RENEWED USE OF BOD/DO MODELS IN WATER QUALITY MANAGEMENT

By Wu-Seng Lung[1] and Robert G. Sobeck Jr.[2]

ABSTRACT: Immediately following the passage of the Clean Water Act over 25 years ago, there was a need to develop water quality management plans (WQMP) for each watershed. Assimilative capacities and wasteload allocations were quantified using primitive tools because of limited water quality data and the lack of skilled modeling professionals. As the quality of receiving waters improves due to increased treatment of waste flows over the last two decades, existing models require updating or postauditing to continue to support the WQMP. In some cases, as presented here, the quality of the waters always met standards, although an old model predicted nonattainment. This situation indicates that there is a need for increased use of water quality models to review the assimilative capacity of the receiving water for regulatory control and water quality management. Finally, the work presented in this paper demonstrates that modeling continues to be the most cost-effective method of water quality planning and that water resource managers should apply water quality modeling on a regular basis to support the present and future needs of the watershed.

INTRODUCTION AND PURPOSE

Traditionally, the major use of models in regulatory control has been for developing wastewater discharge permits and permit related wasteload allocations—particularly for water quality-limited receiving waters. For example, wasteload allocation was used specifically for those instances where there was some doubt that the water quality standards could be achieved by secondary treatment alone. Many of these instances require relatively straightforward application of water quality modeling techniques to quantify point- and non-point-source discharges and resolve specific water quality issues.

Many water quality management plans (WQMP) or river basin plans were developed more than 25 years ago when water quality data were insufficient to support sound modeling technologies. As more data become available, alternative methods of analysis should be considered and applied. In recent years, biochemical oxygen demand/dissolved oxygen (BOD/DO) models are being used to revise the WQMP. In many cases, the water quality has improved and the receiving water has changed from a water quality limited to effluent limited water body. That is a welcome opportunity, as well as a challenge, for regulatory agencies to revisit water quality modeling results that established the assimilative capacity for receiving waters whose water quality has improved or continues to meet the standards.

The purpose of the current paper is to present a case study using a simple BOD/DO model to develop the assimilative capacity for a river receiving point sources. A comprehensive field monitoring program and wastewater effluent characterization were conducted to support the modeling analysis. Results of the modeling study have been used to revise the National Pollutant Discharge Elimination System (NPDES) permit, resulting in a less stringent carbonaceous biochemical oxygen demand (CBOD) limit for the discharge. The work showed that secondary treatment limits for the growth-induced wastewater treatment plant expansion were more than adequate to maintain water quality standards for dissolved oxygen. This action saved local citizens millions of dollars while ensuring that the unused funds could be applied to other necessary water quality management projects.

ROANOKE RIVER AT ALTAVISTA, VIRGINIA

The Roanoke River near the town of Altavista flows from the Smith Mountain–Leesville Dam complex in central Virginia (Fig. 1). In the vicinity of Altavista, there are a number of water supply intakes and wastewater discharges to the Roanoke River, and the waters are classified as a ‘‘public water supply’’ resource in Virginia. Downstream waters in the study area are also classified as ‘‘state scenic waters’’ in Virginia. Two major wastewater treatment facilities, the town of Altavista plant and the Burlington Industries plant, discharge final effluents into this section of the river at Altavista. When the flows of the Altavista plant approached the design limit of 1.8 mgd in 1988, the Virginia Department of Environmental Quality (VDEQ), using an enforcement action, required Altavista to increase the capacity of the plant and modified its NPDES permit. The permit writer issued an NPDES permit for the expanded facilities at Altavista and developed the BOD limits using a model known as the TVA flat water equation. The TVA equation calculation indicated that the current BOD wasteloads permitted in the river were exceeding the ability of the Roanoke River to assimilate those loads and were therefore impairing water quality—specifically dissolved oxygen. The action taken by the permit writer resulted in much more stringent BOD limits than secondary limits for the Altavista plant. The permit writer intended to reduce BOD limits for the Burlington Industries plant, based on the TVA equation, although Burlington was not intending to expand its production capacity.

The permit writer's legal basis for using the TVA equation is that the equation is the regulatory part of the Roanoke River Basin Waste Quality Management Plan (RRBP) and, in Virginia, is considered the law. On the other hand, the RRBP also stated that the state of water quality of the Roanoke River near Altavista meets water quality standards for dissolved oxygen and classifies the reach as effluent limited. The town of Altavista and Burlington Industries decided to investigate the TVA equation and pursue a water quality modeling study due to the potential treatment costs and to better define the economic conditions under which future growth would occur.

REVIEW OF TVA EQUATION

The TVA flat water equation is a multiple regression formula based on the data from 15 assimilative studies in the TVA region (Krenkel and Ruane 1979). The equation was developed to calculate the allowable BOD_5 loading rate for a point source using a minimum amount of field data

[1]Prof. of Civ. Engrg., Thornton Hall, Univ. of Virginia, Charlottesville, VA 22903.

