Appendix A

MODELING FRAMEWORK

The computational framework chosen for the modeling of water quality of the Transquaking River was 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 studying time-variable or steady-state, one, two or three dimensional, linear or non-linear kinetic water quality problems. To date, WASP5.1 has been employed in many modeling applications that have included river, lake, estuarine and ocean environments, and the model has been used to investigate dissolved oxygen, eutrophication, and toxic substance problems. WASP5.1 has been used in a wide range of applications by regulatory agencies, consulting firms, 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. EUTRO5.1 is used to develop the water quality model of the Transquaking River system.

WATER QUALITY MONITORING

The physical and chemical samples were collected by MDE's Field Operations Program staff on February 12, March 16, March 23, July 21, August 18, and September 15, 1998. The physical parameters like dissolved oxygen, salinity, conductivity, and water temperature were measured *in situ* at each water quality monitoring station. Grab samples were collected for chemical and nutrient 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 also described in Table A1. The February and March data were used to calibrate the high flow water quality model whereas July, August and September data were used to calibrate the low flow water quality model for the Transquaking River. Figures A2 – A6 present low flow and high flow water quality profiles along the river.

INPUT REQUIREMENTS [1]

Model Segmentation and Geometry

The spatial domain of the Transquaking River Eutrophication Model (TREM) extends from the confluence of the Transquaking River and the Fishing Bay for about 26.2 miles along the mainstem of the Transquaking River. Following a review of the bathymetry for Transquaking River, the model was divided into 28 segments. Figure A7 shows the model segmentation and the location of the point source. Table A2 lists the volumes, characteristic lengths and interfacial areas of the 28 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 regression equation for the low flow and MDE high flow data was used for the high flow. 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 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 and nonpoint source loadings were taken into consideration by dividing the drainage basin into 18 sub-watersheds (Figure A9). The sub-watersheds were delineated in a manner that is consistent with the finite segments developed for the TREM. The TREM 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 flow for each subwatershed was estimated based on an average value calculated from two sets of high flow measurements (February 12, 1998 & March 23, 1998) at station TRQ0224 and station CCM0160. The estimated high flow was found to be consistent with the average flows for the months

---

[1] The WASP 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 |

of February and March of 1998 for a nearby USGS gage #01488600 (At Adamsville in Marshyhope River Basin). A ratio of flow to drainage area was calculated from the two water quality stations, then multiplied by the area of each of the subwatershed to obtain the high flows. The low flows used in the model from different sub-watersheds of the Transquaking River Basin were based on a regression equation. The regression equation (which includes the abandoned USGS gauge, Station No. 01490000 in Salem just above Big Millpond) is based on 30 years of flow data encompassing USGS gages in the entire Delmarva Peninsula region. This regression equation gives flow for a particular month based on watershed area. Flows were calculated for the months of July, August, and September and were then averaged. The estimated flows from the USGS regression analysis closely correspond to one instantaneous flow measurement taken during the field surveys. The average flow was based on data from abandoned USGS gage on the Transquaking River, and was 18.6 cfs. Table A4 presents flows from different subwatersheds during high, low and average flows.

For high flow, each sub-watershed was assumed to contribute a flow to the Transquaking mainstem. Based on observations in the field, the following assumptions were made about low flow; there was 100% of the relative USGS regression flow coming from the mainstem, there was 50% of the relative USGS flow coming from the subwatersheds which have streams to carry the flow to the mainstem, and there was no flow from the other subwatersheds. These flows and loads were assumed to be direct inputs to the TREM.

Point and Nonpoint Source Loadings

There are two point sources located in the Transquaking River watershed: Dorchester Lumber and Darling International Inc. Dorchester Lumber does not contribute any nutrient loading to the watershed. Darling International, Inc. is the major point source in the basin. It is a rendering plant located at the upper reach of Transquaking River basin. This plant primarily processes chicken fats and other animal fats from other processing plants in the region. The plant discharges approximately 246,000 gallons of wastewater daily into the Transquaking River. The wastewater was found to be rich in nutrients. A recent survey conducted in July 8, 1999 showed that the plant discharges approximately 970 pounds nitrogen/day and 5 pounds phosphorus/day into the River. Table A5 presents the point source loadings used for the calibration of the model.

