Appendix A

MODELING FRAMEWORK

The computational framework chosen for the modeling of water quality of the Lower Wicomico River was the Water Quality Analysis Simulation Program version 5.1 (WASP5.1). This program provides a generalized framework for modeling contaminant fate and transport in surface waters (Di Toro *et al.*, 1983) and is based on the finite-segment approach. It is a very versatile program, capable of being applied in a time-variable or steady-state mode, spatial simulation in one, two or three dimensions, and using linear or non-linear estimations of water quality kinetics. To date, WASP5.1 has been employed in many modeling applications that have included river, lake, estuarine and ocean environments. The model has been used to investigate water quality concerns regarding dissolved oxygen, eutrophication, and toxic substances. WASP5.1 has been used in a wide range of applications by regulatory agencies, consulting firms, academic researchers and others.

WASP5.1 is supported and distributed by U.S. EPA's Center for Exposure Assessment Modeling (CEAM) in Athens, GA (Ambrose *et al.*, 1988). EUTRO5.1 is the component of WASP5.1 that is applicable for modeling eutrophication, incorporating eight water quality constituents in the water column (Figure A1) and sediment bed.

WATER QUALITY MONITORING

Physical and chemical samples were collected by MDE's Field Operations Program staff on February 18, March 11, April 1, July 28, August 24, and September 22, 1998. The physical parameters, dissolved oxygen, salinity, conductivity, and water temperature were measured *in situ* at each water quality monitoring station. Grab samples were also collected for laboratory analysis. The samples were collected at a depth of ½ m from the surface. Samples were placed in plastic bottles and preserved on ice until they were delivered to the University of Maryland Laboratory in Solomons, MD, or the Department of Health & Mental Hygiene in Baltimore, MD for analysis. The field and laboratory protocols used to collect and process the samples are summarized in Table A1. The February and March data were used to calibrate the high flow water quality model. The April data was not used because the temperature was significantly higher than in February and March. The July, August and September data were used to calibrate the low flow water quality model for the Lower Wicomico River. Figures A2 – A6 present low flow and high flow water quality profiles along the river.

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INPUT REQUIREMENTS [1]

Model Segmentation and Geometry

The spatial domain of the Lower Wicomico River Eutrophication Model (LWREM) extends from the confluence of the Lower Wicomico River with the Ellis Bay and Monie Bay for about 18.7 miles along the mainstem of the Lower Wicomico River. Following a review of the bathymetry for the Lower Wicomico River, the system was divided into 34 segments. Figure A7 shows the model segmentation and the location of the WWTPs. Table A2 lists the volumes, interfacial areas, and characteristic lengths of the 34 segments.

Dispersion Coefficients

The dispersion coefficients were calibrated using the WASP5.1 model and in-stream water quality data from 1998. The WASP5.1 model was set up to model salinity. Salinity is a conservative constituent, which means there are no losses due to reactions in the water. The only source in the system is the salinity from the water at the tidal boundary at the mouth. For the model execution, salinities at all boundaries except the tidal boundary were set to zero. Flows were obtained from 3 USGS gages near the basin (described in further detail below). Figure A8 shows the results of the calibration of the dispersion coefficients for low flow. The same sets of dispersion coefficients were used for both the high flow and low flow calibration, because of insufficient salinity data for a reasonable high flow salinity calibration. Final values of the dispersion coefficients are listed in Table A3.

Freshwater Flows

Freshwater flows were calculated on the basis of delineating the Wicomico drainage basin into 11 subwatersheds (Figure A9). These subwatersheds closely correspond with the Maryland Department of Natural Resources 12-digit basin codes. As necessary, the subwatersheds were refined to assure they were consistent with the 34 segments developed for the LWREM. The LWREM was calibrated for two sets of flow conditions: high flow and low flow. The high flow corresponds to the months of February and March, while the low flow corresponds to the months of July, August and September.

The high flows for the subwatersheds were estimated with flows for the months of February and March of 1998 using the USGS gages #01485000, #01485500 and #01486000 near the Lower Wicomico River basin. There was no active USGS gage in the Wicomico Basin in 1998. A ratio of flow to drainage area was calculated, then multiplied by the area of each subwatershed, to

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1 The WASP5.1 model requires all input data to be in metric units, and to be consistent with the model, all data in the Appendix will appear in metric units except the river length. Following are several conversion factors to aid in the comparison of numbers in the main document: mgd x (0.0438) = m^3s | cfs x (0.0283) = m^3s | lb / (2.2) = kg | mg/l x mgd x (8.34) / (2.2) = kg/d |

obtain the flow for the subwatershed. During high flow each subwatershed was assumed to contribute a flow to the Lower Wicomico River.

The low flows for the subwatersheds were estimated using a similar methodology for the months of July, August and September of 1998 with the same three USGS gages noted above. A ratio of flow to drainage area was calculated, then multiplied by the area of the subwatershed, to obtain the flow for the subwatershed. During summer it was assumed that flow was only draining from those subwatersheds which have free-flowing streams to carry the flows. The ratio was not used to estimate the flow coming from subwatershed one (Johnson Pond). The river above Johnson Pond crosses a Paleo channel which has been reported to highly influence low flow conditions (HydroScience, 1975). Also releases from the pond are controlled by a notched weir (Pusey, 2000). For the low flow calibration of the model, flows from Johnson Pond were estimated using instantaneous data measurements taken during the July, August, and September field surveys.

To determine the maximum allowable BOD loads, the 7Q10 flow in the basin had to be estimated. The 7Q10 flow is the 7-day consecutive lowest flow expected to occur every 10 years. It was estimated using the same methodology as for the low flow. The flow to area ratio was estimated using the 7Q10 flow from USGS gage #01486500 in the Wicomico Basin. The 7Q10 flow from Johnson Pond was estimated by a low flow correlation between a monitoring station just below Johnson Pond (WIW0221) and the USGS gage #01486500 on Beaverdam Creek. Figure A10 presents the flow correlation plot.

The average flows were calculated using the same methodology as for the high flows. Flow data from the same three USGS stations for the period of January 1984 to December 1987 was used to calculate the flow to area ratio. During average flow, each subwatershed was assumed to contribute a flow to the Lower Wicomico River. Table A4 presents the flows from the different subwatersheds during high, low, 7Q10, and average flows.

Nonpoint Source Loadings

Nonpoint source loadings were estimated for high flow, low flow and average annual flow conditions. For nonpoint sources, the concentrations of the nutrients nitrogen and phosphorus are modeled in their speciated forms. The WASP5.1 model simulates nitrogen as ammonia (NH_3), nitrate and nitrite ($NO_{2\text{-}3}$), and organic nitrogen (ON); and phosphorus as ortho-phosphate (PO_4) and organic phosphorus (OP). Ammonia, nitrate and nitrite, and ortho-phosphate represent the dissolved forms of nitrogen and phosphorus. The dissolved forms of nutrients are more readily available for biological processes such as algae growth, that can affect chlorophyll *a* levels and dissolved oxygen concentrations. The ratios of total nutrients to dissolved nutrients used in the model scenarios represent values that were measured in the field.

The nonpoint source loadings used for the calibration of the model for both high flow and low flow were calculated using data from seven water quality stations within the Lower Wicomico River Basin. An average of data from July, August and September was used for low flow and an average of February and March was used for high flow. Water quality data from the 1998 survey was used to estimate boundary concentrations as follows: station XCI4789 was used for segment

1, station TTC0011 was used for segment 18, station WIW0221 was used for segment 23, station WIC0009 was used for segment 24, station BVM0007 was used for segment 28, station GHC0013 was used for segment 30, and station SIS0024 was used for segment 34. For the low flow calibration, the boundary concentrations for the remaining free flowing boundaries were based on average data from stations WIW0241 and ADW0001. These two stations were assumed to be a reasonable representation of water quality at the free flowing boundaries. For the high flow calibration, the boundary concentrations for the remaining boundaries were based on average data from stations WIC0073, GHC0013, and SIS0024. These three stations were assumed to be a reasonable representation of water quality for the remaining boundaries. BOD data was not available for high flow, and was assumed to be 2.0 mg/l at all boundaries.

Average annual loads were determined using land use loading coefficients. The land use information was based on 1997 Maryland Office of Planning data, adjusting crop acres using 1997 Farm Service Agency (FSA) data. The total nonpoint source load was calculated by summing all of the individual land use areas and multiplying by the corresponding land use loading coefficients. The loading coefficients were based on the results of the Chesapeake Bay Model (U.S. EPA, 1996), a continuous simulation model. The Bay Model loading rates are consistent with what would be expected in the year 2000 assuming continued Best Management Practice (BMP) implementation at a level consistent with the current rate of progress.

Both calibration loads and average annual loads reflect natural and human sources, including atmospheric deposition, loads coming from septic tanks, loads coming from urban development, agriculture, and forestland.

Point Source Loadings

For point sources, the concentrations of all eight parameters considered are modeled in the same speciated forms as described above in the Nonpoint Source Loadings section.

There are two wastewater treatment plants (WWTP) that discharge directly into the Lower Wicomico River. The Salisbury WWTP (NPDES permit number MD002157) discharges directly into the Wicomico River upstream from where the Tony Tank Creek enters the mainstem of the river. Downstream of its confluence with the Tony Tank Creek, the Fruitland WWTP (NPDES permit number MD005299) also discharges directly to the Wicomico River.

The point source loadings used in the calibration of the model were calculated from actual WWTP flows and concentrations from discharge monitoring reports (DMRs) stored in MDE’s point source database. The DMRs state monthly average flows and concentrations. For higher stream flow conditions, point source loads were simulated as an average of February and March 1998 DMR data. For low flow stream conditions, point source loads were simulated as an average of July, August and September 1998 DMR data. February, March, July, August, and September 1998 data were used to be consistent with the time period of the water quality monitoring data. The point source flows and loads used in calibration can be seen in Table A5. Several point sources that discharge above Johnson Pond are addressed indirectly by inclusion as part of the background load from the upstream model boundary at the dam release point. These upstream point sources are addressed explicitly in a TMDL under development for Johnson Pond.

The point source loadings used for the base-line "critical" scenario (first scenario) and for the annual average flow scenario (second scenario) were calculated from the maximum approved water and sewer plan flow and the maximum allowable effluent limit concentrations described in the plant's surface water discharge NPDES permit (see scenarios description below). For model input parameters for which there is no maximum permit limit, concentrations were estimated based on the type of unit operations or treatment processes used by each plant under consideration.

Environmental Conditions

Eight environmental parameters were used for developing the model of the Lower Wicomico River. They are solar radiation, photoperiod, temperature (T), extinction coefficient (K_e), salinity, sediment oxygen demand (SOD), sediment ammonia flux (FNH_4), and sediment phosphate flux (FPO_4). Most environmental parameters are listed in Table A6. For the low flow calibration of the model, the solar radiation and photoperiod are 450 langleys/day and 0.55 respectively. For the high flow calibration of the model, the solar radiation and photoperiod are 300 langleys/day and 0.50 respectively.

The light extinction coefficient, K_e in the water column was derived from Secchi depth measurements using the following equation:

$$K_e = \frac{1.95}{D_s}$$

where:

K_e = light extinction coefficient (m^{-1})
D_s = Secchi depth (m)

Nonliving organic nutrient components settle from the water column into the sediment at an estimated settling rate velocity of 0.156 *m/day*, and phytoplankton was estimated to settle through the water column at a rate of 0.207 *m/day*. In general, it is reasonable to assume that 50% of the nonliving organics are in the particulate form. Such assignments were borne out through model sensitivity analyses.

Different SOD values were estimated for different LWREM reaches based on observed environmental conditions and literature values (Thomann, 1987; Athens and Georgia 1986). The highest SOD values were assumed to occur in the lower reaches and the upper reaches (in the pond) of the River. High concentrations of nutrients and chlorophyll *a*, which have high potential to settle due to slower stream velocity, were observed in these reaches. A maximum SOD value of 3.0 $g\ O_2/m^2 day$ was used.

Kinetic Coefficients

The water column kinetic coefficients are universal constants used in the LWREM model. They are formulated to characterize the kinetic interactions among the water quality constituents. The initial values were taken from past modeling studies of Potomac River (Clark and Roesh, 1978; Thomann and Fitzpatrick, 1982; Cerco, 1985), and of Mattawoman Creek (Panday and Haire, 1986, Domotor *et al.*, 1987), and the Patuxent River (Lung, 1993). The kinetic coefficients are listed in Table A7.

