doubling Both Upstream and NPS BOD Concentrations on Dissolved Oxygen Concentration

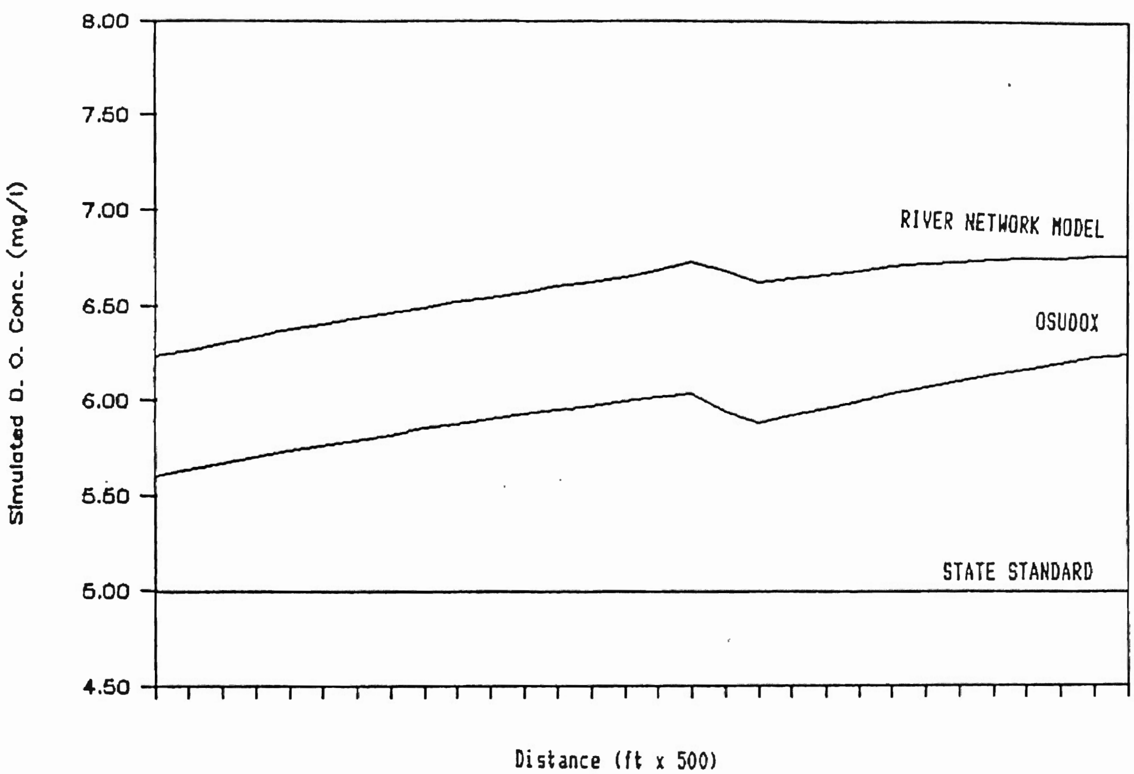

Figure 10. Predicted Effects of Decreasing Both Upstream and NPS BOD Concentration by 50% on Dissolved Oxygen Concentration

Figure 11 illustrates the predicted effect on stream dissolved oxygen concentration of a fivefold increase in the biochemical oxygen demand concentration below the sewage treatment plant. Figure 12, Page 32, shows the predicted result of a tenfold increase in the biochemical oxygen demand concentration in the stream below the sewage treatment plant. In this scenario, the State Dissolved Oxygen Standard of 5.0 parts per million (Oklahoma Water Resources Board, 1982) would be violated.

