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TMDL Case Study

Modeling the Appoquinimink River

Key Feature:	Application of WASP4 to support TMDL development
Project Name:	Appoquinimink River
Location:	EPA Region III/New Castle County, Delaware
Scope/Size:	River, watershed 30,200 acres
Land Type:	Flat plains
Type of Activity:	Agriculture, urban
Pollutants:	Phosphorus (algae)
TMDL Development:	Phased, PS/NPS
Data Sources:	Local, STORET
Data Mechanisms:	WASP4 model, DYNHYD5 submodel
Monitoring Plan:	Yes
Control Measures:	NPDES permit, BMPs

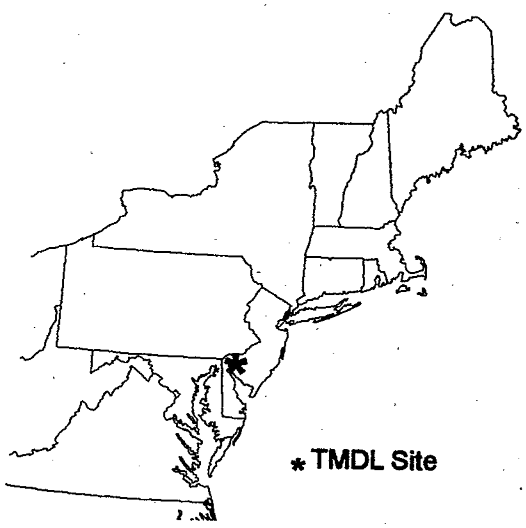

FIGURE 1. Location of the Appoquinimink River watershed

Summary: The Appoquinimink River watershed is located in eastern Delaware (Figure 1). *TMDL Case Study: Appoquinimink River, Delaware* (USEPA, 1993, Case Study Number 9) describes the TMDL for phosphorus developed by the Delaware Department of Natural Resources and Environmental Control (DNREC) for the Appoquinimink River using the phased approach to TMDL development. The objectives of the TMDL included characterization of the nonpoint source nutrient loads and their impact on water quality and description of further modeling studies necessary to refine the TMDL. DNREC used available ambient water quality data and existing point and nonpoint source loading data to conduct the initial assessment and characterize the Appoquinimink's water quality problems. In addition, the EUTRO4 version of EPA's Water Quality Analysis Simulation Program (WASP4), a water quality model, was used to analyze the dissolved oxygen (DO) and nutrient economy of the river. Phosphorus overenrichment was determined to be the ultimate cause of excursions of applicable DO criteria. A phosphorus TMDL of 18,947 lb/yr was calculated as the sum of the point source allocation (6,862 lb/yr) and the background/nonpoint source allocation (12,085 lb/yr). These allocations reflect a reasonable margin of safety and will prevent further water quality degradation.

This case study describes the specific modeling efforts in more detail. The WASP4 model was used to predict the water quality impacts of various point and nonpoint source loading scenarios. With the additional information about nonpoint source loads collected as part of the initial phase of TMDL development, the modeling study found that even the most aggressive pollution control scenario—which consisted of total removal of point source loads, 50 percent removal of nonpoint source phosphorus and nitrogen loads, and 50 percent removal of the oxygen demand (SOD), ammonia, and phosphorus flux of sediments—provided only a marginal difference in DO levels. These results indicated that the system is driven by SOD. The TMDL has included a schedule for continued monitoring and modeling to address the SOD issue.

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BACKGROUND

Editor's note: This case study presents details about the technical modeling aspects of TMDL Case Study: Appoquinimink River, Delaware (USEPA, 1993, Case Study Number 9) *to provide an example of dynamic water quality modeling for a river system in which dissolved oxygen (DO) deficit is the primary water quality problem.*

The Resource

The Appoquinimink River watershed is located in the flat coastal plain of eastern Delaware. The river's headwaters and major tributaries drain agricultural lands to feed Shallcross Lake, Silver Lake, Noxontown Pond, and Wiggins Mill Pond (Figure 2). Below these lakes is the tidal freshwater segment of the Appoquinimink, which is bounded by the head of tide at Noxontown Pond and Silver Lake (river mile 10.2) at the upstream end and by Drawyer Creek's confluence with the Appoquinimink River (river mile 5.0) at the downstream end. The only point source within this reach, the Middletown-Odessa-Townsend wastewater treatment plant (MOT WWTP), discharges 0.5 million gallons per day (mgd) at river mile 6.7. Salinity within the 5-mile reach generally remains below 5 parts per thousand, which, according to Delaware's water quality standards, classifies the reach as freshwater (DNREC, 1990). For freshwater systems, section 11.1 of the Standards requires a representative daily (24-hour) average DO concentration of 5.5 milligrams per liter (mg/L) from June through September and an instantaneous minimum DO concentration of 4.0 mg/L.

The designated uses of the tidal freshwater portion of the Appoquinimink are primary contact recreation; secondary contact recreation; fish, aquatic life, and wildlife; industrial water supply; and agricultural water supply. Recreational uses such as swimming have been sharply curtailed because of water quality constraints, especially the excessive algal growth and DO deficit that have resulted from phosphorus loadings (Water Resources Agency, 1986).