Initial Conditions

The initial conditions used in the model were chosen to reflect the observed values as closely as possible. However, because the model simulated a long period of time, it was found that initial conditions did not impact the final results.

CALIBRATION & SENSITIVITY ANALYSIS

The EUTRO5.1 model for low flow was calibrated with July, August and September 1998 data. Tables A8 and Table A9 shows the nonpoint source flows and concentrations associated with the calibration input file. Figure A11 show the results of the calibration of the model for low flow. As can be seen, in Figure A11, the model did a good job of capturing the trend in the dissolved oxygen data, organic phosphorus, and organic nitrogen. The model did an excellent job of capturing the peak chlorophyll *a*, and BOD concentrations and also the general trend. It was also able to replicate the ammonia, nitrate plus nitrite, and the ortho-phosphate trends and all three variables show a peak around the Salisbury WWTP.

The EUTRO5.1 model for high flow was calibrated with February and March 1998 data. Table A8 and Table A10 shows the nonpoint source flows and concentrations associated with the calibration input file. The results are presented in Figure A12. As can be seen the model did well in capturing almost all the state variables. One exception is for organic phosphorus and the ortho-phosphate; however, this is not very significant given that the range of values is very small.

SYSTEM RESPONSE

The EUTRO5.1 model of Lower Wicomico River was applied to several different point and nonpoint source loading conditions under various stream flow conditions to project the impacts of nutrients on algal production, as chlorophyll *a*, and low dissolved oxygen. By simulating various stream flows, the analysis accounts for seasonally.

Model Run Descriptions

The first scenario represents the expected conditions of the stream under current loading conditions during low flow. The 7Q10 flow was used and estimated as described above. The total nonpoint source loads were computed as the product of observed 1998 base-flow concentrations and the estimated low flow. Because the loads are based on observed concentrations, they account for all background and human-induced sources. The point source loads of PO4, OP, BOD, and DO were calculated based on the WWTP National Pollutant Discharge Elimination System (NPDES) permitted concentrations and approved water and sewer plan maximum flows. The point source loads of NH4, NO23, and ON were calculated based on 1998 plant monitoring data and future maximum flows. Several point sources that discharge above Johnson Pond are addressed indirectly by inclusion as part of the background load from the upstream model boundary at the dam release point. The point source loads discharging above Johnson Pond are captured in the 1998 water quality samples taken just below the dam, which are used to calculate the load from the upper watershed to the river. All the environmental parameters used for the low flow calibration of the model remained the same for this scenario.

The second scenario represents the expected conditions of the stream during average flow. The average annual flow was estimated based on data from three USGS gages near the Lower Wicomico River basin as described above. Nonpoint source load estimation methods, based on EPA Chesapeake Bay model output, are described above. All the environmental parameters remained the same as scenario 1 except for the temperature. The point source loads are the same as for Scenario 1. A summer average temperature of 25.9 ^{o}C was used for all segments, it was estimated based on historical water temperatures for the months of July, August and September for the years 1986 to 1998 from three locations near the Lower Wicomico River. They are Fishing Bay, Nanticoke River and Manokin River. The boundary and initial condition values for CHL*a*, DO, and BOD were assumed to be the average of the 6 water quality measurements taken in 1998 during low flow and high flow conditions. The nonpoint source and point source loads for model Scenarios 1 and 2 can be seen in Table A11, Table A12, and Table A13.

A number of iterative model runs involving nutrient reductions were explored to determine the maximum allowable loads. The third and fourth scenarios show the water quality response in the river for the maximum allowable loads for low flow and average annual cases respectively. Load reductions from the Johnson Pond TMDL (MDE, 2000), Tony Tank Lake TMDL (MDE, 1999), and Wicomico Creek TMDL (MDE, 2000) were incorporated. To estimate feasible nitrogen and phosphorus nonpoint source reductions, the percent of the load that is controllable was estimated for each subwatershed. It was assumed that all of the loads from cropland, feedlots, and urban were controllable, and that loads from atmospheric deposition, septic tanks, pasture, and forest were not controllable. This analysis was performed on the average annual loads, because loads from specific land uses were not available for low flow. However, the percent controllable was applied to the low flow loads as well as the average annual loads.

For the runs where the nutrient loads to the system were reduced, a method was developed to estimate the reductions in nutrient fluxes and SOD from the sediment layer. First an initial estimate was made of the total organic nitrogen and organic phosphorus settling to the river bottom, from particulate nutrient organics, living algae, and phaeophytin, in each segment. This was done by running the base-line condition scenario once with estimated settling of organic and chlorophyll *a*, then again with no settling. The difference in the organic matter between the two runs was assumed to settle to the river bottom where it would be available as a source of nutrient flux and SOD. All phaeophytin was assumed to settle to the bottom. The amount of phaeophytin was estimated from in-stream water quality data. To calculate the organic loads from the algae, it was assumed that the nitrogen to chlorophyll *a* ratio was 12.5, and the phosphorus to chlorophyll *a* ratio was 1.25. This analysis was then repeated for the reduced nutrient loading conditions. The percentage difference between the amount of nutrients that settled in the base-line condition scenarios and the amount that settled in the reduced loading scenarios was then applied to the nutrient fluxes in each segment. The reduced nutrient scenarios were then run again with the updated fluxes. A new value of settled organics was calculated, and new fluxes were calculated. The process was repeated several times, until the reduced fluxes remained constant.

Along with reductions in nutrient fluxes from the sediments, when the nutrient loads to the system are reduced, the sediment oxygen demand will also be reduced (US EPA, 1997). It was assumed that the SOD would be reduced in the same proportion as the nitrogen fluxes, to a minimum of $0.5 gO_2/m^2\ day$.

The third scenario represents improved conditions associated with the maximum allowable loads to the stream during critical low flow. This scenario simulates an estimated 40% reduction in controllable nonpoint source loads of total nitrogen and total phosphorus from subwatersheds 1, 2, 3, and 5 (including the Johnson Pond basin and the Tony Tank Lake basin), and reduced loads from subwatershed 9, consistent with the draft Wicomico Creek TMDL (MDE, 2000). The reductions in subwatersheds 1, 2, 3, and 5 were made due to their proximity and influence on algal growth. And the reductions from subwatershed 9 are motivated by the water quality goals for Wicomico Creek.

Consistency with the Wicomico Creek TMDL was achieved by taking the Wicomico Creek Eutrophication Model output concentrations from the low flow future condition scenario and using them as inputs to the LWREM at segment 24 (Wicomico Creek). There are no explicit low flow TMDLs for either the Johnson Pond basin (subwatershed 1) or Tony Tank Lake basin (subwatershed 5). The annual total phosphorus reductions required in the TMDLs for these basins are greater than the 40% reduction in controllable nonpoint source loads used in scenario 3. Consequently, the TMDLs for these two basins will help to achieve the phosphorus reductions and indirectly the nitrogen reductions used in this scenario. This scenario accounts for nitrogen, phosphorus, and BOD margins of safety computed as 5% of the total NPS load allocations.

The point source load reflects maximum flow (estimated under the assumption of maximum approved water and sewer plan flows) and reduced loads. The point sources upstream of the dam are addressed explicitly in a TMDL under development for Johnson Pond. All the environmental parameters (except nutrient fluxes and SOD) and kinetic coefficients used for the calibration of the model remained the same as Scenario 1.

The fourth scenario represents conditions associated with the maximum allowable loads to the stream during average annual flow. The flow was the same as Scenario 2. The nonpoint source loads for most subwatersheds were similar to Scenario 2. The phosphorus loads from the Johnson Pond watershed and the Tony Tank Lake watershed were reduced to equal the average annual TMDLs for those two watersheds. The nitrogen and phosphorus loads from the Wicomico Creek watershed were reduced to equal its average annual TMDLs. A 3% margin of safety was included in the nonpoint source load calculation. The point source load reflects maximum approved water and sewer plan flows and nutrient and BOD concentrations consistent with operational upgrades necessary to meet water quality standards during low flow periods. All the environmental parameters and kinetic coefficients used for the calibration of the model remained the same as Scenario 2. The temperature was the same as in scenario 2. The nutrient fluxes and SOD were the same as in scenario 2.

Scenario Results

<u>Base-line Loading Condition Scenarios</u>:

1. *Flow:* Simulates critical low stream flow (7Q10 flow) conditions during summer season. Nonpoint source water quality parameters (e.g., nutrient concentrations) are based on 1998 observed data. Point source loads assume maximum approved water and sewer plan flow and appropriate parameter concentrations expected to occur at that flow (10.2 mgd for Salisbury and 1.0 mgd for Fruitland).

2. *Average Annual Flow:* Simulates average stream flow conditions, with average annual nonpoint source loads estimated on the basis of 1997 land use, and projected year-2000 nutrient loading rates from the EPA Chesapeake Bay Watershed Model. Point source loads assume maximum approved water and sewer plan flow and appropriate parameter concentrations expected to occur at that flow (10.2 mgd for Salisbury and 1.0 mgd for Fruitland).

The LWREM calculates the daily average dissolved oxygen concentrations in the stream. This is not necessarily protective of water quality when one considers the effects of diurnal dissolved oxygen variation due to photosynthesis and respiration of algae. The photosynthetic process centers about the chlorophyll containing algae, which utilize radiant energy from the sun to convert water and carbon dioxide into glucose, and release oxygen. Because the photosynthetic process is dependent on solar radiant energy, the production of oxygen proceeds only during daylight hours. Concurrently with this production, however, the algae require oxygen for respiration, which can be considered to proceed continuously. Minimum values of dissolved oxygen usually occur in the early morning predawn hours when the algae have been without light for the longest period of time. Maximum values of dissolved oxygen usually occur in the early afternoon. The diurnal range (maximum minus minimum) may be large and if the daily mean level of dissolved oxygen is low, minimum values of dissolved oxygen during a day may approach zero and hence create a potential for fish kill. The diurnal dissolved oxygen variation due to photosynthesis and respiration is calculated by the LWREM based on the amount of chlorophyll *a* in the water. For the rest of the model results, the minimum dissolved oxygen concentration is reported.

The first scenario represents the expected summer low flow conditions when water quality is impaired by high chlorophyll *a* levels, and low dissolved oxygen concentrations. The results for scenarios 1 and 2 can be seen in Figures A13 & A14. In scenario 1, the peak chlorophyll *a* level is above the threshold of 50 μg/l, but the dissolved oxygen level falls below the water quality standard of 5 mg/l. Scenario 2 does not show any standards violations.

<u>Future Condition TMDL Scenarios</u>:

3. *Low Flow:* Simulates the future condition of maximum allowable loads for critical low stream flow conditions during summer season to meet the water quality in the Lower Wicomico River.

4. *Average Annual Flow:* Simulates the future condition of maximum allowable loads under average stream flow and average annual loading conditions.

The results of the third scenario indicate that, under summer low flow conditions, the water quality target for dissolved oxygen and chlorophyll *a* is satisfied at all locations along the mainstem of the Lower Wicomico River. The result of scenario 3 is presented in Figures A15.