[2]Consulting Engr. and Hydro., Charlottesville, VA 22901.

Note. Discussion open until January 1, 2000. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on February 10, 1998. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 125, No. 4, July/August, 1999. ©ASCE, ISSN 0733-9496/99/0004-0222–0227/$8.00 + $.50 per page. Paper No. 17576.

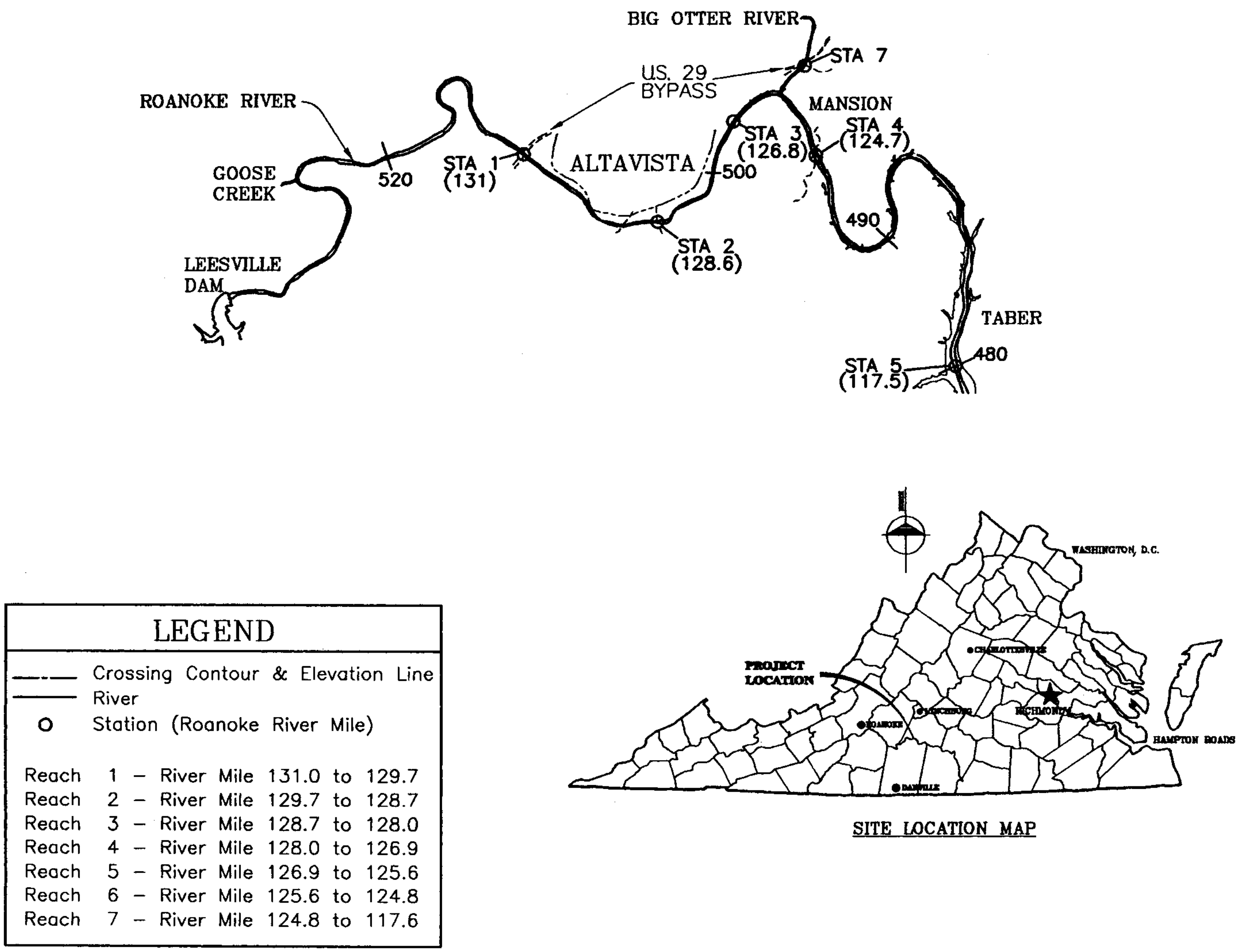

FIG. 1. Study Area in Roanoke River near Altavista

$$Y = 10{,}138\,\frac{(\mathrm{DO}_{\mathrm{mix}})^{1.094}Q^{0.864}S^{0.06}}{T^{1.423}(\mathrm{DO}_{\mathrm{sag}})^{1.474}} \quad (1)$$

where Y = assimilative capacity of the stream (lb BOD_5/day; 10,138 = regression constant; $\mathrm{DO}_{\mathrm{mix}}$ = in-stream dissolved oxygen concentration (mg/L) following complete mixing; Q = sum of stream flow and waste flow (cfs); T = stream water temperature (°C); S = stream bed slope (ft/ft); and $\mathrm{DO}_{\mathrm{sag}}$ = minimum allowable DO of the stream (mg/L).