Although there are no numerical standards for nutrient concentrations, the water quality standards do recognize that nutrient overenrichment is a significant problem in some of Delaware's surface waters. For this reason, it is DNREC's policy to minimize nutrient input to surface waters from any controllable source, establishing the types of, and need for, nutrient controls on a site-specific basis.

DNREC chose the Appoquinimink River as the site of this TMDL because it was identified as water quality-limited and requiring a TMDL; a wastewater management decision was pending at the MOT WWTP; a single point source made the TMDL relatively simple; and information on nonpoint source loadings was available.

Modeling Strategy

DNREC chose to use WASP4 because it is the most complete EPA-supported water quality model in terms of kinetics and processes. WASP4 is a detailed receiving water quality model that allows users to interpret and predict water quality responses to natural phenomena and

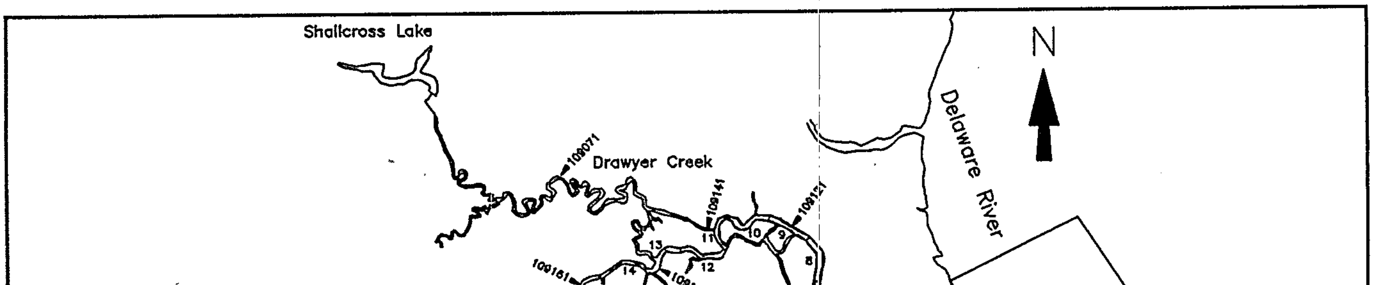

FIGURE 2. Appoquinimink River WASP4 segmentation and location of monitoring stations

man-made stresses for various pollution management decisions. The main advantage of using WASP4 is its ability to portray the relative spatial influences of each major pollutant source on the receiving waters, as well as a representation of the transport and water quality kinetics phenomena (i.e., mixing and diel processes).

Because DNREC suspected that a nutrient and algal problem was contributing to depressed DO levels, the EUTRO4/WASP4 submodel for nutrient and eutrophication analyses was applied. Initially, only enough data were available to run steady-state simulations of existing conditions in the Appoquinimink for characterization purposes. Ultimately, DNREC wanted to predict the effects of pollution reduction controls on water quality, especially DO levels, to facilitate TMDL development.

Data Issues

Ambient water quality data and existing point and nonpoint source loading data were available to conduct an initial assessment and characterization of water quality problems in the Appoquinimink River. Most of the ambient data came from intensive water quality surveys that were conducted for New Castle County from September through October 1990 to assess the human health and environmental impacts that might be caused by increasing the MOT WWTP discharge. Ambient water quality monitoring program data from 1985 through 1990 were also available from EPA's STORET data base to supplement the intensive survey data. Table 1 of TMDL Case Study Number 9 summarizes the available water quality data. Monitored parameters included DO, temperature, 5-day biological oxygen demand (BOD_5), ammonia nitrogen (NH_3-N), total Kjeldahl nitrogen (TKN), total phosphorus (TP), soluble orthophosphorus (SOP), salinity, and pH. No data on chlorophyll-*a* concentrations were available.

A diel DO profile was also developed at the river mile 6.4 station, just above the treatment plant discharge. The diel DO data collected during October 1990 indicated violations of the daily average criterion of 5.5 mg/L. Periodic grab samples collected from 1985 to 1990 also indicated several violations of the minimum criterion of 4.0 mg/L. To more completely characterize the factors contributing to these violations of the DO standard using the WASP4 water quality model, DNREC needed to monitor the Appoquinimink and its tributaries.

Monitoring began in November 1991 and is still under way. The monitoring has included synoptic water quality surveys of the tidal river and major tributaries; measurement of tributary flows and nutrient concentrations to estimate nutrient loads; analyses of sediment nutrient content; and diel monitoring of DO, temperature, and salinity at selected stations in the tidal river for periods of several consecutive days. The additional data have allowed DNREC to calibrate the WASP4 model to a higher order of complexity, making it more predictive. Previous modeling efforts that were conducted at lower levels of complexity only mimicked river responses.

The previous effort used the Level 3 order of complexity within the EUTRO4/WASP4 model. This level simulates DO processes using full linear DO balance equations that include nitrification and the effects of photosynthesis and respiration from given phytoplankton levels. The variables simulated are ammonia nitrogen, nitrate nitrogen, carbonaceous biochemical oxygen demand (CBOD), dissolved oxygen, and organic nitrogen. With the more sophisticated model, the effects of combinations of various point and nonpoint source reductions were predicted, providing valuable information to decision makers who must ultimately decide how the DO problem will be solved. Specifically, intermediate eutrophication processes and benthic reactions (nutrient enrichment, eutrophication, and DO depletion) were simulated using the Level 6 order of complexity. In addition to the system variables simulated in Level 3, inorganic phosphorus, phytoplankton carbon, and organic phosphorus are also simulated.