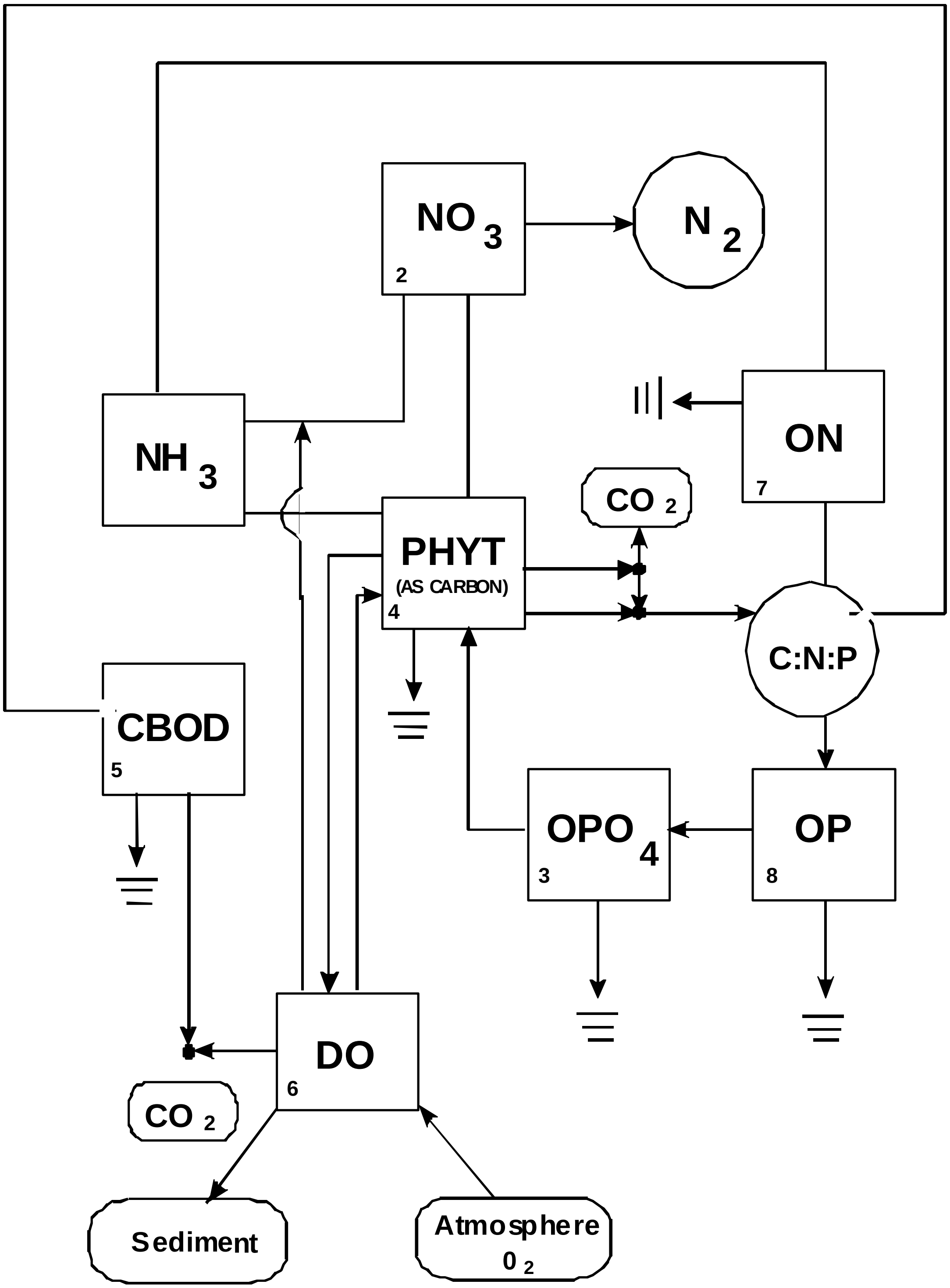

Figure A1: State Variables and Kinetic Interactions in EUTRO5

Table A1: Field and Laboratory Protocols

Parameter	Units	Detection Limits	Method Reference
IN SITU:			
Flow	cfs	0.01 cfs	Meter (Marsh-McBirney Model 2000 Flo-Mate)
Temperature	degrees Celsius	-5 deg. C to 50 deg. C	Linear thermistor network; Hydrolab Multiparameter Water Quality Monitoring Instruments Operating Manual (1995) Surveyor 3 or 4 (HMWQMIOM)
Dissolved Oxygen	mg/L	0 to 20 mg/l	Au/Ag polargraphic cell (Clark); HMWQMIOM
Conductivity	micro Siemens/cm (µS/cm)	0 to 100,000 µS/cm	Temperature-compensated, five electrode cell Surveyor 4; or six electrode Surveyor 3 (HMWQMIOM)
pH	pH units	0 to 14 units	Glass electrode and Ag/AgCl reference electrode pair; HMWQMIOM
Secchi Depth	meters	0.1 m	20.3 cm disk
GRAB SAMPLES:			
Ammonium	mg N / L	0.003	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Nitrate + Nitrite	mg N / L	0.0007	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Nitrite	mg N / L	0.0003	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Total Dissolved Nitrogen	mg N / L	0.03	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Particulate Nitrogen	mg N / L	0.0123	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Ortho-phosphate	mg P / L	0.0007	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Total Dissolved Phosphorus	mg P / L	0.0015	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Total Phosphorus	mg P / L		Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Particulate Phosphorus	mg P / L	0.0024	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Dissolved Organic Carbon	mg C / L	0.15	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Particulate Carbon	mg C / L	0.0759	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Silicate	mg Si / L	0.01	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Total Suspended Solids	mg / L	2.4	Chesapeake Biological Laboratory. Standard Operating Procedures. TR No. 158-97
Chlorophyll *a*	µg/L	1 mg/cu.M	Standard methods for the Examination of Water and Wastewater (15th ed.) #1002G. Chlorophyll. Pp 950-954
BOD_5	mg/l	0.01 mg/l	Oxidation ** EPA No. 405