VDEQ applied (1) to the Roanoke River near Altavista using the following data:

- $\mathrm{DO}_{\mathrm{mix}}$ = 6.4 mg/L
- Q = 220 cfs
- T = 30°C
- S = 0.0013
- $\mathrm{DO}_{\mathrm{sag}}$ = 5.4 mg/L

The total assimilative capacity of the Roanoke River in the vicinity of Altavista, calculated with the TVA flat water equation, equals 3,600 lb/day of BOD_5. With an upstream background BOD_5 load of 1,675 lb/day, the available BOD_5 allocation for the point-source discharges equals 1,925 (= 3,600 − 1,675) lb/day. Note that the NPDES permit BOD_5 loads prior to the VDEQ enforcement action were 2,332 lb/day and 675 lb/day for the Burlington and Altavista plants, respectively. The total available capacity of 1,925 lb/day is less than the sum of the loads (2,332 + 675 = 3,007 lb/day) allowed in the original NPDES permits. It should be pointed out that the dissolved oxygen levels in the river below the Altavista and Burlington Industries plants are well above the standard of 5.4 mg/L.

There are a number of technical issues concerning the use of (1) in wasteload allocations. First, waste characteristics are not considered in the equation. What is the CBOD_u-to-CBOD_5 ratio of the wastewater? This ratio is closely related to the in-stream deoxygenation rate of the waste, K_d (Lung 1998). Eq. (1), however, does not account for this factor, i.e., how rapidly the waste is being stabilized in the stream. Consider two waste discharges, one with a high K_d rate and the other with a low K_d rate. With all other factors in (1) being equal between these two discharges, should the wasteloads from these two sources be the same? They should not, yet (1) would project equivalent demands. Second, reaeration in the stream is not considered in (1). Finally, time of travel is another important factor in stream BOD/DO modeling, but is not incorporated into the TVA equation.

BOD/DO MODEL OF ROANOKE RIVER

A simple model, STREAM (Lung 1987; *Technical* 1995), was used to simulate the BOD/DO relationship in the present study. STREAM is a one-dimensional, steady-state model based on the Streeter-Phelps equation, and has the capability of incorporating CBOD, nitrogenous biochemical oxygen demand (NBOD), oxygen production due to algal photosynthesis, oxygen consumption by algal respiration, and sediment oxygen demand (Thomann and Mueller 1987; Chapra 1997). Its water column kinetics are very similar to those of the QUAL2E (*The enhanced* 1987) model. In configuring STREAM for the Roanoke River, three water quality variables are modeled: $CBOD_u$, NBOD, and DO.

One of the key parameters of STREAM is the reaeration coefficient, K_a. Hydraulic geometry and river flow conditions in the study area suggest that the O'Connor-Dobbins equations (*Technical* 1995) should be used to quantify K_a

$$K_a(20°\mathrm{C}) = \frac{12.9U^{0.5}}{H^{1.5}} \tag{2}$$

where U = average stream velocity (ft/s); and H = average stream depth (ft).

The study area of 13 mi is divided into seven reaches (Fig. 1). Average depth and velocity in each reach were measured through stream surveys and incorporated into the model to calculate the stream reaeration coefficient in each reach (Table 1). Saturated dissolved oxygen concentrations in each reach were calculated using the following equation (*Technical* 1995):

$$C_s = \frac{468}{31.6 + T} \tag{3}$$

where T = water temperature (°C); and C_s = saturated DO concentration (mg/L). This equation is accurate to within 0.03 mg/L compared with the Benson-Krause equation, on which the Standard Methods tables are based (*Technical* 1995).

DATA TO SUPPORT MODELING ANALYSIS

Two water quality surveys were conducted with river flows at Altavista of 836 cfs and 294 cfs, in October 1993 and September 1995, respectively. Stream flows were obtained at various locations along the Roanoke River from U.S. Geological Survey gauging stations at Altavista, APCO records on Goose Creek and discharge over Leesville Dam, and VDEQ records on Goose Creek and the Big Otter River entering the Roanoke River below Altavista (Fig. 1). Hydraulic geometry parameters such as width, depth, cross-sectional area, and velocity were measured at various locations. During the 1995 survey, VDEQ conducted a time-of-travel study through a portion of the river. Dye was released from the outfall of the Burlington Industries plant and tracked by collecting samples of the dye, which were analyzed with a fluorometer. The hydraulic geometry conditions associated with these two surveys are presented in Table 1. Fig. 2 shows a time-of-travel plot for the flows associated with the two surveys. Also shown in Fig. 2 is the time-of-travel for the seven-day, 10-year low flow (7*Q*10) condition (225 cfs).