TMDL DEVELOPMENT

The Initial Modeling Effort

The EUTRO4 version of EPA's WASP4 water quality model was used for the initial analysis of the DO and nutrient economy of the Appoquinimink River to determine the cause of the DO criteria violations. The model was run to simulate DO and nutrient concentrations in the river. The WASP4 model runs were steady-state, tidally averaged simulations of a one-dimensional channel to represent the tidal freshwater portion of the Appoquinimink. Model simulations were run using the Full Linear DO Balance (Level 3 order of complexity), as defined in the WASP4 user's manual. Key processes modeled included CBOD, nitrification, reaeration, and sediment oxygen demand (SOD). Although they were considered important, algal photosynthesis and respiration rates were not modeled as part of this initial effort because there were no chlorophyll-*a* data. Instead, algal photosynthesis and respiration rates were estimated using screening-level analyses that involved evaluating available STORET data.

Point Sources

The diel variation of DO concentrations that was noted during an intensive water quality survey suggested that phytoplankton productivity and respiration were occurring at significant rates. The 24-hour average DO concentration was 5.2 mg/L, with a maximum level of 6.1 mg/L and a minimum level of 4.2 mg/L (Ritter and Levan, 1992). It was also suspected that the excessive algal biomass production and subsequent die-off and sedimentation of organic matter were contributing to higher-than-normal SOD.

Phosphorus was determined to be the limiting factor in phytoplankton growth. Because most of the phosphorus from the wastewater treatment plant would be bioavailable as SOP, likely causing eutrophic conditions throughout the reach and possibly in downstream waters, discharge limits were established. To take action and prevent more frequent violations of the DO standard, DNREC decided to use the phased approach to TMDL development, establishing a TMDL that capped existing phosphorus loads and called for additional monitoring and modeling to determine whether the TMDL would have to be refined.

The point source load limit was established by statistical analysis of the effluent phosphorus load measurements. The data were analyzed to define a monthly average load limit at a 95 percent confidence level. The monthly average phosphorus load was determined to be 14.57 pounds per day (lb/day), of which the 95th percentile value of a normal distribution is 18.8 lb/day. This translates into equivalent loads of 572 pounds per month and 6,862 pounds per year (lb/yr). This allocation was incorporated into the NPDES permit as final effluent limits for the MOT WWTP. The permit goes into effect May 9, 1994.

Nonpoint Sources

Rural Clean Water Program studies conducted from 1980 through 1986 measured nonpoint source loading rates of phosphorus and nitrogen in the Appoquinimink's Wiggins Mill subwatershed. Using a log-transformed distribution of the seasonal data, a Monte Carlo simulation program, PC-MC, was run to generate annual loads by repeated random sampling of the seasonal distributions. Monte Carlo simulation is a stochastic modeling technique that involves the random selection of sets of input data for use in repetitive model runs. Monte Carlo simulation allows the modeler to obtain statistical data without running the model continuously. A total of 2,000 annual load simulations were run to develop an entire distribution of annual loads based on random sampling of the seasonal load distribution. The median annual phosphorus load for the Wiggins Mill sub-basin was determined to be 1,760 lb/yr. This value was extrapolated to the watershed area upstream from the tidal freshwater segment of the Appoquinimink by multiplying by the ratio of watershed area (14,900 acres upstream from the river reach/2,170 acres in the Wiggins Mill sub-basin) to yield an annual nonpoint source phosphorus load limit of 12,085 lb/yr.

DNREC decided that although these readily available estimates were adequate to use for the first phase of the Appoquinimink TMDL, they were not appropriate to use for subsequent refinements of the TMDL. Land use patterns and the widespread implementation of BMPs since the last studies were conducted in 1986 have certainly altered nonpoint source loading rates. The validity of extrapolating the Wiggins Mill loading rates to the rest of the Appoquinimink watershed is also questionable because of differences among the subwatersheds. Additional studies to characterize nonpoint source nutrient loads to the reach and to assess the effect of Noxontown Pond, Silver Lake, and Shallcross Lake on the nonpoint source loads actually delivered to the reach were therefore proposed as part of the initial TMDL analyses.

The studies to estimate existing nonpoint source loads for the entire Appoquinimink watershed were completed by the end of 1992. DNREC monitored the outflows of Silver Lake and Noxontown Lake to determine actual nonpoint source loads to the upper boundary of the tidal river. These studies are documented in *Nutrient Budgets for the Appoquinimink Watershed* (Ritter and Levan, 1992), which outlines the nonpoint source nitrogen and phosphorus budgets that were developed using the unit loading rate method and also details land uses that were determined from 1989 aerial photographs, national wetlands inventory maps, and parcel base maps.