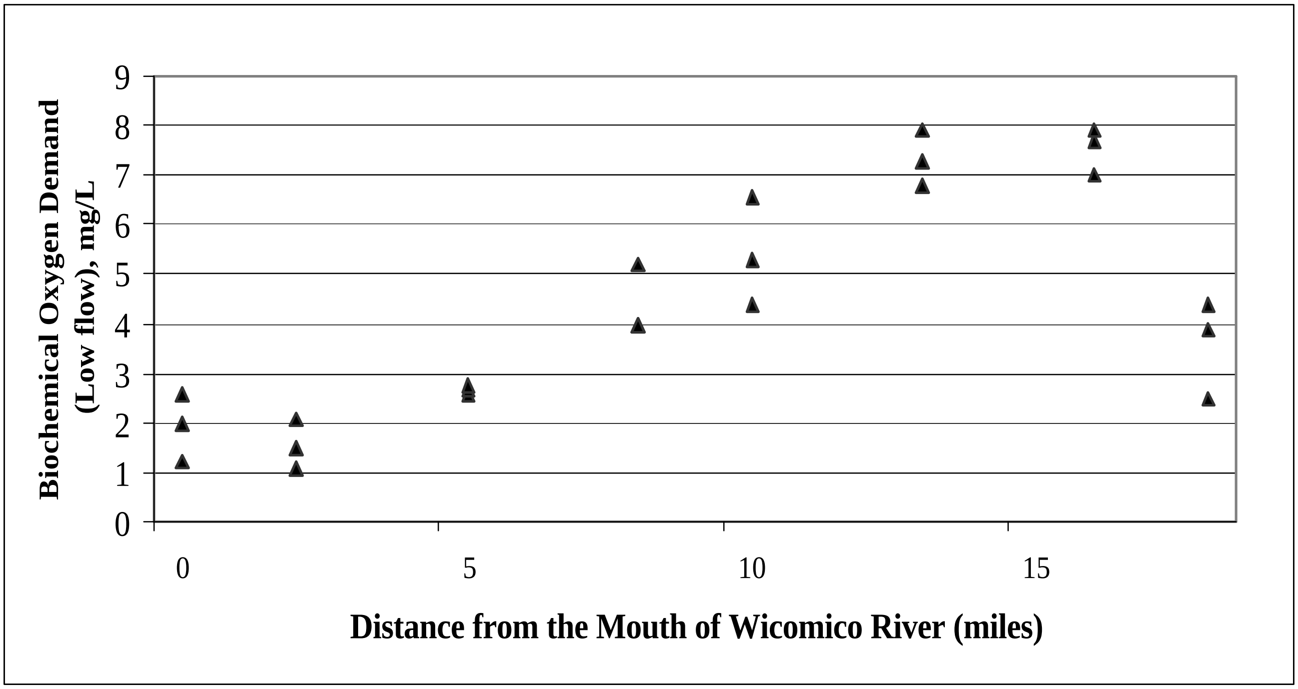

Figure A2: Longitudinal Profile of BOD Data

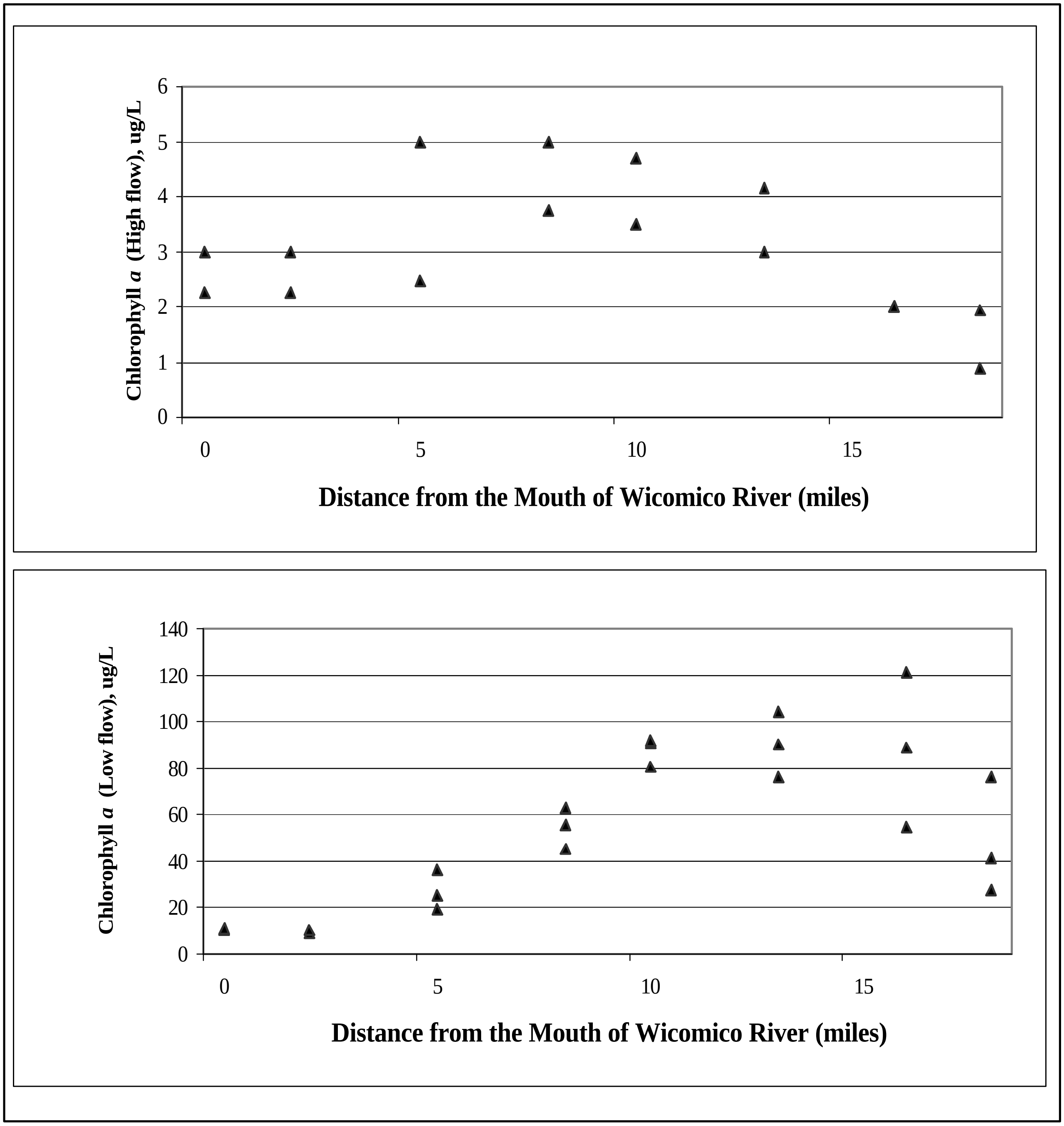

Figure A3: Longitudinal profile of Chlorophyll *a* data

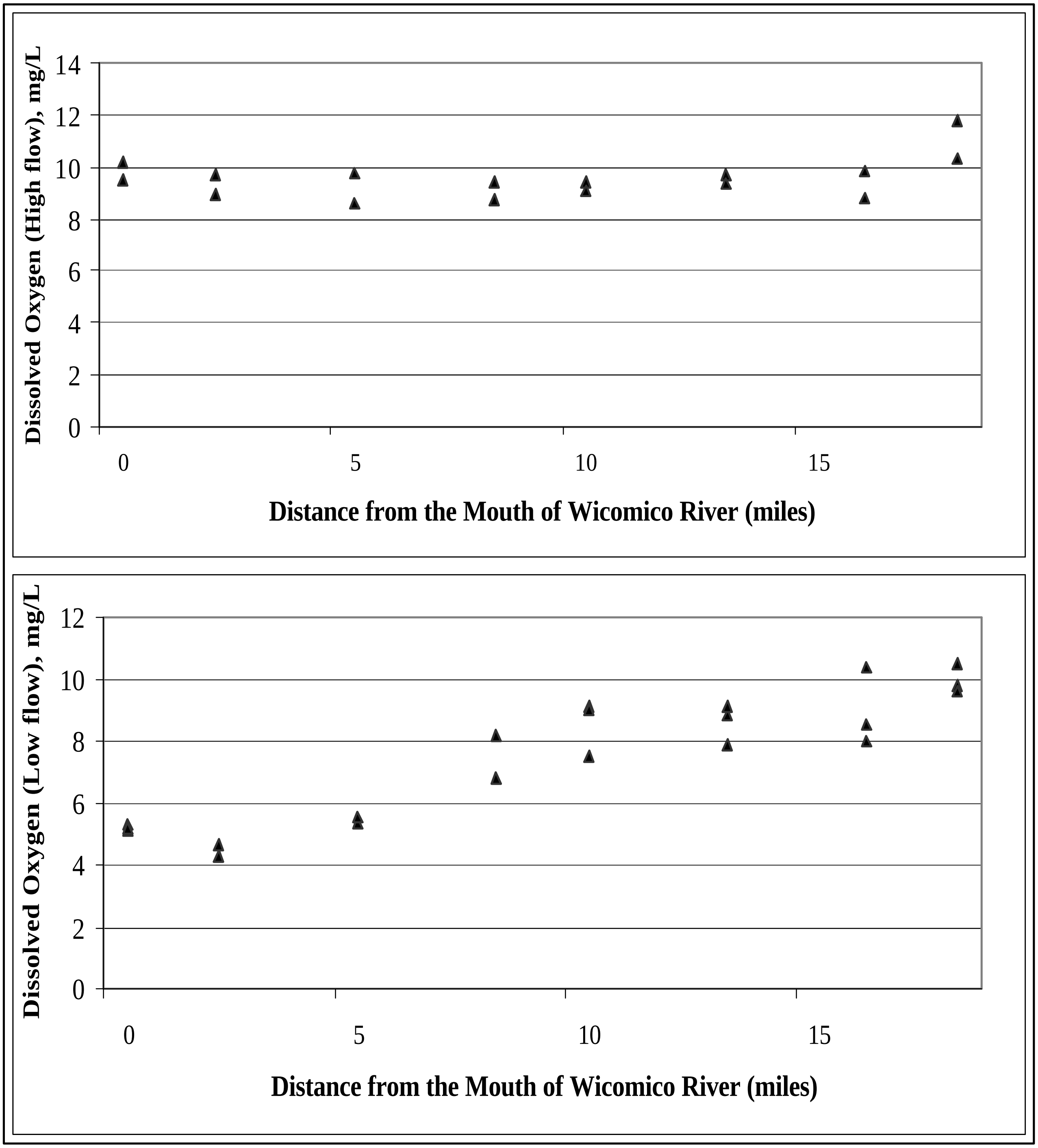

Figure A4: Longitudinal Profile of Dissolved Oxygen Data

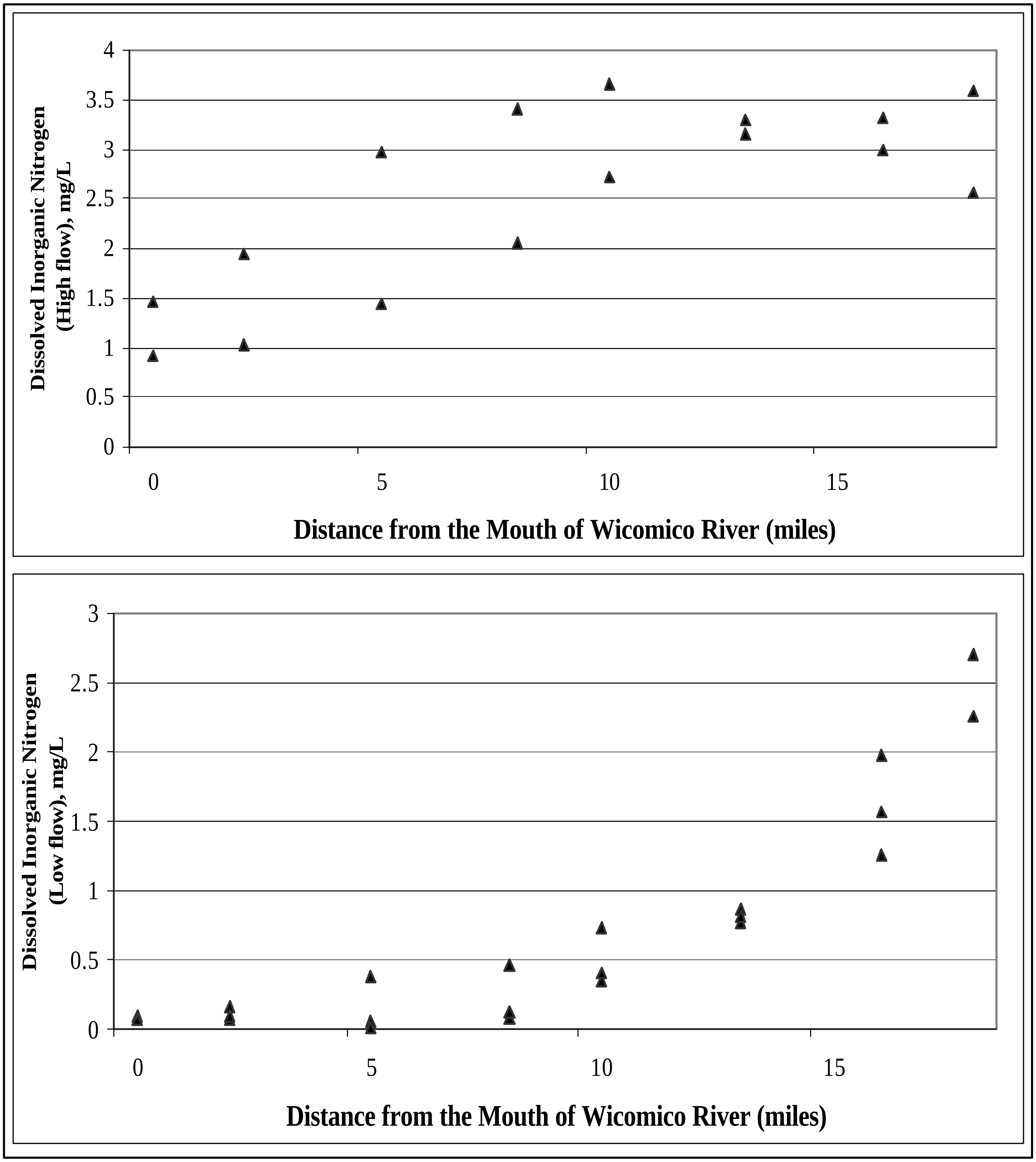

Figure A5: Longitudinal Profile of Inorganic Nitrogen Data

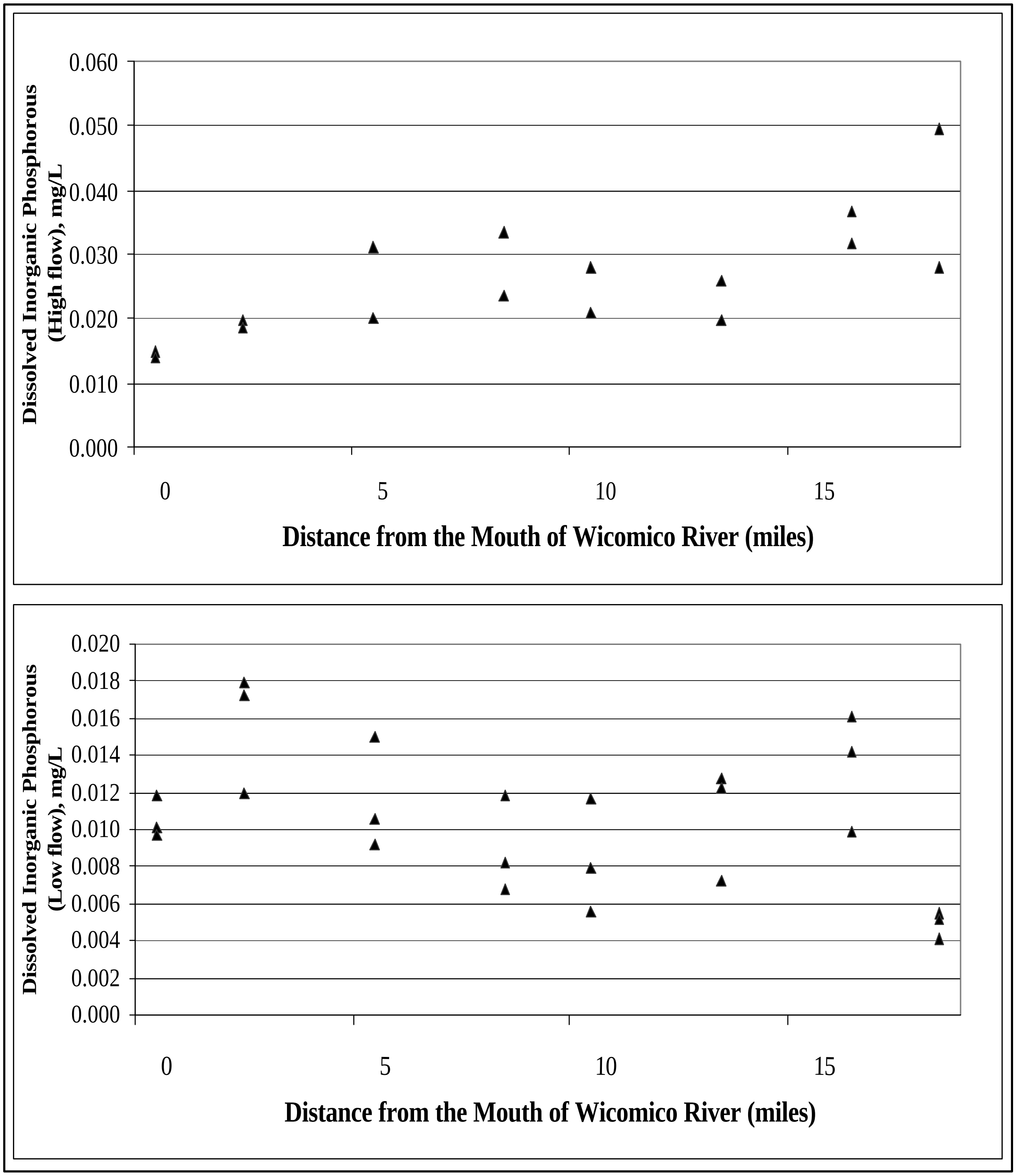

Figure A6: Longitudinal Profile of Inorganic Phosphorus Data

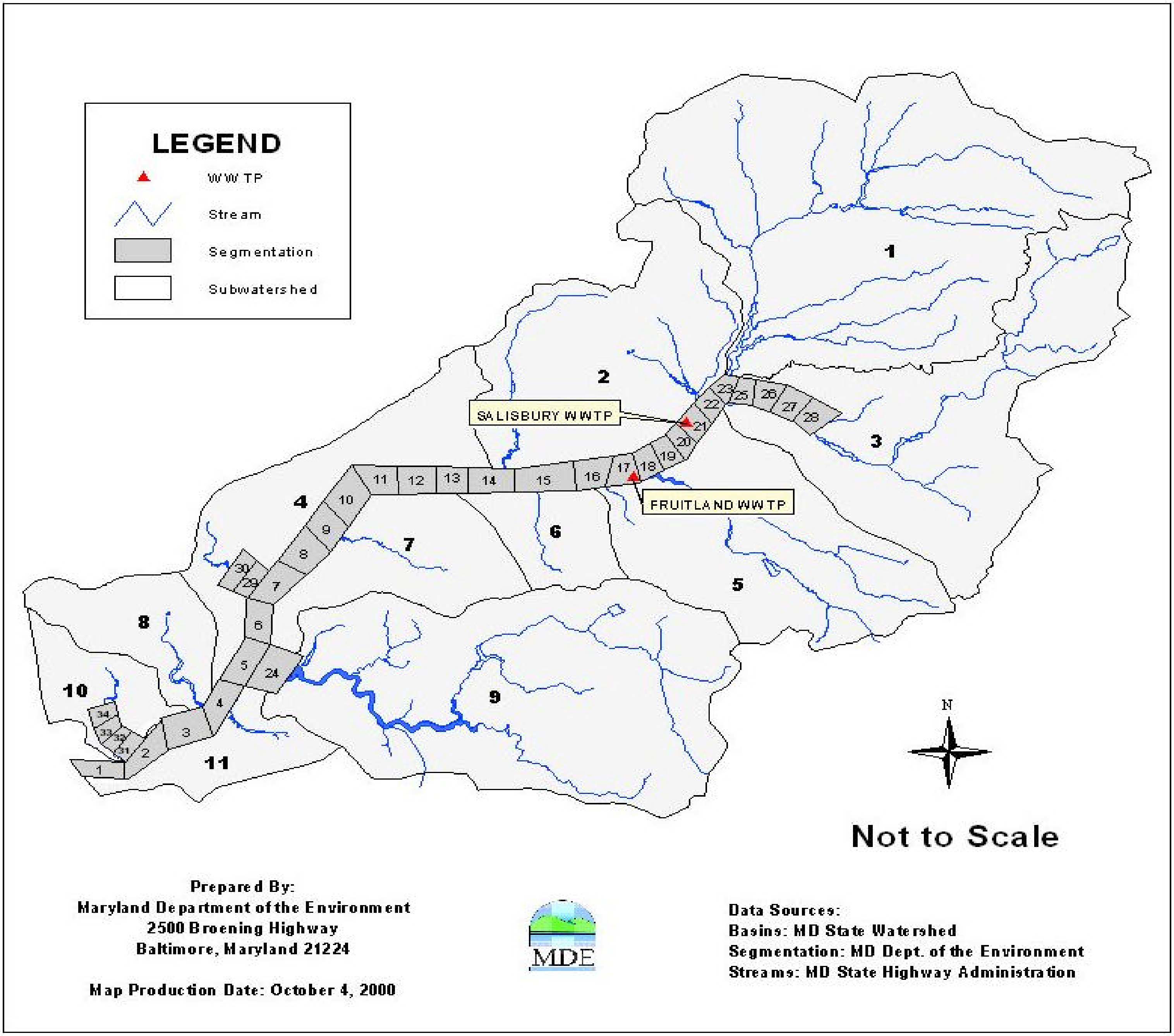

Figure A7: Model Segmentation, including Subwatersheds

Table A2: Volumes, Characteristic Lengths, Interfacial Areas used in the LWREM

Segment No.	Volume (m^3)	Interfacial Area (m^2)	Characteristic Length (m)
1	3,974,190	3179	1678
2	2,209,789	1557	1732
3	1,717,116	994	1632
4	1,658,589	1110	1528
5	1,568,333	1061	1513
6	1,457,123	1012	1565
7	1,441,877	850	1922
8	1,408,760	651	1290
9	1,367,656	1534	1070
10	1,327,633	1023	1660
11	891,781	577	1518