Samples taken from the river (see sampling stations in Fig. 1) were analyzed for $CBOD_u$, organic nitrogen, ammonium, nitrite+nitrate, total phosphorus, orthophosphate, alkalinity, total solids, and total dissolved solids. In-situ measurements of DO, pH, temperature, and conductivity were conducted using a Surveyor II Hydrolab.

The same water quality parameters were analyzed for the wastewater treatment effluent samples. Treatment plant flows were obtained from the continuous monitoring records. Table 2 lists the point-source flows and CBOD and NBOD loads discharged to the Roanoke River during the surveys.

Long-term CBOD tests of the wastewater effluent samples for a period of 50 days were conducted on the effluents to determine the $CBOD_u$ concentrations and the decay rate of the CBOD. Fig. 3 shows the $CBOD_u$ concentrations in effluents of the Altavista and Burlington plants. The data were analyzed with the least-squares method to determine the first-order CBOD decay rate at 0.07 day^{-1}. Such a low rate suggests well stabilized effluents. Using the following equation:

TABLE 1. Hydraulic Geometry during Water Quality Surveys

Reach mile points (1)	Flow (cfs) (2)	Cross-sectional area (sq ft) (3)	Velocity (ft/s) (4)	Depth (ft) (5)
(*a*) September 1995				
131.0–129.7	294.0	267	1.10	2.55
129.7–128.7	300.0	400	0.75	3.03
128.7–128.0	302.8	481	0.62	4.00
128.0–126.9	302.8	511	0.59	3.50
126.9–125.6	312.9	502	0.62	3.00
125.6–124.8	434.9	806	0.54	4.12
124.8–117.6	457.9	501	0.94	2.35
(*b*) October 1993				
131.0–129.7	831.0	704	1.18	3.55
129.7–128.7	835.8	1,116	0.75	5.03
128.7–128.0	836.0	981	0.85	6.00
128.0–126.9	838.4	811	1.03	5.50
126.9–125.6	848.4	562	1.51	3.00
125.6–124.8	931.9	556	1.68	3.12
124.8–117.6	944.2	541	1.74	2.35
(*c*) 7*Q*10 Condition				
131.0–129.7	225.0	234	0.96	2.32
129.7–128.7	232.0	365	0.64	2.95
128.7–128.0	232.4	445	0.52	3.77
128.0–126.9	238.0	474	0.56	3.36
126.9–125.6	241.0	455	0.53	2.73
125.6–124.8	263.5	745	0.35	4.03
124.8–117.6	266.8	434	0.61	2.25

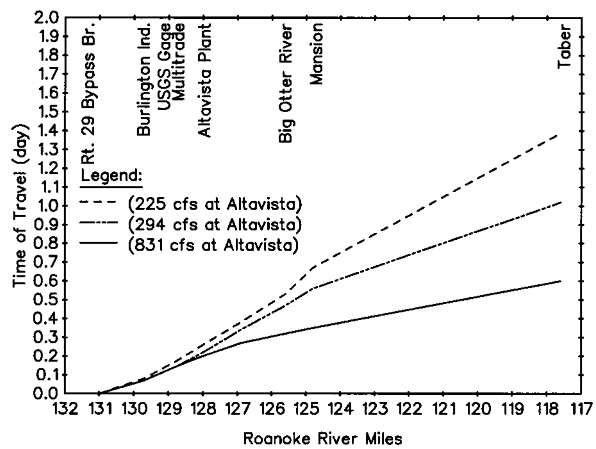

FIG. 2. Travel Times in Roanoke River under Three Flows at Altavista

TABLE 2. Point-Source Loads during Water Quality Surveys

Point source (1)	Flow (mgd) (2)	$CBOD_u$ (lb/day) (3)	NBOD (lb/day) (4)	DO deficit (mg/L) (5)
(*a*) September 1995				
Burlington Industries	3.88	639	105	4.5
Altavista plant	1.86	109	4.1	2.6
Big Otter River	78.9	4,644	26	1.0
(*b*) October 1993				
Burlington Industries	3.14	368	112	3.6
Altavista plant	1.56	323	4.1	0.0
Big Otter River	54.0	902	451	1.0
(*c*) Existing Permits				
Burlington Industries	4.50	2,332	112	4.0
Multitrade	0.31	62	0	4.0
Altavista plant	3.60	675	4.1	4.0

$$\frac{\mathrm{CBOD}_u}{\mathrm{CBOD}_5} = \frac{1}{1 - e^{-5K_1}} \tag{4}$$

a CBOD_u to CBOD_5 ratio of 3.39 was derived for the Roanoke River near Altavista using 1993 and 1995 data. Such a high ratio clearly indicates that the effluents are highly stabilized, with the residue in a refractory form that biodegrades very slowly, resulting in a low consumption rate of dissolved oxygen (in-stream deoxygenation). This ratio is also consistent with literature values for well treated effluents (Lung 1998).