Ritter and Levan estimated nitrogen and phosphorus loading rates for different land uses in pounds per acre per year (lb/ac/yr) for dry, normal, and wet conditions. These loading rates were then multiplied by the acreage in the six subwatersheds of the Appoquinimink River basin to obtain annual loads in pounds. A summary of nitrogen and phosphorus loads from each of the subwatersheds for a normal year is presented in Table 1. The loading rates determined by this study were applied in the water quality modeling study of the Appoquinimink River to better define the impact of nonpoint source nutrient loads on the river's water quality and to provide a basis for refining the TMDL.

The Second Modeling Effort

DNREC used the preliminary WASP4 model as the basis for developing a more complex model of the Appoquinimink River that includes tidal hydrodynamics (circulation patterns of water in the estuary caused by

TABLE 1. Nitrogen and phosphorus loads during a normal year from subwatersheds of the Appoquinimink River (Ritter and Levan, 1992)

Subwatershed	Nitrogen Load (lb/yr)	Phosphorus Load (lb/yr)
Appoquinimink I	22,987	2,005
Appoquinimink II	78,456	786
Drawyer Creek	219,489	5,316
Silver Lake	102,386	2,541
Noxontown Pond	23,487	3,104
Hangman's Run	49,342	1,226

tides), phytoplankton dynamics (changes in phytoplankton population and phytoplankton interaction with nutrients), and benthic nutrient fluxes (the exchange of nutrients between bottom sediments and the water column). Additional field data collected during the period from March 1992 to January 1993 allowed for better determination of river geometry, boundary conditions, nonpoint source loads, and various kinetic rates than in previous models.

Calibrating and Validating the Model

Model calibration is the first stage of testing and tuning a model to a set of field data not used in the original model construction (Thomann and Mueller, 1987). This tuning should include a consistent and rational set of theoretically defensible parameters and inputs.

Calibration allows the modeler to better estimate appropriate transport and reaction rate coefficients in the model. Model calibration is not a curve-fitting exercise; it should reflect wherever possible more fundamental theoretical constructs and parameters. Models that have widely varying coefficients to merely "fit" the observed data are not considered to be calibrated.

Once the model is calibrated to one set of data, another set of external data is tested to further examine model validity. This subsequent testing is commonly known as model validation. As in this case, a validated model is often used to forecast expected water quality for a variety of potential scenarios.

The Hydrodynamic Model

The Appoquinimink River was segmented into 27 nodes and 26 connecting channels (Figure 2). For each segment the surface area and average depth at mean sea level were determined for input to the DYNHYD hydrodynamic submodel. For each channel, the channel depth, channel length, cross-sectional area, downstream (positive flow) direction, and Mannings *n* roughness coefficient were estimated. The channel geometries (depth and width) were estimated from data measured by the USGS at 10 stations along the Appoquinimink River. The geometries for segments between the measured cross-sections were estimated by interpolation.

Boundary tides at the mouth of the Appoquinimink River were estimated from the National Oceanic and Atmospheric Administration (NOAA) tide predictions using Reedy Point as the primary station. The times and heights of the high and low tides were then corrected to Liston Point, which is about 3 miles south of the mouth of the Appoquinimink River. The high and low tides over the period August 11 to October 19, 1991, were used as the boundary-forcing conditions in the model. Tributary flows in the model were set to constant values for the following locations for the August-October period:

Noxontown Pond	4.0 cfs	model segment 26
Silver Lake	4.0 cfs	model segment 27
Drawyer Creek	13.5 cfs	model segment 11

These flows were estimated based on the drainage area of each subwatershed and flows measured by a nearby USGS gage on Morgan Creek near Kennedyville, Maryland. Hydrodynamic transport was calibrated to chloride concentrations measured in the river. Because chlorides are nonreactive chemicals, they can act as a tracer. Thus, chloride concentration values plotted along the river are longitudinally correct. The model dispersion coefficients, roughness coefficients, and upstream inflow rates were varied until the model results matched the measured chlorides. Good agreement for the August-October period was attained using the above stream flows and dispersion coefficients of 15.0 m^2/sec at the mouth (segment 1), 10.0 m^2/sec for segments 2 to 13, 5.0 m^2/sec for segments 14 to 20, and 1.0 m^2/sec for segments 21 to 27 (Figure 3). To eliminate excessive tide-induced oscillation of chlorides at the boundary segment (segment 1), it was necessary to make this segment very large.

The transport and dispersion were validated to the May-July 1991 chloride data set, and good agreement was also obtained using the same dispersion coefficients used for the August-October 1991 period. The upstream boundary flows and the flow at Drawyer Creek were the same as for the calibration period shown above. The validation results show very good model agreement with the observed chloride data (Figure 4).