12	826,881	598	1307
13	781,114	667	1121
14	698,632	726	1554
15	595,047	173	2440
16	591,437	315	1560
17	589,651	443	900
18	496,417	867	600
19	443,618	788	600
20	409,075	691	670
21	385,877	530	758
22	359,187	488	764
23	190,809	452	837
24	2,249,800	2307	1554
25	848	0.947	937
26	777	0.897	902
27	710	0.848	879
28	600	0.801	844
29	20,114	21.56	1032
30	18,308	20.54	883
31	20,240	21.56	950
32	19,750	21.05	950
33	19,260	20.53	950
34	18,771	20.02	950

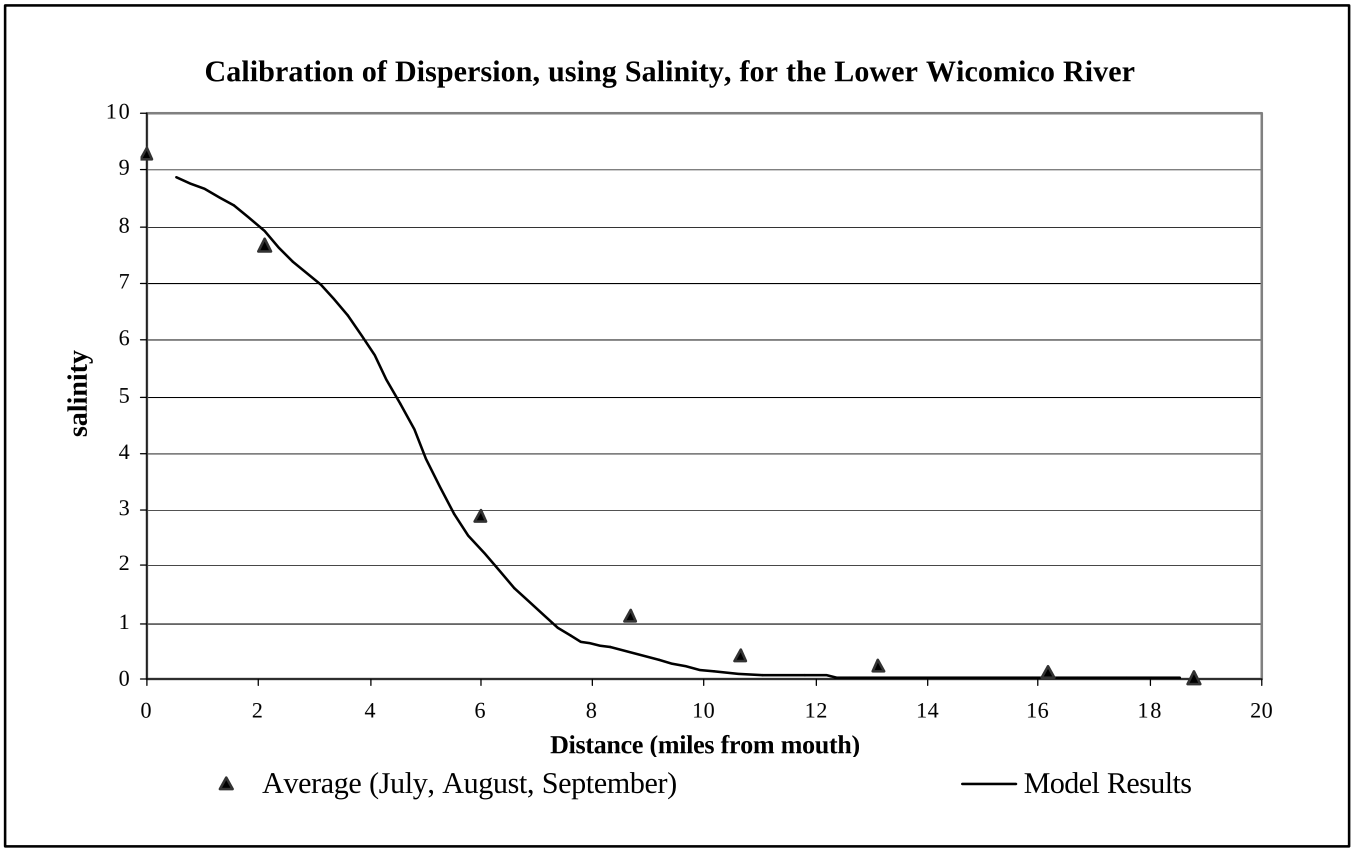

Figure A8: Results of the Calibration of Dispersion Coefficients for Low Flow

Table A3: Dispersion Coefficients used in the LWREM

Exchange Pair	Dispersion Coefficient (m^2/sec)
0-1	24
1-2	18
2-3	12
3-4	9
4-5	4
5-6	2
6-7	2
7-8	1.8
8-9	1.5
9-10	1.5
10-11	1.2
11-12	1.2
12-13	1.2
13-14	1.2
14-15	1.2
15-16	1.2
16-17	1.2
17-18	1.2
18-19	1.2
19-20	1.2
20-21	1.2
21-22	1
22-23	0
23-0	0
5-24	4
24-0	0
22-25	1
25-26	1
26-27	1
27-28	1
28-0	0
7-29	2
29-30	2
30-0	1
2-31	18
31-32	16
32-33	14
33-34	12
34-0	10