The nonpoint source loadings used for the calibration of the model for both high flow and low flow were calculated using data from three water quality stations within Transquaking River Basin. The nonpoint source loads reflect atmospheric deposition, loads coming from septic tanks, loads coming from urban development, agriculture, and forest land. Data from station XDI1306 was used as a boundary condition for segment 1; data from station CCM0160 was used as a boundary condition for segment 27, and data from station CCM0002 was used as a boundary condition for segment 28. Data from CCM0160 was used as a boundary condition for segment 27 because no other measurements were available, and this is the only free flowing station in the watershed, and was assumed to be a good representative of water quality. The boundary conditions for remaining boundaries were also based on data from station CCM0160 because of the unavailability of data and the same logic as for segment 27. BOD data was not available for high flow, and it was assumed to be 2.0 mg/l at all boundaries

For both point and 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 (NO23), 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 have been measured in the field.

Environmental Conditions

Eight environmental parameters were used for developing the model of the Transquaking 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) (Table A6).

Light extinction coefficients, K_e in the water column were derived from the 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 a settling rate velocity of 0.052 *m/day*, and phytoplankton settles through the water column at a rate of 0.233 *m/day*. In general, 50% of the nonliving organics were considered in the particulate form. Such assignments were borne out through model sensitivity analyses.

The SOD values in the lower reaches and the upper reaches (in the pond) of the River were higher due to the high concentrations of chlorophyll *a,* which were settling out and the high inputs of nutrients. A maximum value of 3.5 $mg\ O_2/m^2 day$ was used. This value is considered reasonable based on the condition of the stream and the literature (Thomann, 1987).

Kinetic Coefficients

The water column kinetic coefficients are universal constants used in the TREM 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 (Haire and Panday, 1985, 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 as close to the observed values as possible. However, since the model was run for a long period of time (150 days) it was found that initial conditions did not impact the final results.

CALIBRATION & SENSITIVITY ANALYSIS

The EUTRO5 model for low flow was calibrated with July, August and September 1998 data. Tables A8, A9 & A10 shows the nonpoint source flows and loads associated with the calibration input file. Figure A10 – A17 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. The model did an excellent job of capturing the peak chlorophyll *a,* and BOD concentrations and also the general trend (Figure A10, A12). The model attempted to capture the peak nitrate plus nitrite concentrations, but could not because of the sudden change in the concentrations (Figure A13). The model captured the ammonia and organic nitrogen concentrations very well (Figure A14, and A15). It was able to replicate the organic phosphorus and the ortho-phosphate trends although it did not capture the peak values (Figure A16, and A17), and low concentrations.

The EUTRO5 model for high flow was calibrated with February and March 1998 data. The results are presented in Figures A18 to A25. As can be seen the model did well in capturing almost all the state variables except for organic phosphorus, where the range of values is very small.

SYSTEM RESPONSE

The EUTRO5 model of Transquaking River was applied to several different point and nonpoint source loading conditions under various stream flow conditions to project the impacts of nutrients on eutrophication and low dissolved oxygen in the River. By modeling various stream flows, the model runs simulate seasonality.

Model Run Descriptions

The first scenario represents the expected conditions under current loads of the stream during low flow. The flow was taken from the regression analysis as mentioned above. The total nonpoint source loads were computed using 1998 base-flow field data. The nonpoint source loads reflect atmospheric deposition, loads from septic tanks, and other nonpoint source loads coming off the land. The point source loads reflect maximum design flows and concentrations (1999 plant monitoring data was used to supplement permit information) at all point sources. All the environmental parameters and kinetic coefficients used for the calibration of the model remained the same for scenario 1.

The second scenario represents the expected conditions of the stream during average flow. The flow was the average annual flow (18.6 cfs) based on data from the abandoned USGS gage in the Transquaking. The nonpoint source loads were determined using land use loading coefficients. The land use information was based on 1997 Maryland Office of Planning data, and was adjusted 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), which was a continuous simulation model. They account for both atmospheric deposition and loads from septic tanks. The loading rates predicted loads for the year 2000 assuming Best Management Practice (BMP) implementation at a level consistent with current progress. The point source loads were the same as for scenario 1. All the kinetic coefficients remained the same as for the calibration of the low flow model. All the environmental parameters remained the same except for the temperature. The temperature was changed to a summer average of 27.5 ^{o}C for all segments. The Chesapeake Bay Program loading rates only enable us to estimate nutrient loadings for the average flow condition. The missing values for loadings (BOD, CHL*a*, DO) were assumed to be the same as for the low flow condition. The nonpoint source loads for model scenarios 1 and 2 can be seen in Table A11 and A12.