The Water Quality Model

WASP4/EUTRO4 was linked to DYNHYD to provide a dynamic water quality and hydrodynamic model of the Appoquinimink River. Dynamic simulations provide a

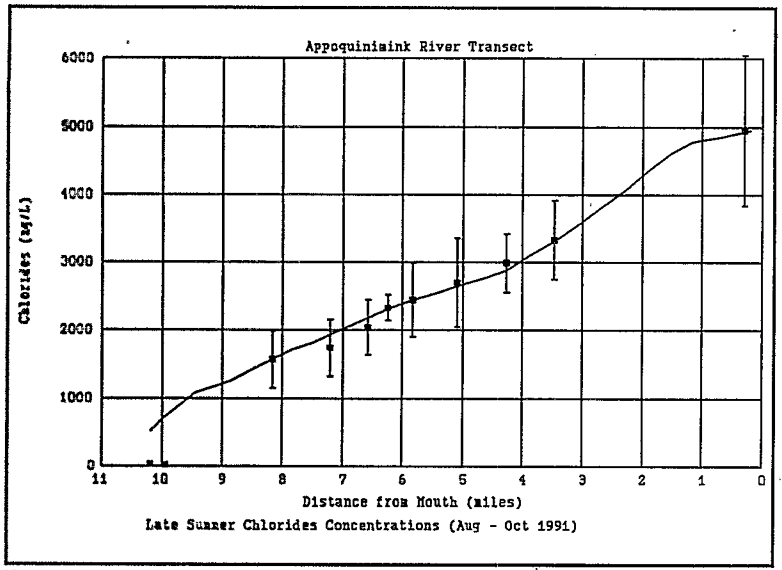

FIGURE 3. Appoquinimink River WASP4 chlorides calibration (August-October 1991)

more realistic representation of the waterbody than steady-state simulations where flows and loadings remain constant over time. WASP4 allowed the user to model the dynamic tidal action in the river. One point source (the MOT WWTP) was located in model segment 16. WASP4 was able to account for discharge from the MOT WWTP that traveled upstream, as well as downstream. The loadings for the MOT WWTP are presented in Table 2. After the WASP4 source code was modified to accommodate additional nonpoint source segments, the nonpoint source loads were distributed over the 27 model segments based on the average annual loading rates for dry weather conditions determined by

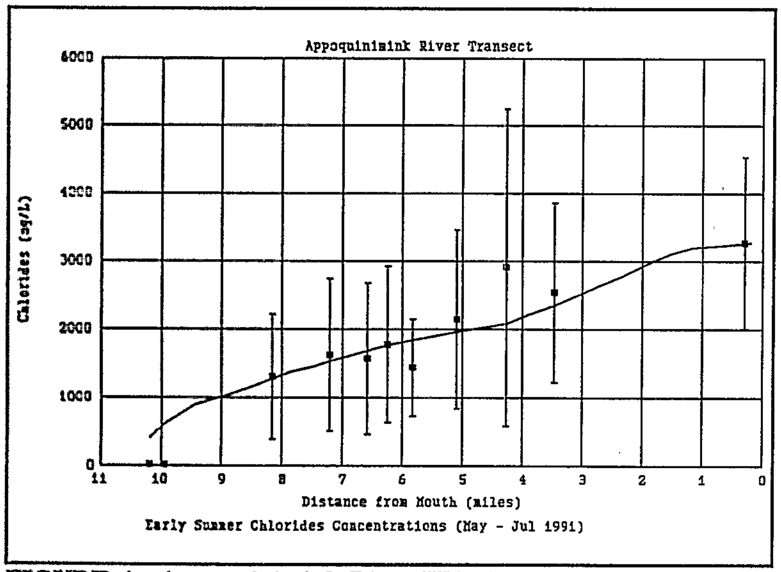

FIGURE 4. Appoquinimink River WASP4 chlorides validation (May-July 1991)

Ritter and Levan (1992). For the previous model application, nonpoint source loads were extrapolated from the 1986 Rural Clean Water Program report for the Wiggins Mill watershed; the nonpoint source loads from Ritter and Levan (1992) are lower by a factor of about 8 (Table 3).

The upstream and downstream boundary conditions for the eight system variables were taken from DNREC's preliminary version of the WASP4 model. These variables represent those simulated by the model. The boundary conditions are presented in Table 4. These concentrations must be specified for each water quality constituent at each boundary. A boundary is a tributary inflow, a downstream outflow, or an open water end of the model network across which dispersive mixing can occur. The boundary conditions presented in Table 4 are the average of the August, September, and October 1991 data.

TABLE 2. Point source loadings from the Middletown-Odessa-Townsend wastewater treatment plant

Parameter	Loading, mg/L (kg/day)
Flow	0.500 mgd
CBOD	19.50 (36.9)
Organic nitrogen	5.00 (9.5)
Ammonia nitrogen	10.00 (18.9)
Nitrate nitrogen	0.00 (0.0)
Total phosphorus	3.38 (6.4)

No field measurements of SOD were made in the Appoquinimink River. SOD rates were set to values between 0.500 and 1.000 $gO_2/m^2/day$ for segments upstream of the MOT WWTP and 1.50 $gO_2/m^2/day$ for segments downstream of the plant based on typical ranges for estuarine muds found in the literature (USEPA, 1985). The SOD rates were adjusted within this range until the model was calibrated. Some field data on the chemical composition (i.e., carbon, phosphorus, and nitrogen) of the river sediment were available, but no information was available on benthic flux of ammonia nitrogen and phosphorus, so they were set based on stoichiometry and the classical ratios of O:C:N:P (109:41:7.2:1) developed by A.C. Redfield (Stumm and Morgan, 1981).