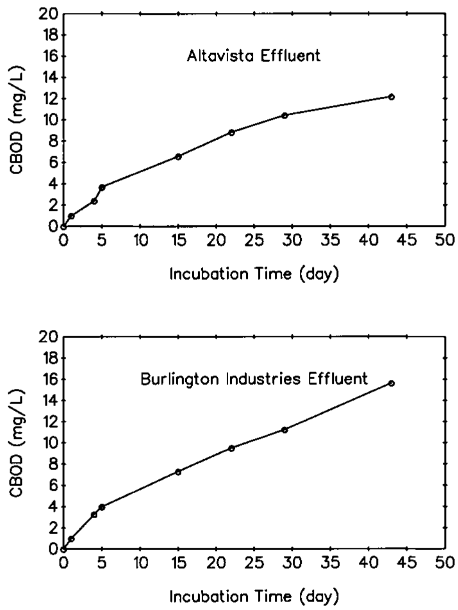

FIG. 3. Long-Term CBOD Results of Final Effluents from Altavista Plant and Burlington Industries

MODEL CALIBRATION AND VERIFICATION ANALYSES

Data from the October 1995 survey were used for model calibration, as the river was near the 7Q10 condition. The 1993 data were then used to verify the model using the calibrated model coefficients. Results of the modeling analysis for these two data sets are presented in Fig. 4, comparing model results of CBOD_u, NBOD, and DO with measured data. In general, model results match the data quite well. The low in-stream deoxygenation rate contributes to the relatively constant CBOD_u concentrations in the river, showing insignificant decay of well treated effluents. Also noted are the relatively low CBOD_u concentrations in the ambient water. It should be pointed out that ammonium concentrations in the study area are very low, even below the detection limit during the 1995 survey. Perhaps the most significant observation is that the DO concentration profile does not show the classic depression, sag, and recovery along the river. Instead, the minimum DO concentration is located near the discharge point of Burlington Industries. DO concentrations increase progressively in the downstream direction, eventually approaching the saturated level. Thus, the first stage of the classic DO profile is missing. This is becoming a typical characteristic of many stream DO concentration profiles with small river flows and well treated effluents.

MODEL PROJECTION ANALYSIS

The calibrated and verified model was then reconfigured for the 7Q10 (225 cfs) condition for model projections. Water temperature was assumed to be 30°C. The permit loads for Burlington Industries and Altavista were first evaluated using the model.

Since the permit loads are expressed in CBOD_5 and the STREAM model uses CBOD_u, it is necessary to convert the