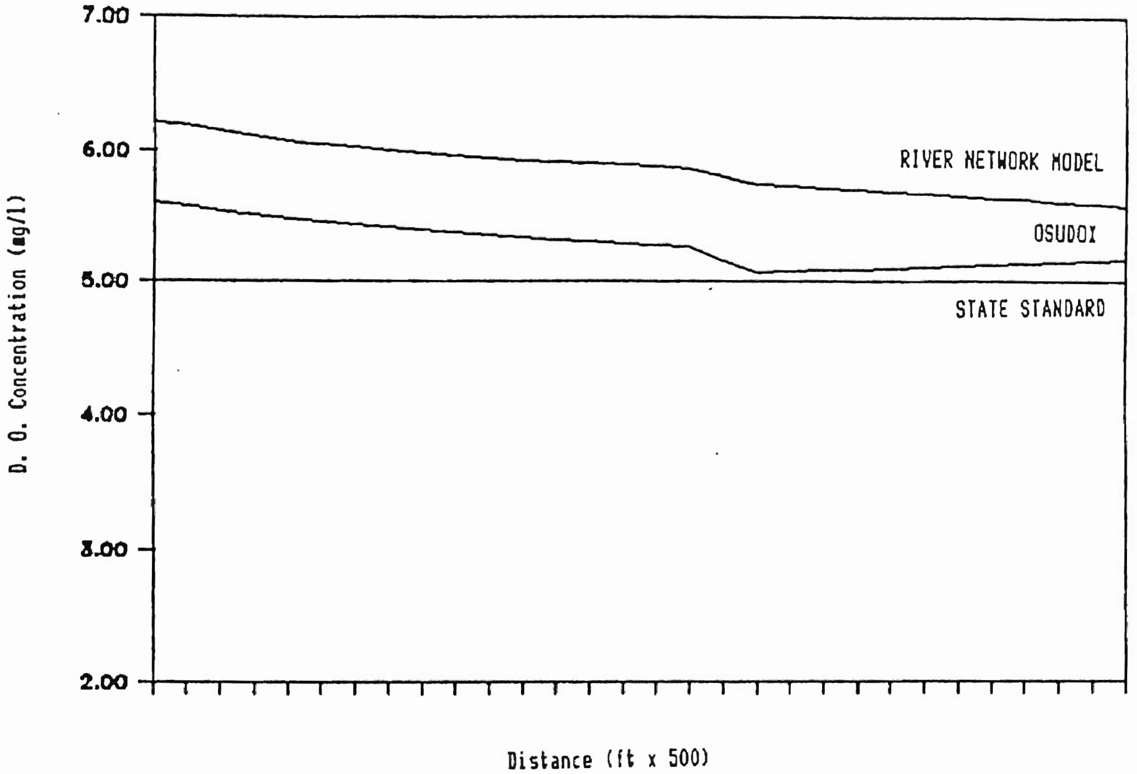

Figure 11. Predicted Effects of a Fivefold Increase in Upstream BOD Concentration