Oxygen-deficient waters are replenished via atmospheric reaeration. The reaeration rate coefficient is a function of the average water

TABLE 3. Nonpoint source loading rates (kg/day) used in the first and second WASP4 model applications on the Appoquinimink River

Parameter	Initial effort (RCWP, 1986)	Second effort (Ritter and Levan, 1992)
Total phosphorus	16.12	2.234
Orthophosphate	6.48	0.893
Total nitrogen	615.3	82.29

velocity, depth, wind, and temperature. In the EUTRO4/WASP4 model, the user may specify a single reaeration rate constant or spatially variable reaeration rate constants, or may allow the model to calculate variable reaeration rates based on flow or wind. In this application, the reaeration rate was calculated by the model. EUTRO4/WASP4 will use either the flow-induced rate or the wind-induced rate, whichever is larger. EUTRO4/WASP4 calculates flow-induced reaeration based on the Covar method and wind-induced reaeration based on O'Connor (Ambrose et al, 1993).

Photosynthetically active radiation (PAR) measurements were made at a number of locations in the river from May 1991 to June 1992. The PAR data, along with measured chlorophyll-*a* concentrations, were analyzed to determine the background light extinction coefficients for the model segments. Regression analysis on the PAR versus depth data yields the total extinction rate (K_e). The portion of the total extinction attributed to chlorophyll-*a* can be determined by the following formula (Thomann and Mueller, 1987):

$$K_{e(c)} = 0.0088P + 0.054P^{2/3}$$

where P is the chlorophyll-*a* concentration in μg/L. The background extinction coefficient ($K_{e(o)}$) can then be determined by:

$$K_{e(o)} = K_e - K_{e(c)}$$

These background extinction coefficients were incorporated into the WASP4 model.

The model calibration results, averaged over the period from August to October 1991, are presented in Figure 5. The daily average DO is slightly under predicted by the model, although most of the values fall within the range of the standard deviations of the observed data. The model chlorophyll-*a* is consistently lower than the observed chlorophyll-*a* data. Two possible explanations for this discrepancy are (1) the model chlorophyll-*a* is depth-averaged over the water column while the chlorophyll-*a* samples were collected near the surface where the concentration tends to be higher or (2) there may be a consistent bias in the laboratory analyses of the chlorophyll-*a* samples. Nitrogen and phosphorus concentrations predicted by the model were within the range of the observed data.

The model was validated using data for the period May to July 1991. Boundary conditions used for the validation period are shown in Table 5. Model validation results are shown in Figure 6. The observed chlorophyll-*a* concentrations were in the range 10-35 μg/L, and the model did a better job of predicting these lower levels of chlorophyll-*a*.

Overall, the WASP4 model of the Appoquinimink appears to adequately simulate the events measured in the field. The only difference in kinetic coefficients

TABLE 4. August to October 1991 calibration boundary conditions (mg/L) for an application of WASP4 to the Appoquinimink River

System Variable	Location			
	Downstream Boundary	Silver Lake	Noxontown Pond	Drawyer Creek
Ammonia	0.10	0.20	0.20	0.20
Nitrate+Nitrite	1.0	1.0	1.0	1.0
Orthophosphate	0.10	0.05	0.05	0.05
Chlorophyll-*a*	0.016	0.064	0.064	0.032
CBOD	4.0	7.0	7.0	7.0
Dissolved oxygen	7.25	8.60	8.30	8.0
Organic nitrogen	0.40	1.67	0.44	0.40
Organic phosphorus	0.02	0.05	0.08	0.05