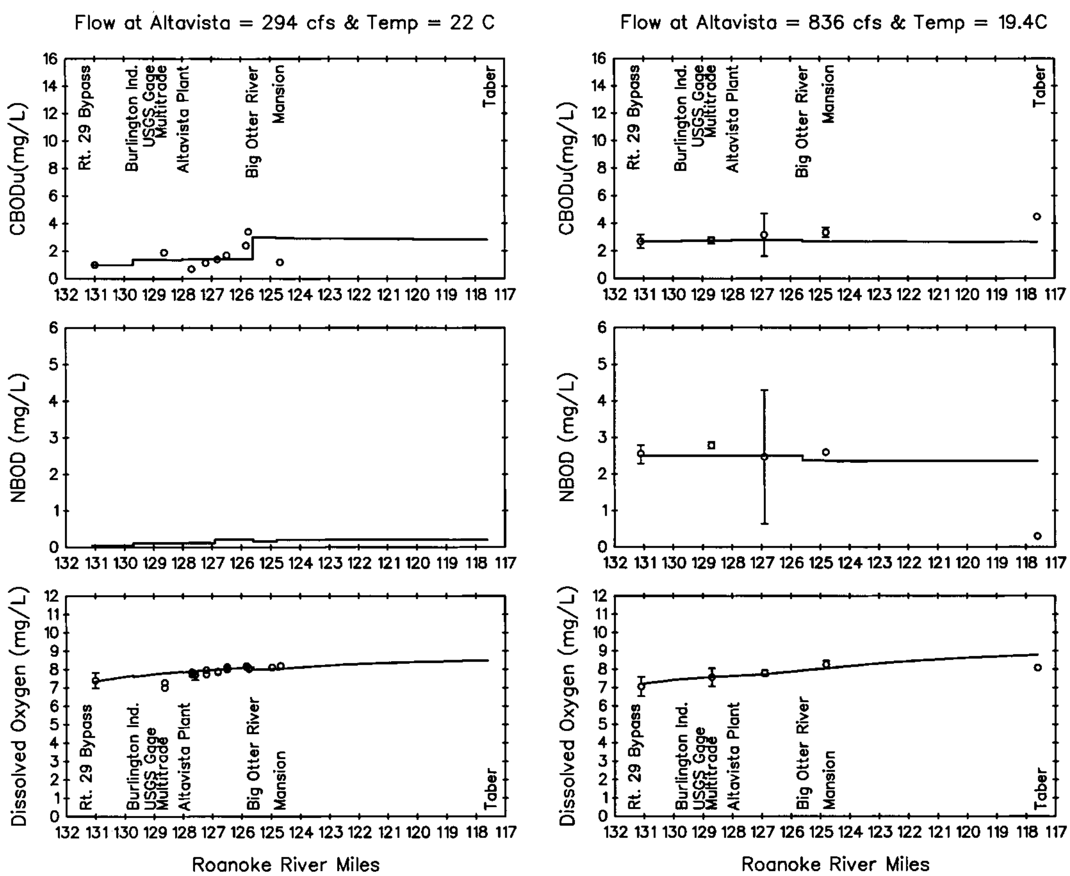

FIG. 4. Model Calibration and Verification Results Using Data from 1993 (Flow = 836 cfs) and 1995 (Flow = 294 cfs)

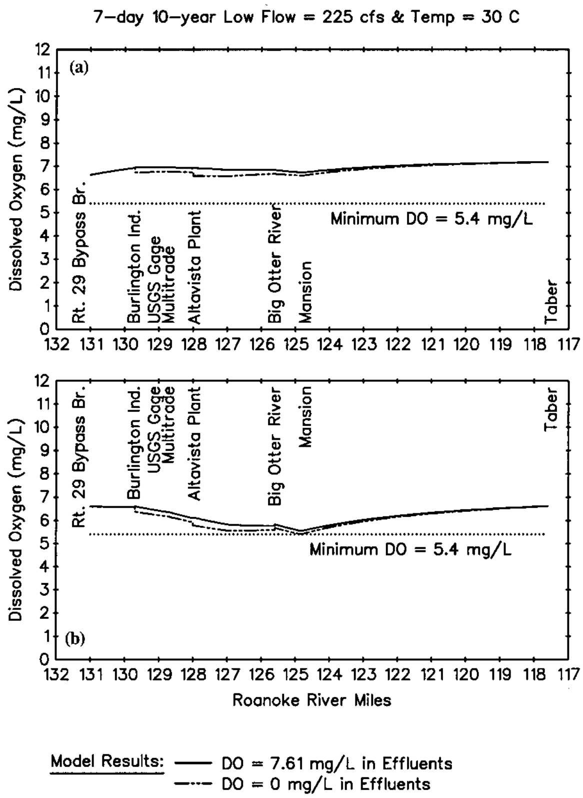

FIG. 5. Model Prediction Results under 7-Day, 10-Year Low Flow Condition

permit loads. Such a ratio of $CBOD_u$ to $CBOD_5$ is closely related to the in-stream deoxygenation coefficient [(4)]. Since the permit CBOD loads for both Burlington Industries and Altavista treatment plants are much higher than the loads measured in 1993 and 1995, it was assumed that the higher loads would be associated with this less stable waste, thereby yielding a higher deoxygenation rate, K_d. A K_d value of 0.2 day^{-1} is considered appropriate for wastewater effluent following secondary treatment (Thomann and Mueller 1987), associated with a $CBOD_u$ to $CBOD_5$ ratio of 1.58. This ratio was used to convert the $CBOD_5$ loads in Table 2 to $CBOD_u$ loads for the model projection analysis. (Using a $CBOD_u$ to $CBOD_5$ ratio of 1.58 associated with a K_d rate of 0.2 day^{-1} would result in a greater oxygen demand in the river than would the ratio of 3.39 and a K_d of 0.07 day^{-1}, as used in the model calibration and verification analyses.)

Fig. 5(a) shows the model results with the current permit loads under the 7*Q*10 condition. The dissolved oxygen concentrations are consistently above the 5.4 mg/L minimum and are gradually approaching the saturation concentration of 7.61 mg/L (30°C). Different dissolved oxygen concentrations in the effluents show a very small difference in the predicted dissolved oxygen concentrations in the river [Fig. (5)]. In general, a significant assimilative capacity exists in the Roanoke River near Altavista under the 7*Q*10 condition.

The model was then used to quantify the assimilative capacity of the Roanoke River from river mile 131 (Rt. 29 bypass) to river mile 125 (Mansion) under the 7*Q*10 condition. It was assumed that any additional CBOD loads will enter at river mile 131. A K_d rate of 0.2 day^{-1} for CBOD deoxygenation in the river was assumed for secondary treatment for future wasteloads. The additional load will reduce the dissolved oxygen concentration in the river but will not depress the DO level to below 5.4 mg/L anywhere in the river. Results of the model analysis are shown in Fig. 5(b) for variable DO concentrations in the effluents of assumed treatment levels. A minimum DO of 5.4 mg/L is reached at river mile 124.8, with an additional $CBOD_u$ load of 17,500 lb/day entering at river mile 131. Again, varying dissolved oxygen concentrations in the effluents has an insignificant impact on in-stream dissolved oxygen levels.