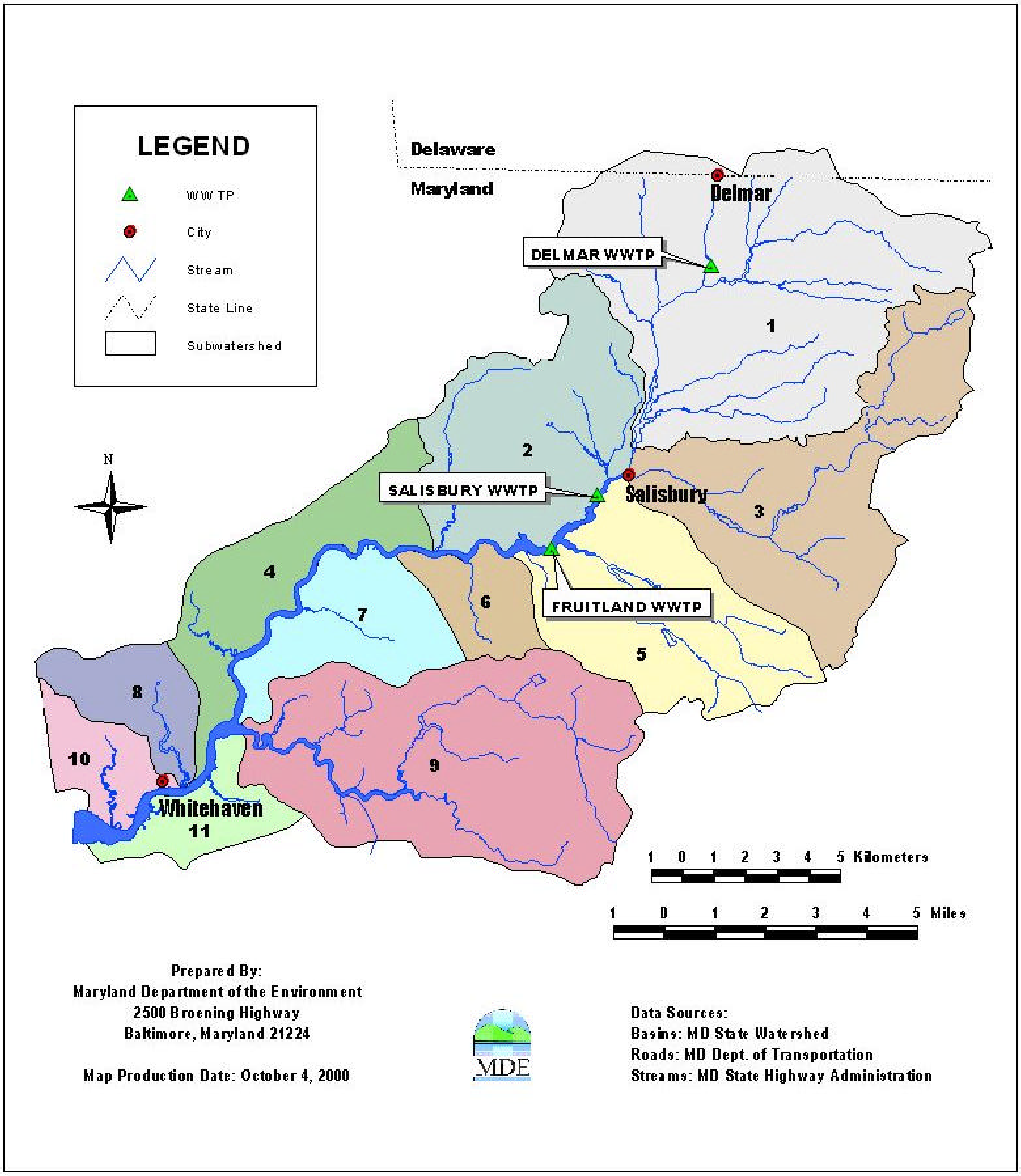

Figure A9: The Eleven Subwatersheds of the Lower Wicomico River Drainage Basin

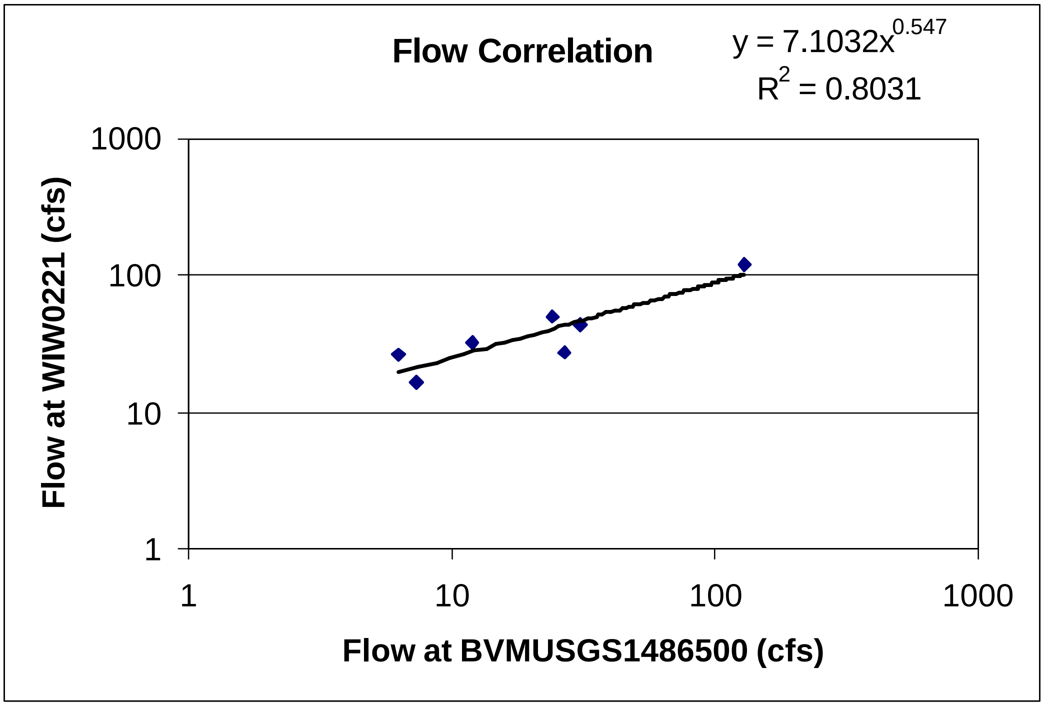

Figure A10: Low Flow Correlation between USGS1486500 and WIW0221

Table A4: Subwatersheds Flows for Low, High, and Average Conditions

Subwatershed No	Flow Symbols	Low Flow (m^3/s)	7Q10 Flow (m^3/s)	High Flow (m^3/s)	Average Flow (m^3/s)
1	Q1	0.566	0.283	5.680	4.462
2	Q2	0.000	0.000	2.705	2.125
3	Q3	0.086	0.068	3.445	2.706
4	Q4	0.044	0.035	1.761	1.383
5	Q5	0.066	0.052	2.636	2.071
6	Q6	0.000	0.000	0.691	0.543
7	Q7	0.000	0.000	1.349	1.060
8	Q8	0.000	0.000	0.854	0.671
9	Q9	0.116	0.090	4.605	3.617
10	Q10	0.017	0.013	0.664	0.521
11	Q11	0.000	0.000	0.735	0.577

Table A5: Point Source Loadings for the Calibration of the Model

Parameter*		Salisbury WWTP	Fruitland WWTP
Flow	**High Flow**	0.235	0.033
	Low Flow	0.230	0.0176
NH_4	**High Flow**	339	38.2
	Low Flow	303	20.5
NO_{23}	**High Flow**	183	4.33
	Low Flow	142	2.33
PO_4	**High Flow**	17.1	7.13
	Low Flow	21.9	3.83
Chla	**High Flow**	0	0
	Low Flow	0	0
CBOD	**High Flow**	1031	179
	Low Flow	597	85.7
DO	**High Flow**	162	21.6
	Low Flow	139	8.91
ON	**High Flow**	148	8.37
	Low Flow	46.8	4.50
OP	**High Flow**	15.4	1.36
	Low Flow	6.6	0.73

*** All loadings in kg/day. Flow in m^3/sec**

Table A6: Environmental Parameters for the Calibration of the Model

Segment	Ke (m^{-1})		T (°C)		Salinity (gm/L)		SOD (g O_2/m^2 day)		FNH_4 (mg NH_4-N/m^2 day)		FPO_4 (mg PO_4-P/m^2 day)	
Number	High flow	Low flow	High flow	Low flow	High flow	Low flow	High flow	Low flow	High flow	Low flow	High flow	Low flow
1	6.5	3.0	8.5	27.0	3.7	9.1	1.0	2.0	0	120	0	4.2
2	6.5	3.0	8.5	27.0	2.6	8.2	1.0	2.5	0	120	0	4.2
3	6.5	3.0	8.5	27.0	1.7	7.4	1.0	3.0	0	120	0	4.2
4	6.5	3.0	8.5	27.0	1.2	6.3	1.0	3.0	0	120	0	4.2
5	6.5	3.0	8.5	27.0	0.7	5.2	1.0	3.0	0	120	0	4.2
6	6.5	3.0	8.5	27.0	0.3	4.0	1.0	3.0	0	120	0	4.2
7	6.5	3.0	8.5	27.0	0	2.92	1.0	3.0	0	120	0	4.2
8	4.4	3.0	8.5	27.0	0	2.35	1.0	3.0	0	120	0	4.2
9	4.4	3.0	8.5	27.0	0	1.80	1.0	2.5	0	180	0	12.6
10	4.4	4.4	8.5	27.0	0	1.23	1.0	2.5	0	180	0	12.6
11	4.4	4.4	8.5	27.0	0	1.00	1.0	2.0	0	180	0	12.6
12	4.4	4.4	8.5	27.0	0	0.80	1.0	2.0	0	180	0	12.6
13	4.4	4.4	8.5	27.0	0	0.63	1.0	1.0	0	180	0	12.6
14	4.4	4.4	8.5	27.0	0	0.50	1.0	1.0	0	180	0	12.6
15	4.4	4.4	8.5	27.0	0	0.37	1.0	1.0	0	180	0	12.6
16	4.4	4.4	8.5	27.0	0	0.32	1.0	1.0	0	180	0	12.6
17	4.4	4.4	9.5	27.0	0	0.26	1.0	1.0	0	9	0	1.05
18	3.3	4.4	9.5	27.0	0	0.20	1.0	1.0	0	9	0	1.05
19	3.3	4.4	9.5	27.0	0	0.17	1.0	1.0	0	9	0	1.05
20	3.3	4.4	9.5	26.0	0	0.14	1.0	1.0	0	9	0	1.05
21	3.3	4.4	9.5	26.0	0	0.11	1.0	1.0	0	9	0	1.05
22	4.4	4.4	9.5	26.0	0	0.08	1.0	0.5	0	9	0	1.05
23	4.4	6.5	9.5	25.5	0	0.05	1.0	0.5	0	9	0	1.05
24	7.5	3	8.5	27.0	0.7	5.10	1.0	0.5	0	9	0	1.05
25	12	11	9.5	26.0	0	0.06	1.0	0.5	0	9	0	1.05
26	12	11	9.5	26.0	0	0.04	1.0	0.5	0	9	0	1.05
27	12	11	9.5	27.0	0	0.02	1.0	0.5	0	9	0	1.05
28	12	11	9.5	27.0	0	0.00	1.0	0.5	0	9	0	1.05
29	6.5	8.5	8.5	26.0	0	3.00	1.0	0.5	0	9	0	1.05
30	6.5	8.5	7.5	25.5	0	3.10	1.0	0.5	0	9	0	1.05
31	6.5	8.5	8.5	27.0	2.3	8.10	1.0	0.5	0	9	0	1.05
32	7.5	8.5	8.5	26.0	2.0	8.00	1.0	0.5	0	9	0	1.05
33	7.5	8.5	8.5	26.0	1.6	7.90	1.0	0.5	0	9	0	1.05
34	7.5	8.5	8.5	25.5	1.2	7.70	1.0	0.5	0	9	0	1.05

Table A7: EUTRO5 Kinetic Coefficients

Constant	Code	Value
Nitrification rate	K12C	0.08 *day*-1 at 20^{o} C
temperature coefficient	K12T	1.08
Denitrification rate	K20C	0.08 *day*-1 at 20^{o} C
temperature coefficient	K20T	1.08
Saturated growth rate of phytoplankton	K1C	2.0 *day*-1 at 20^{o} C
temperature coefficient	K1T	1.08
Endogenous respiration rate	K1RC	0.06 *day*-1 at 20^{o} C
temperature coefficient	K1RT	1.045
Nonpredatory phytoplankton death rate	K1D	0.05 *day*-1
Phytophankton Stoichometry		
Oxygen-to-carbon ratio	OCRB	2.67 $mg\ O_2 / mg\ C$
Carbon-to-chlorophyll ratio	CCHL	45
Nitrogen-to-carbon ratio	NCRB	0.25 *mg N/mg C*
Phosphorus-to-carbon ratio	PCRB	0.025 $mg\ PO_4\text{-}P/ mg\ C$
Half-saturation constants for phytoplankton growth		
Nitrogen	KMNG1	0.015 *mg* N / L
Phosphorus	KMPG1	0.001 *mg* P / P
Fraction of dead phytoplankton recycled to organic		
nitrogen	FON	0.5
phosphorus	FOP	0.5
Light Formulation Switch	LGHTS	1 = Smith
Saturation light intensity for phytoplankton	IS1	300. *Ly/day*
BOD deoxygenation rate	KDC	0.20 *day*-1 at 20^{o} C
temperature coefficient	KDT	1.05
Reaeration rate constant	k2	0.20 *day*-1 at 20^{o} C
Mineralization rate of dissolved organic nitrogen	K71C	0.02 *day*-1
temperature coefficient	K71T	1.08
Mineralization rate of dissolved organic phosphorus	K58C	0.15 *day*-1
temperature coefficient	K58T	1.08
Phytoplankton settling velocity		0.207 *m/day*
Inorganics settling velocity		0.156 *m/day*

Table A8: Contributing Watersheds to each Model Segment, and flows for the segments

Flows to Segment	Sub-watershed	Low Flow (m^3/s)	7Q10 Flow (m^3/s)	High Flow (m^3/s)	Average Flow (m^3/s)
3	8	0	0	0.854	0.671
4	11	0	0	0.735	0.577
9	7	0	0	1.350	1.060
10	4	0	0	0.352	0.277
12	4	0	0	0.352	0.277
14	2	0.029	0.022	1.140	0.893
15	6	0	0	0.691	0.543
18	5	0.066	0.052	2.640	2.070
19	2	0	0	0.487	0.383
22	2	0.027	0.021	1.080	0.850
23	1	0.566	0.283	5.680	4.460
24	9	0.072	0.091	4.600	3.620
28	3	0.067	0.053	2.690	2.110
30	4	0.027	0.021	1.060	0.830
34	10	0.017	0.013	0.664	0.521

Table A9: Nonpoint Source Concentrations for the Low Flow Calibration of the Model

Segment No.	NH4 *mg/l*	NO23 *mg/l*	PO4 *mg/l*	CHAA *ug/l*	CBODu *mg/l*	DO_fld *mg/l*	ON *mg/l*	OP *mg/l*
1	0.04167	0.0315	0.0267	10.6	3.22	5.21	0.932	0.0287
14	0.02700	2.5400	0.0191	17.6	5.58	7.73	0.688	0.0291
18	0.02317	0.0998	0.0200	21.7	4.50	8.97	0.881	0.0294
22	0.02700	2.5400	0.0191	17.6	5.58	7.73	0.688	0.0291
23	0.04650	2.3583	0.0200	48.2	3.93	9.97	1.143	0.0309
24	0.03267	0.0467	0.0329	22.7	4.93	4.91	1.237	0.0395
28	0.04867	0.4733	0.0214	11.1	5.98	8.23	0.759	0.0355
30	0.01633	0.0091	0.0628	76.5	5.72	5.10	1.824	0.0784
34	0.02233	0.0088	0.0670	9.3	4.78	2.70	1.103	0.0309