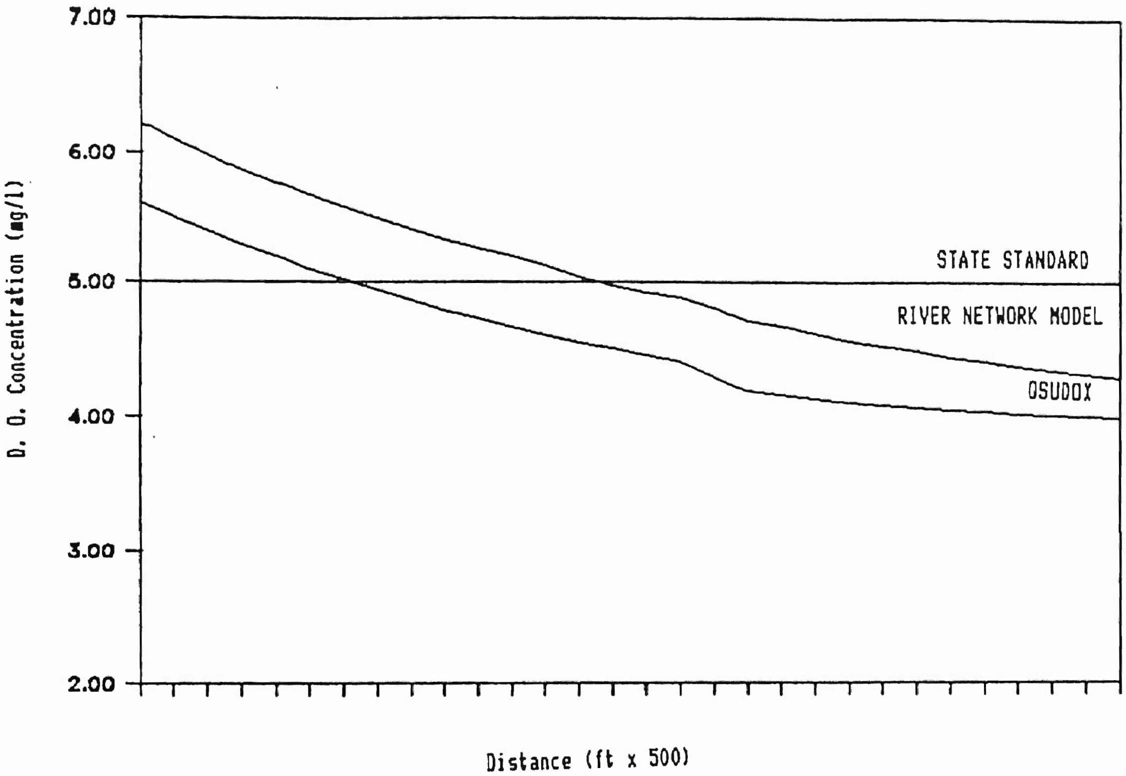

Figure 12. Predicted Effects of a Tenfold Increase in Upstream BOD Concentration

As illustrated in the preceding eight figures, an infinite variety of conditions, which might possibly occur in the river system, may be simulated and a fairly accurate prediction of the effects on dissolved oxygen in the stream can be made. An important feature to note in the preceding graphs is the essentially equivalent outputs the two methods produced throughout the simulations.

These types of modeling exercises afford the water quality planner the opportunity to evaluate various land use and water resource options. Armed with this information, sound decisions concerning land use and water quality can be made.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Available small stream steady-state dissolved oxygen models have been found to provide accurate results and have been shown to be applicable to a single small river system in Oklahoma. Due to the presence of a significant non-point source wasteload, high nitrogenous biochemical oxygen demands, as well as benthic and photosynthetic demands, simple unsegmented models and nomographs proved to be insufficient in this effort and failed to provide accurate predictive outputs.

Of the remaining models evaluated, given their essentially equivalent outputs, a selection decision would be made based upon the ease of use of the model, the format of the input data, the desired output data format, as well as river characteristics, and user familiarity with the model. Although no model is one-hundred percent accurate, they do provide water quality managers with an important and powerful tool to aid in the development of sound water quality management plans.

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APPENDIX

PERTINENT EQUATIONS

The equation utilized to calculate the dispersion coefficient for Kingfisher Creek is shown below.

$$E = 77\ n\ v\ R^{5/6}$$

Where

E = Eddy Diffusion Coefficient

n = Manning Roughness Coefficient

v = velocity, feet per second

R = Hydraulic Radius, feet

(Metcalf and Eddy, Inc., 1972)

A generalized version of the Streeter-Phelps Dissolved Oxygen Deficit Equation is presented below.

$$D_t = \frac{k_1 L_A}{k_2 - k_1} \left(10^{-k_1 t} - 10^{-k_2 t} \right) + D_A\, 10^{-k_2 t}$$

Where

D = oxygen deficit

L = ultimate carbonaceous oxygen demand

k_1 = BOD decay rate, per day

k_2 = stream reareation coefficient, per day

(Nemerow, 1985)

An equation used to calculate the Reareation Coefficient is shown below.

$$k_1 = 0.11 \frac{H}{t}$$

Where

k_1 = reareation coefficient, per day

H = change in stream bed elevation, feet

t = time, days

(Tsivoglou and Neal, 1972)

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