MODEL SENSITIVITY: ONE PERSPECTIVE

Since the characteristics of these additional loads are not certain at the present time, model sensitivity runs were conducted to develop a range of possible loads for the assessment of the assimilative capacity. Thomann and Mueller (1987) reported a range of K_d rates from 0.1 day^{-1} to 0.3 day^{-1} for primary and secondary effluents. It should be pointed out that the $CBOD_u$ to $CBOD_5$ ratio varies with these K_d rates accordingly. These ratios were incorporated into a model sensitivity analysis: K_d = 0.1 day^{-1} (ratio = 2.54), K_d = 0.2 day^{-1} (ratio = 1.58), and K_d = 0.3 day^{-1} (ratio = 1.29).

The two extreme cases for the K_d values of 0.1 day^{-1} and 0.3 day^{-1} would result in additional $CBOD_u$ loads of 37,500 lb/day and 10,800 lb/day, respectively. Perhaps a better perspective can be demonstrated by comparing the total assimilative capacity (in terms of $CBOD_5$ loads) with that generated by the TVA equation. Fig. 6 shows a plot of total assimilative capacity versus the CBOD deoxygenation rate, K_d, which reflects the wastewater characteristics. The solid curve in Fig. 6 represents the total assimilative capacity (i.e., including the $CBOD_5$ loads from Burlington Industries, the Altavista wastewater treatment plant, and additional loads) in the Roanoke River near Altavista under the 7*Q*10 condition while maintaining a minimum dissolved oxygen concentration of 5.4 mg/L. This solid curve applies to the K_d values ranging from 0.1 day^{-1} to 0.3 day^{-1}, characterizing a variety of treatment levels: from advanced secondary to advanced primary. The dash-dot line represents the total assimilative capacity predicted by the TVA equation. The model results yield a much higher assimilative capacity than the TVA equation does by taking into account the BOD kinetics in the receiving water, which in turn depend on the wastewater characteristics. Without the BOD kinetics, the TVA equation assumes that the effluent is marginally treated. In fact, results from Fig. 6 suggest that the TVA equation is associated with very high K_d rates, resulting in very conservative predictions. Measured K_d rates from long-term CBOD tests of the Altavista effluents in the present study are close to 0.07 day^{-1}, indicating a well treated waste. A significant assimilative capacity is therefore expected at such a low CBOD deoxygenation rate.

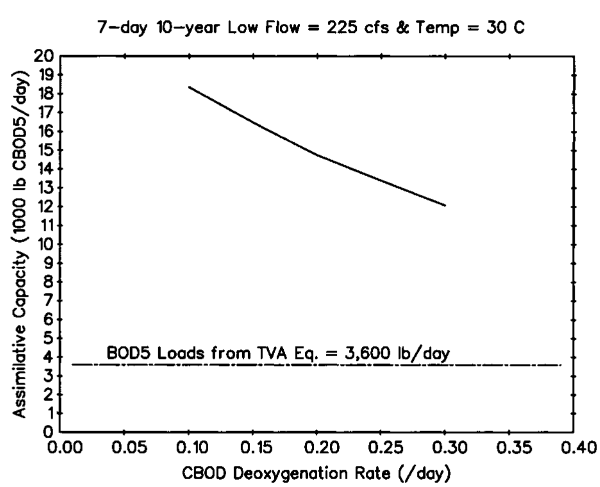

FIG. 6. Assimilative Capacity Based on STREAM Model and TVA Equations

IMPACT OF MODELING WORK ON PERMITS

The first draft permit issued by the VDEQ in 1994 required the Altavista plant to meet final effluent BOD_5 limits of 9 mg/L and 14 mg/L for monthly average and weekly average concentrations, respectively. Water quality modeling results from the initial phase provided evidence of available assimilative capacity, and VDEQ established a final effluent limit for BOD of 24 mg/L. Following the completion of the modeling analysis, the VDEQ modified the NPDES permit and issued the final effluent $CBOD_5$ limits of 30 mg/L and 45 mg/L for monthly average and weekly average concentrations, respectively. Since the water quality model supporting the WQMP is considered regulatory, it was necessary to amend the regulations by replacing the TVA equation with the calibrated and verified BOD/DO model.