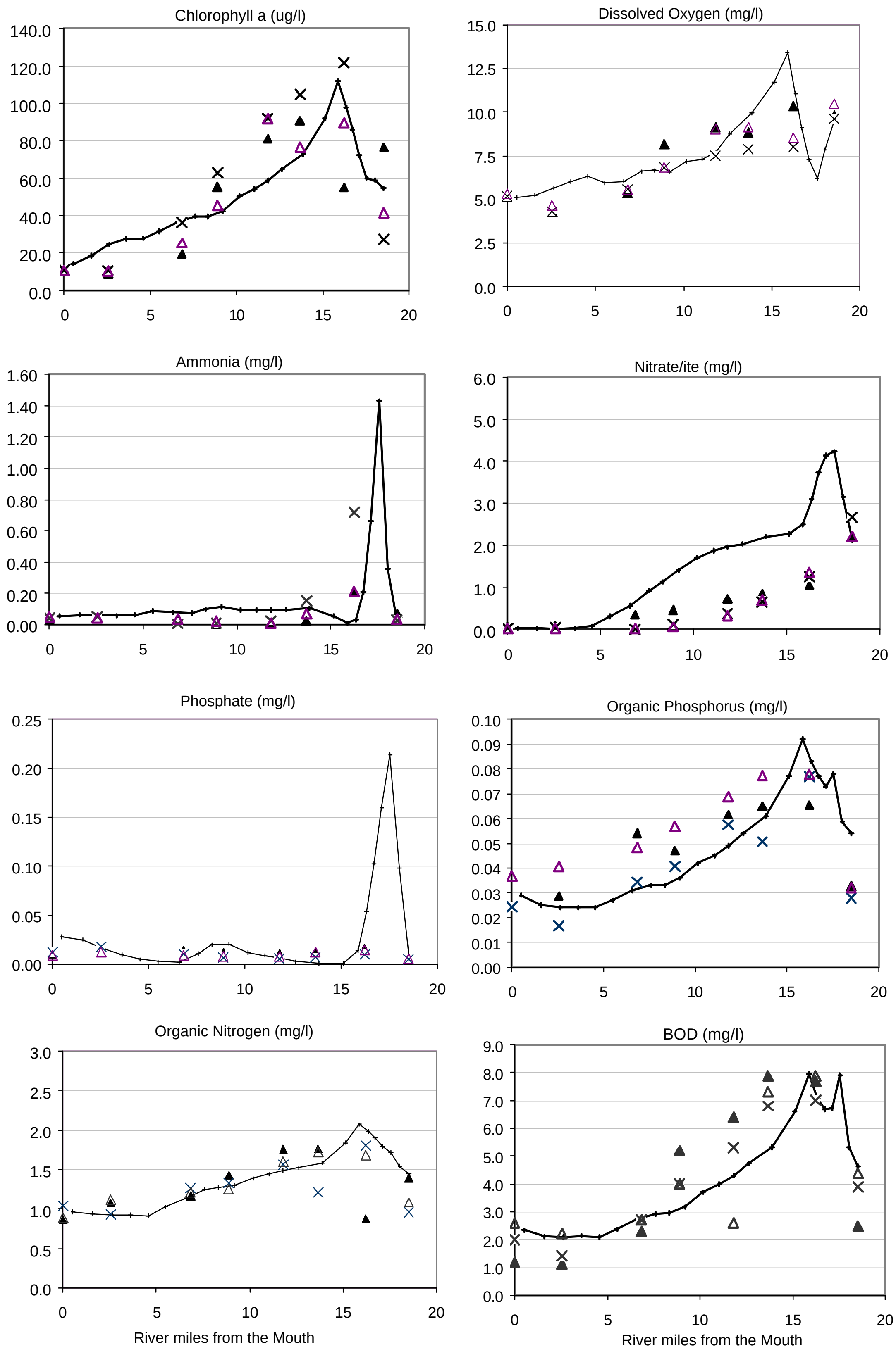

Figure A11: Low Flow Calibration of the Lower Wicomico River Model

Table A10: Nonpoint Source Concentrations for the High Flow Calibration of the Model

Segment No.	NH4 *mg/l*	NO23 *mg/l*	PO4 *mg/l*	CHAA *ug/l*	CBODu *mg/l*	DO_fld *mg/l*	ON *mg/l*	OP *mg/l*
1	0.1120	1.073	0.0489	2.62	3.33	9.84	0.713	0.0455
3	0.0840	1.004	0.0890	3.35	3.33	9.55	1.030	0.0601
4	0.0840	1.004	0.0890	3.35	3.33	9.55	1.030	0.0601
9	0.0840	1.004	0.0890	3.35	3.33	9.55	1.030	0.0601
10	0.0840	1.004	0.0890	3.35	3.33	9.55	1.030	0.0601
12	0.0840	1.004	0.0890	3.35	3.33	9.55	1.030	0.0601
14	0.0840	1.004	0.0890	3.35	3.33	9.55	1.030	0.0601
15	0.0840	1.004	0.0890	3.35	3.33	9.55	1.030	0.0601
18	0.0550	1.930	0.0391	1.81	3.33	9.60	0.633	0.0319
19	0.0840	1.004	0.0890	3.35	3.33	9.55	1.030	0.0601
22	0.0840	1.004	0.0890	3.35	3.33	9.55	1.030	0.0601
23	0.0620	3.010	0.0481	1.42	3.33	11.1	0.448	0.0268
24	0.1255	1.305	0.0461	4.20	3.33	9.43	0.750	0.0469
28	0.0795	1.752	0.0913	1.90	3.33	9.60	0.688	0.0353
30	0.1320	1.009	0.0586	2.72	3.33	9.60	1.130	0.0613
34	0.0665	0.341	0.1250	1.93	3.33	9.75	1.206	0.0828

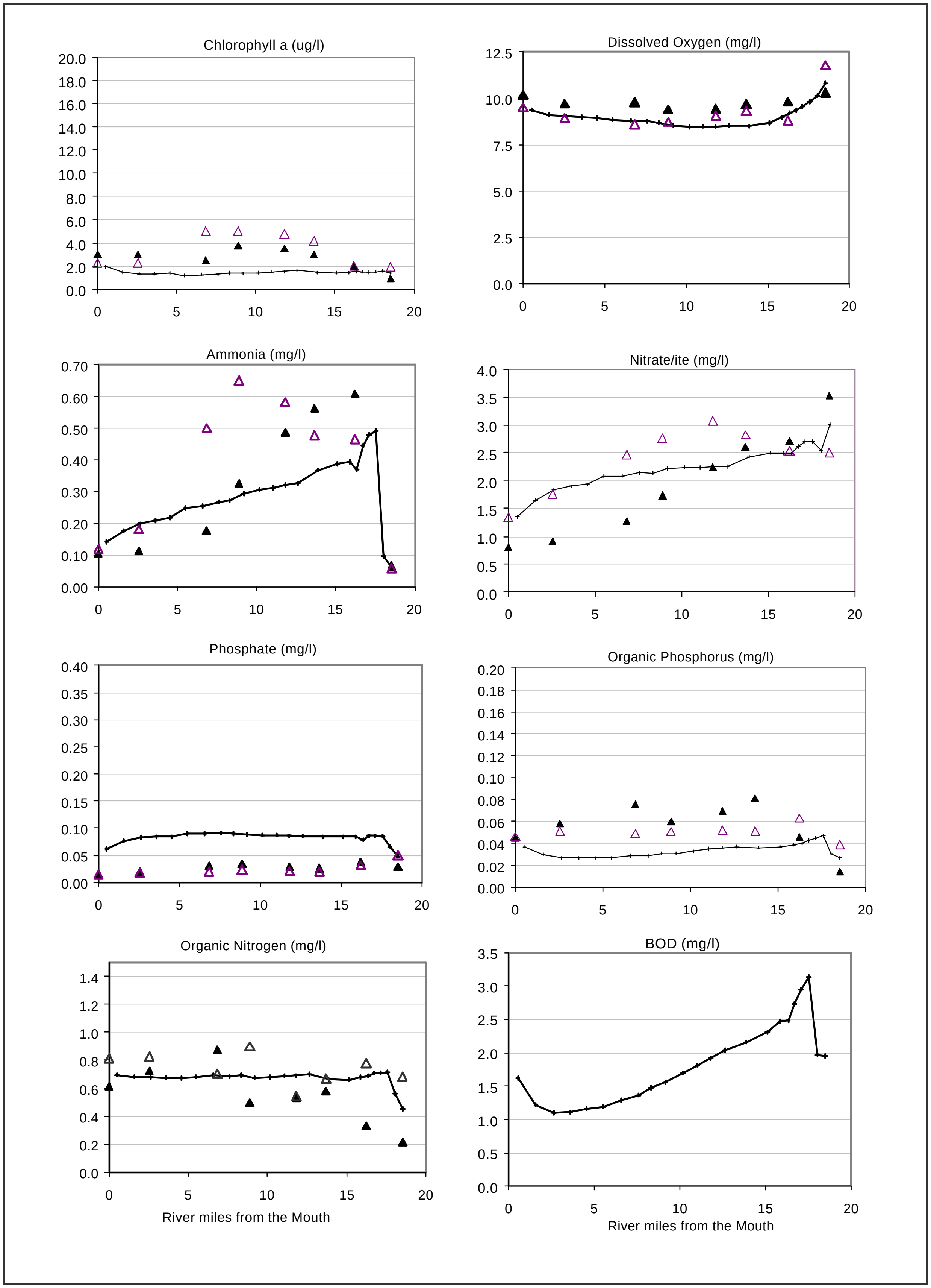

Figure A12: High Flow Calibration of the Lower Wicomico River Model

Table A11: Nonpoint Source Concentrations for the Base-line Low Flow Condition

Segment No.	NH4 *mg/l*	NO23 *mg/l*	PO4 *mg/l*	CHAA *ug/l*	CBODu *mg/l*	DO_fld *mg/l*	ON *mg/l*	OP *mg/l*
1	0.04167	0.0315	0.0267	10.6	3.22	5.21	0.932	0.0287
14	0.02700	2.5400	0.0191	17.6	5.58	7.73	0.688	0.0291
18	0.02317	0.0998	0.0200	21.7	4.50	8.97	0.881	0.0294
22	0.02700	2.5400	0.0191	17.6	5.58	7.73	0.688	0.0291
23	0.04650	2.3583	0.0200	48.2	3.93	9.97	1.143	0.0309
24	0.03267	0.0467	0.0329	22.7	4.93	4.91	1.237	0.0395
28	0.04867	0.4733	0.0214	11.1	5.98	8.23	0.759	0.0355
30	0.01633	0.0091	0.0628	76.5	5.72	5.10	1.824	0.0784
34	0.02233	0.0088	0.0670	9.3	4.78	2.70	1.103	0.0309

Table A12: Nonpoint Source Concentrations for the Base-line Average Flow Condition

Segment No.	NH4 *mg/l*	NO23 *mg/l*	PO4 *mg/l*	CHAA *ug/l*	CBODu *mg/l*	DO fld *mg/l*	ON *mg/l*	OP *mg/l*
1	0.0420	0.032	0.0267	6.90	3.28	7.53	0.932	0.0287
3	0.0180	0.192	0.0080	54.11	5.25	4.30	0.123	0.0094
4	0.0530	0.404	0.0150	54.11	5.25	4.30	0.188	0.0201
9	0.0410	0.361	0.0170	54.11	5.25	4.30	0.192	0.0205
10	0.0390	0.360	0.0138	54.11	5.25	4.30	0.170	0.0169
12	0.0390	0.360	0.0138	54.11	5.25	4.30	0.170	0.0169
14	0.0530	0.560	0.0260	54.11	5.25	4.30	0.255	0.0293
15	0.0400	0.396	0.0180	54.11	5.25	4.30	0.197	0.0210
18	0.0499	0.572	0.0182	27.64	3.29	9.50	0.208	0.0213
19	0.0530	0.560	0.0260	54.11	5.25	4.30	0.255	0.0293
22	0.0530	0.560	0.0260	54.11	5.25	4.30	0.255	0.0293
23	0.0385	0.430	0.0157	26.20	3.63	10.1	0.181	0.0177
24	0.0385	0.326	0.0163	13.40	4.13	6.92	0.197	0.0193
28	0.0418	0.474	0.0133	7.49	4.66	8.77	0.168	0.0151
30	0.0394	0.361	0.0139	42.28	4.53	6.80	0.170	0.0170
34	0.0492	0.327	0.0118	6.12	4.05	5.40	0.160	0.0173

Table A13: Point Source Loadings for the Base-line Low Flow and Average Flow Condition