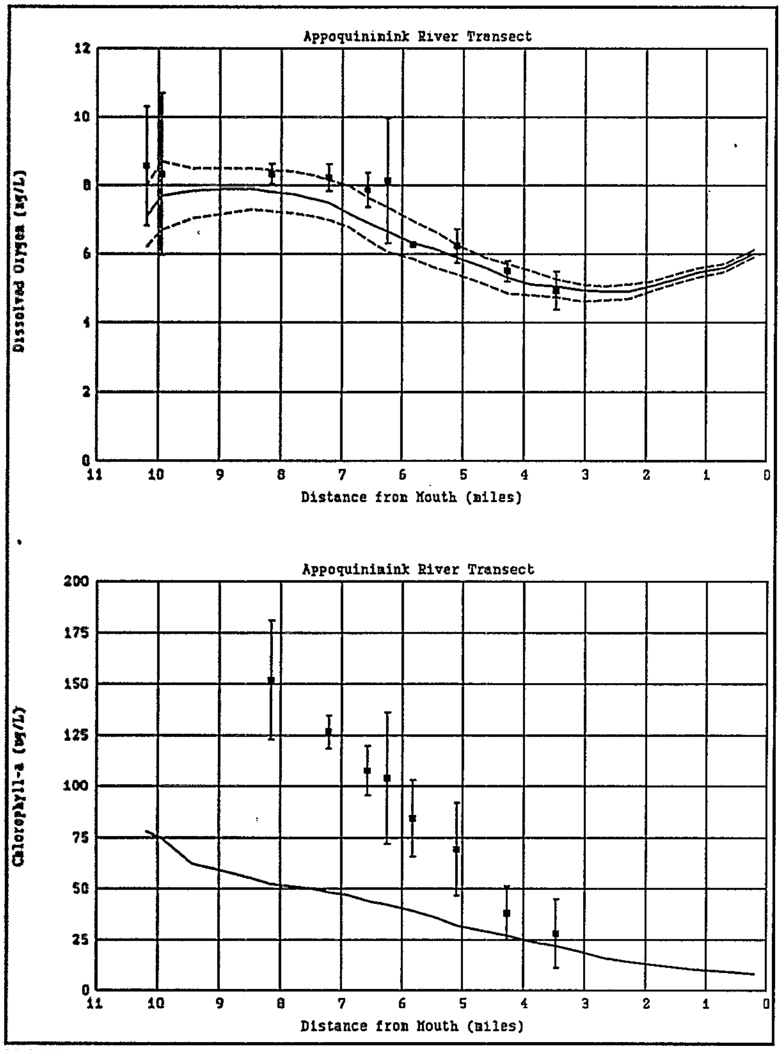

FIGURE 5. Appoquinimink River WASP4 dissolved oxygen and chlorophyll-*a* calibration (August-October 1991)

between the calibration and validation run was the phytoplankton growth rate (K1C), which was set to 2.200/day in the calibration run and 2.000/day in the validation run. All other kinetic coefficients were identical.

Uncertainties

Uncertainties in modeling are encountered when data required by the application are insufficient or unknown. Often such uncertainties are accounted for by conservative estimates based on best professional judgment and data available from similar or nearby watersheds and from the literature.

The most significant unknown in the Appoquinimink model is the magnitude and the spatial and temporal variation of SOD and other nutrient fluxes from the benthos in the river. Other unknown or poorly defined parameters that added uncertainty to the calibration and validation were as follows:

- The discharges from Noxontown Pond and Silver Lake were not measured during the calibration and validation periods.
- The concentrations of chlorophyll-*a* from Noxontown Pond and Silver Lake were not known.
- The concentrations of all system parameters at the Delaware River boundary were not measured. Values measured at the sampling stations furthest downstream (109101 and 109121) were used to estimate the Delaware River boundary conditions.

TABLE 5. May to July 1991 validation boundary conditions (mg/L) for an application of WASP4 to the Appoquinimink River

System Variable	Location			
	Downstream Boundary	Silver Lake	Noxontown Pond	Drawyer Creek
Ammonia	0.05	0.17	0.11	0.05
Nitrate+Nitrite	1.40	3.47	0.47	0.50
Orthophosphate	0.05	0.04	0.02	0.05
Chlorophyll-*a*	0.008	0.032	0.032	0.004
CBOD	4.0	7.0	7.0	7.0
Dissolved oxygen	6.87	8.00	7.90	6.0
Organic nitrogen	0.30	0.59	1.01	0.30
Organic phosphorus	0.05	0.05	0.04	0.05

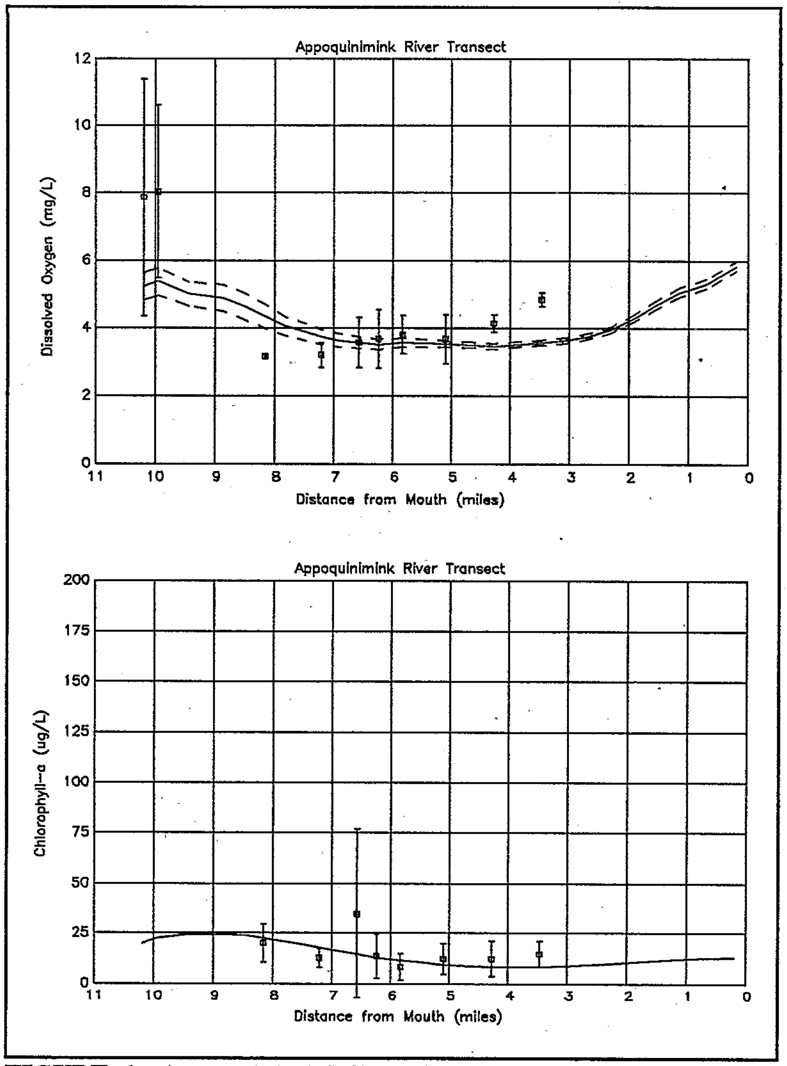

FIGURE 6. Appoquinimink River WASP4 dissolved oxygen and chlorophyll-*a* validation (August-October 1991)