ECONOMIC BENEFITS

The modeling work encompassed by this project has a direct bearing on three issues: water quality planning, costs, and benefits. The water quality planning documents for each watershed, or political area, are developed to consider the state of waters, the desired conditions (beneficial use), and future impacts to the watershed from growth. The water quality model is an integral component of the watershed management plan, since it quantifies all of the constituent relationships for pollutants in the ambient water, thereby allowing us to make assessments on how particular actions will affect the health of the Roanoke River. The combined concerns of natural habitat, potable water supply, energy supply, and recreation are represented in one form by the model statement, since the model is a measure of how suitable the receiving water is for the planned use. When permitting issues become the prime reason for revisiting water quality models, it indicates that planning aspects have been disregarded. That is, the planning documents are intended to be revisited on some regular basis under the Clean Water Act and revisiting should include periodic modeling to ensure that component is current and able to generate sound projections for the future. The most pressing reason for performing water quality modeling in the planning stages is that much less money is invested in modeling compared to the planned action, and the modeling allows us to weigh the costs associated with the other issues in the watershed.

In the case presented, the first draft permit issued for the planned expansion of the Altavista plant would have cost nearly $17,000,000 based on the TVA equation. The cost of the entire modeling work completed between 1993 and 1996, as reported in the present paper, was less than $100,000. Results from the modeling study indicated that secondary treatment was adequate, and the plant expansion costs were reduced to $7,000,000. The benefit of performing the modeling is obvious: $10,000,000 were saved and water quality was preserved. If the water quality modeling had been completed, $130,000 spent on the chemical feed requirement would have been saved—providing a second example within the same case study that modeling is cost-effective. More importantly, if use of the TVA equation had prevailed, the additional costs associated with the upgrade construction would have misdirected significant public funds for growth.

SUMMARY AND CONCLUSIONS

The current paper presents the results of a project on the Roanoke River that reassessed the state of water quality modeling within the water quality management plan. This action was necessitated by the long-term use of an inappropriate water quality model for the watershed. The original model could not represent the pertinent aspects of the BOD/DO relationship for the current state of wastewater treatment in the watershed. Consideration of mass-balance calculations and kinetic relationships is beyond the capabilities of the original management model. The newly constructed model resolved the current state of the river and established the assimilative capacity for BOD components that may be discharged into the watershed while preserving water quality criteria. While the modeling effort saved the local citizens millions of dollars (and equivalent draw on revolving loan funds), it also established the various costs associated with other sources of BOD, such as nitrogenous matter, by resolving the impact of those sources on the dissolved oxygen budget of the river. This knowledge can be used to promote water resource planning decisions as future growth in the area is considered alongside water quality concerns.

Application of water quality modeling has been concerned with permitting issues related to specific discharges throughout the United States. The attention given to these applications indicates that there is a need to consider water quality modeling on a larger basis, such as the entire watershed. Furthermore, other water quality issues such as nonpoint pollution, maintenance of natural habitat, and potable water supply also relate directly to water quality modeling in a watershed. The nature of the work presented in the current case study indicates that water quality modeling should be exercised more in the field of water resources engineering since the issues are broad. The Clean Water Act requires that watershed management plans (conceptual, narrative, or quantitative) should be reviewed on some regular cycle in a fashion similar to the review of the state of the waters. Where quantitative modeling has been established for a watershed, or tributaries, the steps of calibration, verification, or postauditing should be accomplished to ensure that the model is current and able to make effective predictions for water quality management decisions. If an obsolete modeling tool has been employed, and the tool is not capable of representing the state of the receiving waters, a more current tool should be used to supplant the dated code. Water quality management is a significant component of water resources, and water quality modeling can be a powerful tool for managers to use in making watershed decisions while also providing users with important data.

APPENDIX. REFERENCES

Chapra, S. C. (1997). *Surface water-quality modeling*. McGraw-Hill, New York.

The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS: Documentation and user manual. (1987). *EPA/600/3-87/007*, Environmental Protection Agency, Washington, D.C.

Krenkel, P. A., and Ruane, R. J. (1979). ''Chapter 18: Basic approach to water quality modeling.'' *Modeling of rivers*, H. W. Shen, ed., Wiley, New York.

Leo, M. W., Thomann, R. V., and Gallagher, T. W. (1984). ''Before and after case studies: Comparisons of water quality following municipal treatment plant improvements.'' *Rep. Prepared for EPA Ofc. of Water Programs Operations*.

Lung, W. S. (1987). ''Water quality modeling using personal computers.'' *J. Water Pollution Control Fedn.*, 59(10), 909–913.

Lung, W. S. (1998). ''Trends in BOD/DO modeling for wasteload allocations.'' *J. Envir. Engrg.*, ASCE, 124(10), 1004–1007.

Technical guidance manual for developing total maximum daily loads–Book II: Streams and rivers; Part 1: Biochemical oxygen demand/dissolved oxygen and nutrient/eutrophication. (1995). *EPA 823-B-95-007*, Environmental Protection Agency, Office of Water, Washington, D.C.

Thomann, R. V., and Mueller, J. A. (1987). *Principle of surface water quality modeling and control*. HarperCollins, New York.