Parameter*		Salisbury WWTP		Fruitland WWTP	
		m^3/sec	mgd	m^3/sec	mgd
Flow	Average Flow	0.447	10.2	0.0438	1
	Low Flow	0.447	10.2	0.0438	1
		kg/day	mg/l	kg/day	mg/l
NH_4	Average Flow	586.3	15.16	51.20	13.51
	Low Flow	586.3	15.16	51.20	13.51
NO_{23}	Average Flow	273.3	7.070	5.799	1.530
	Low Flow	273.3	7.070	5.799	1.530
PO_4	Average Flow	37.50	0.9714	3.677	2.520
	Low Flow	37.50	0.9714	3.677	2.520
Chla	Average Flow	0	0	0	0
	Low Flow	0	0	0	0
CBOD	Average Flow	1933	50.00	189.5	50.00
	Low Flow	1933	50.00	189.5	50.00
DO	Average Flow	193.3	5.000	18.95	5.000
	Low Flow	193.3	5.000	18.95	5.000
ON	Average Flow	91.49	2.367	11.22	2.367
	Low Flow	91.49	2.367	11.22	2.367
OP	Average Flow	39.71	1.029	3.893	1.029
	Low Flow	39.71	1.029	3.893	1.029

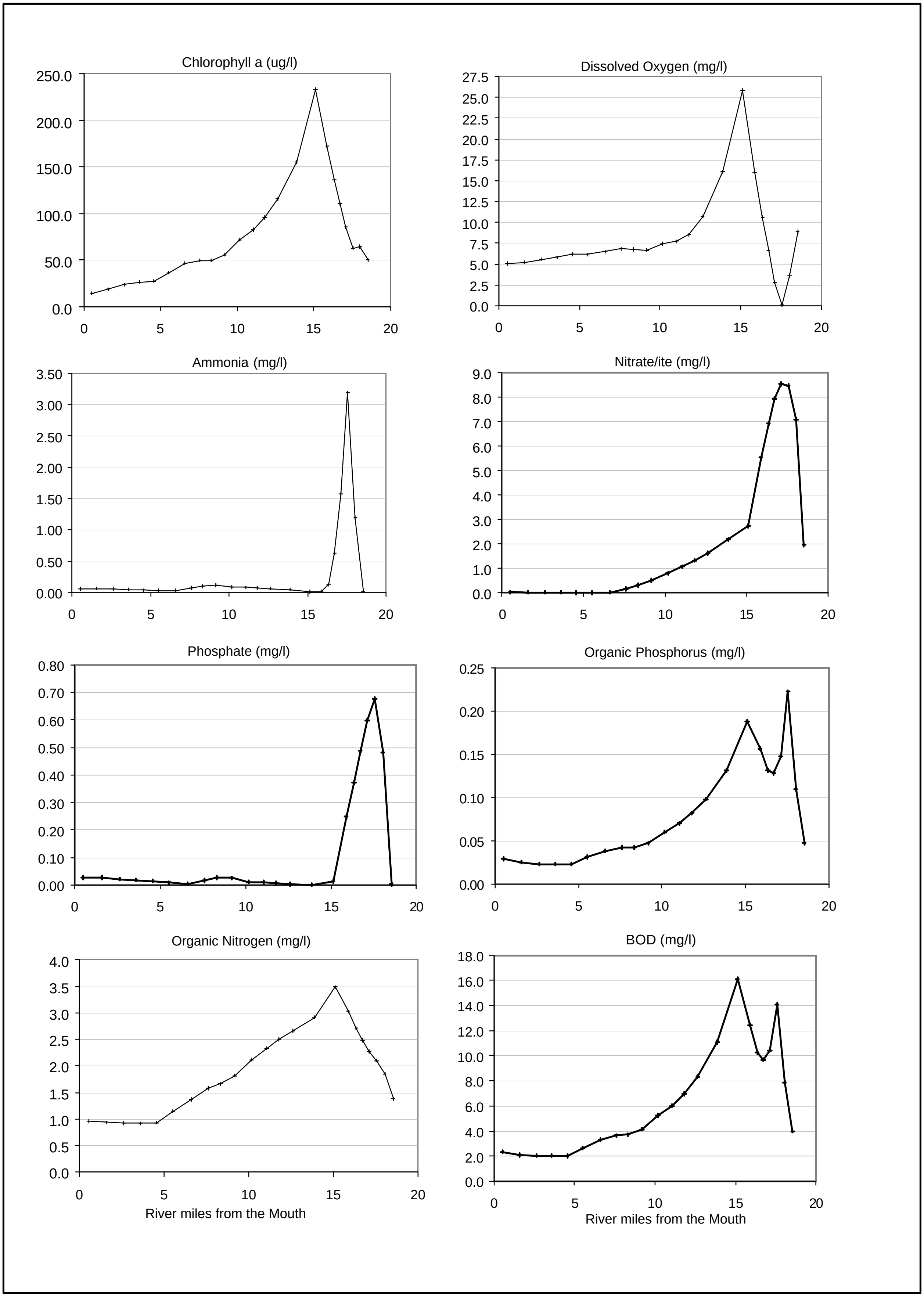

Figure A13: Baseline Low Flow Scenario of the Lower Wicomico River Model

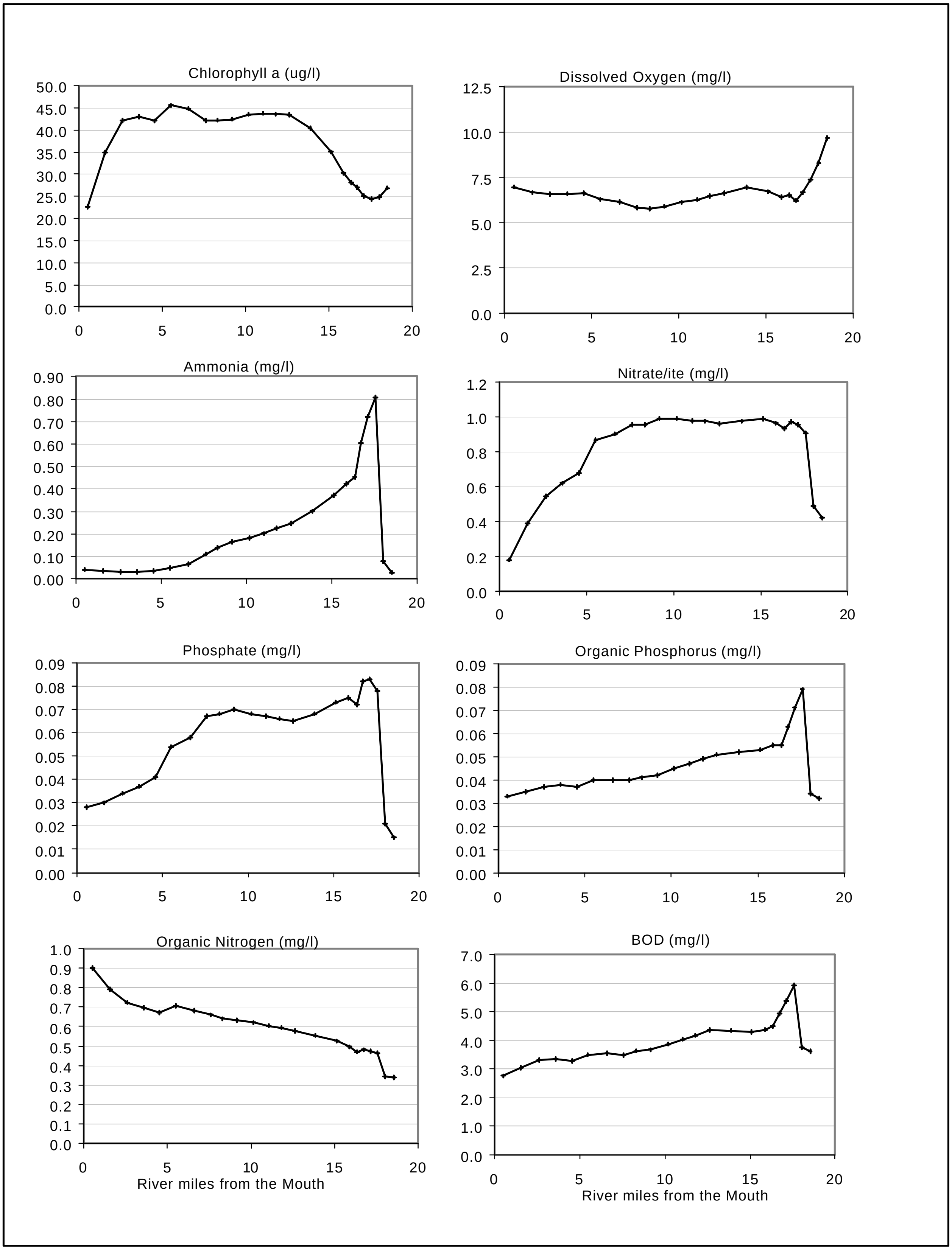

Figure A14: Baseline Average Flow Scenario of the Lower Wicomico River Model

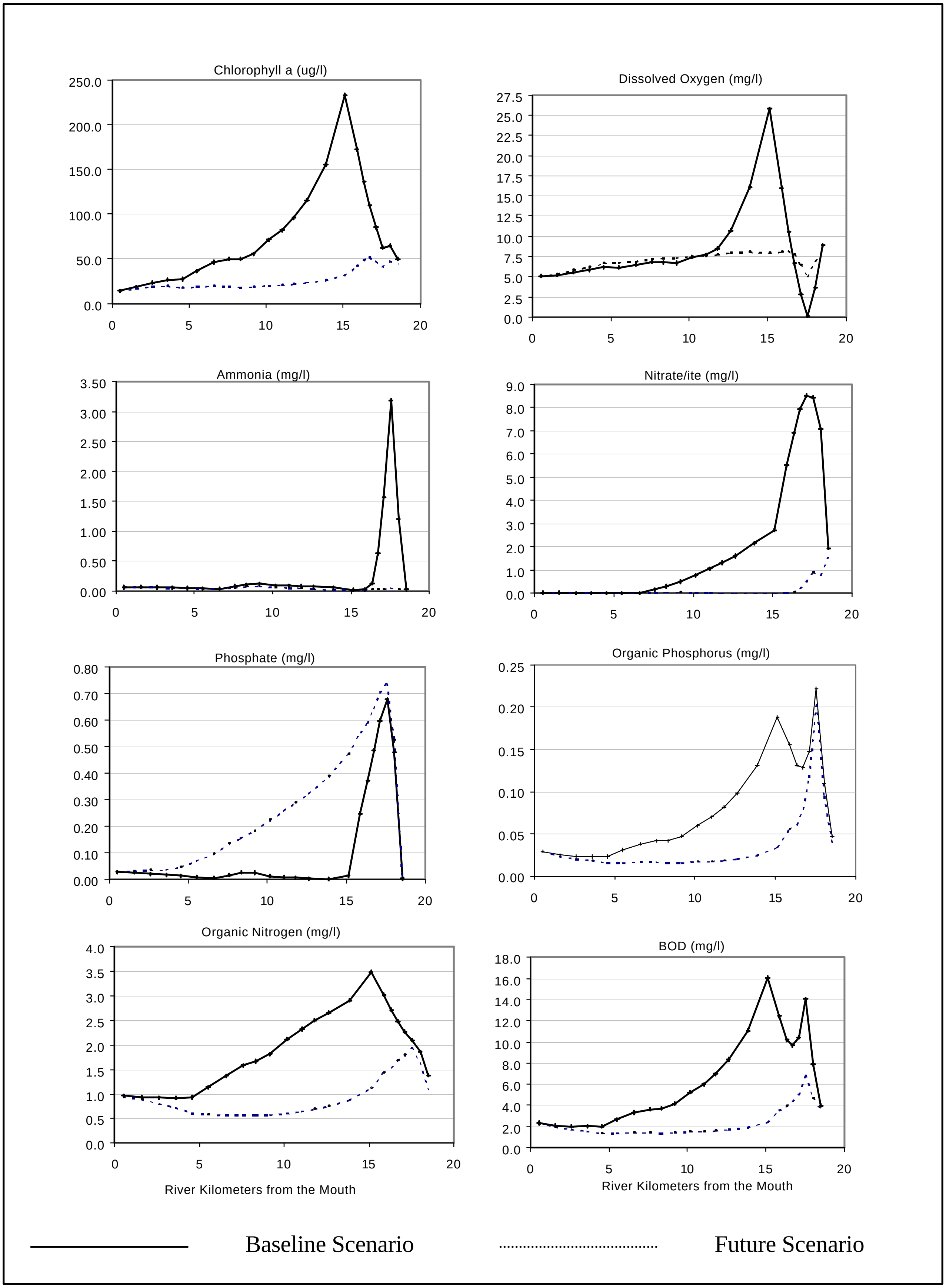

Figure A15: Future Condition Low Flow Scenario of the Lower Wicomico River

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