- The flow and boundary concentrations for Drawyer Creek were largely undefined.
- No time-variable loading of nutrients caused by nonpoint source storm runoff was available for inclusion in the model. All nonpoint source loadings were constant in time-based on the most recent work of Ritter and Levan (1992).

Initial runs of the model significantly under predicted chlorophyll-*a* concentrations. Investigation of possible causes led to the discovery of an error in the WASP4 user's manual and an undocumented default setting in the WASP4 (version 4.32) code. The model was run with the DiToro light formulation for algal growth, but the WASP4 manual incorrectly listed the light switch option for this light reduction factor as LGHTSW = 2. A review of the WASP4 source code indicated that LGHTSW = 1 for the DiToro light formulation and that the LGHTSW = 2 option is for the Smith light formulation. The undocumented default setting was related to the zooplankton grazing formulation. Even if the zooplankton population in the river is set to zero (ZOO = 0.00), the model intercepts this constant and resets it to 1.0 mg carbon/L unless the grazing rate constant is set explicitly to zero as well (K1G=0.00). Because the model was allowing zooplankton to graze on phytoplankton, lower chlorophyll-*a* concentrations were being predicted.

APPLYING THE WASP4 MODEL: Alternative Management Scenarios

Following successful calibration and validation, the WASP4 model was used to predict the water quality impacts of various reductions in point and nonpoint source loadings to the Appoquinimink River system. A total of 14 scenarios were run, each with a different combination of point and nonpoint source phosphorus and nitrogen loads. Each alternative was compared to a base run that represented existing conditions in the Appoquinimink River under critical summer conditions. For the base run, the upstream freshwater flow was set to the 7-day, 10-year low flow (7Q10) of 0.32 cfs (0.16 cfs was input to segment 26 and segment 27, representing the outflow from Noxontown Pond and Silver Lake, respectively). The boundary conditions were the same as those used for the May to July 1991 validation period. Nonpoint source loads were the same as those used in the model calibration and validation. The MOT WWTP loadings represent existing loads for a flow of 0.5 mgd.

Figure 7 shows the results of the most aggressive pollution reduction control scenario. In this case the MOT WWTP was removed; nonpoint point source total phosphorus and total nitrogen loads were reduced by 50 percent; and sediment fluxes of SOD, ammonia, and phosphate were reduced by 50 percent. Even with these nutrient loading reductions, the model results indicate that the daily average DO standard of 5.5 mg/L will not be attained. The boundary loadings at the upstream locations (Noxontown Pond and Silver Lake) or at Drawyer Creek were not changed from the base run.

CONCLUSIONS

The original plan was to develop cost and confidence curves for different pollution control scenarios. However, the discovery that even the most aggressive pollution control scenario (Figure 7) provided only a marginal difference in DO concentrations indicated that

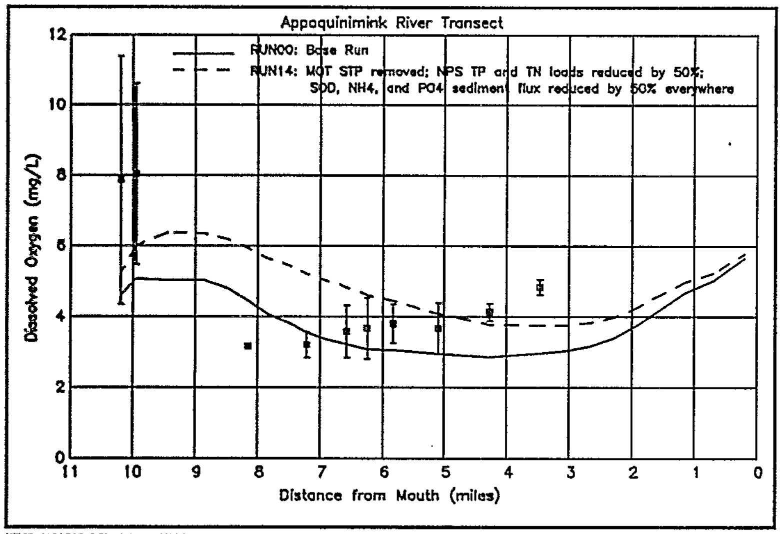

FIGURE 7. WASP4 dissolved oxygen results for Alternative Run 14 on the Appoquinimink River

the majority of oxygen demand is coming from the sediment.

Given this information, the next phase of TMDL activity on the Appoquinimink will:

- Define the phosphorus load reductions necessary to meet DO criteria;
- Further characterize nonpoint source nutrient loads;
- Monitor and model SOD; and
- Specify how the TMDL will be implemented.

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