In the next two scenarios, the model was used to predict the water quality response in the River with different sets of load reductions. 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. Several model loading scenarios were performed for both low flow and average flow to estimate the necessary reductions in controllable load.

The reduction in nutrients also affects the starting concentrations of chlorophyll *a* in the river. The amount of nitrogen and phosphorus available for algae growth was calculated after the reduction in nutrient loads, to help estimate the amount of chlorophyll *a* at the boundaries. The amount of chlorophyll *a* that could be grown was calculated twice, once assuming nitrogen was the limiting nutrient, and again assuming phosphorus was the limiting nutrient. The lower of two values was compared to the low flow boundary value for chlorophyll *a* , and lower of these two were then taken to be the boundary for average flow. All calculated values for the chlorophyll *a* boundaries were found to be higher than the low flow chlorophyll *a* boundaries and hence low flow chlorophyll *a* boundaries were used.

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 sediments, from particulate nutrient organics, living algae, and phaeophytin, in each segment. This was done by running the expected condition scenario once with correct settling of organics and chlorophyll *a*, then again with no settling. The difference between the two runs was what was assumed to settle to the sediments. 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 10.0, and the phosphorus to chlorophyll *a* ratio was 1.0. This analysis was then repeated for the reduced nutrient loading conditions. The percentage difference between the amount of nutrients that settled in the expected 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 amount 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 in the stream during low flow. The flow was the same as scenario one. The total nonpoint source loads were based on the 1998 base-flow field data. A margin of safety of 5% was included in the load calculation. The nitrogen and phosphorus loads were reduced to meet chlorophyll *a*, and dissolved oxygen standards in the water. The point source load reflects maximum design flow and reduced loads. Modeling input assumed the reduction would be implemented at major point sources under anticipated summer operating conditions. More information about point source loads can be found in the Technical Memorandum entitled “Significant Nutrient Point and Nonpoint Sources in the Tranasquaking River Watershed.” 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 improved conditions in the stream during average annual flow. The flow was the same as scenario 2. The total nonpoint source loads were based on the loadings calculated for scenario 2. The nitrogen and phosphorus loads were reduced to meet chlorophyll *a*, and dissolved oxygen standards in the water**.** Nonpoint nutrient loads were decreased by 35% and a 3% margin of safety was included in the load calculation. The point source loads were same as for scenario 3. All the environmental parameters (except nutrient fluxes and SOD) and kinetic coefficients used for the calibration of the model remained the same as scenario 2. The temperature was same as in the scenario 2.

Scenario Results

Expected Condition Under Current Loads Scenarios:

1. *Low Flow:* Assumes low stream flow conditions. Assumes the 1998 base-flow nonpoint source loads, and maximum point source design flow and load (1999 data).

2. *Average Annual Flow:* Assumes average stream flow conditions. Assumes the 2000 average annual nonpoint source loads, and maximum point source design flow and load (1999 data).

The TREM 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 TREM 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 A26-A41. In both scenarios, the peak chlorophyll *a* levels are above the desired goal of 50 µg/l. It can be seen that the dissolved oxygen level falls below the water quality standard of 5 mg/l in both the scenarios.

Future Condition Scenarios:

3. *Low Flow:* Assumes low stream flow conditions. Assumes the 1998 base-flow nonpoint source loads plus a 5% margin of safety. Assumes the point load from the plant at design discharge and reduced loading condition make up the balance of the total allowable load.

4. *Average Annual Flow:* Assumes average stream flow conditions. Assumes the year 2000 average annual nonpoint source loads reduced by 35% plus 3% margin of safety. Assumes the point load from the plant at design discharge and reduced loading condition make up the balance of the total allowable load.

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 Transquaking River. Similarly, for the average flow condition the water quality targets have been found to be satisfied. The results of scenario 3 and scenario 4 are presented in Figures A42-A57.

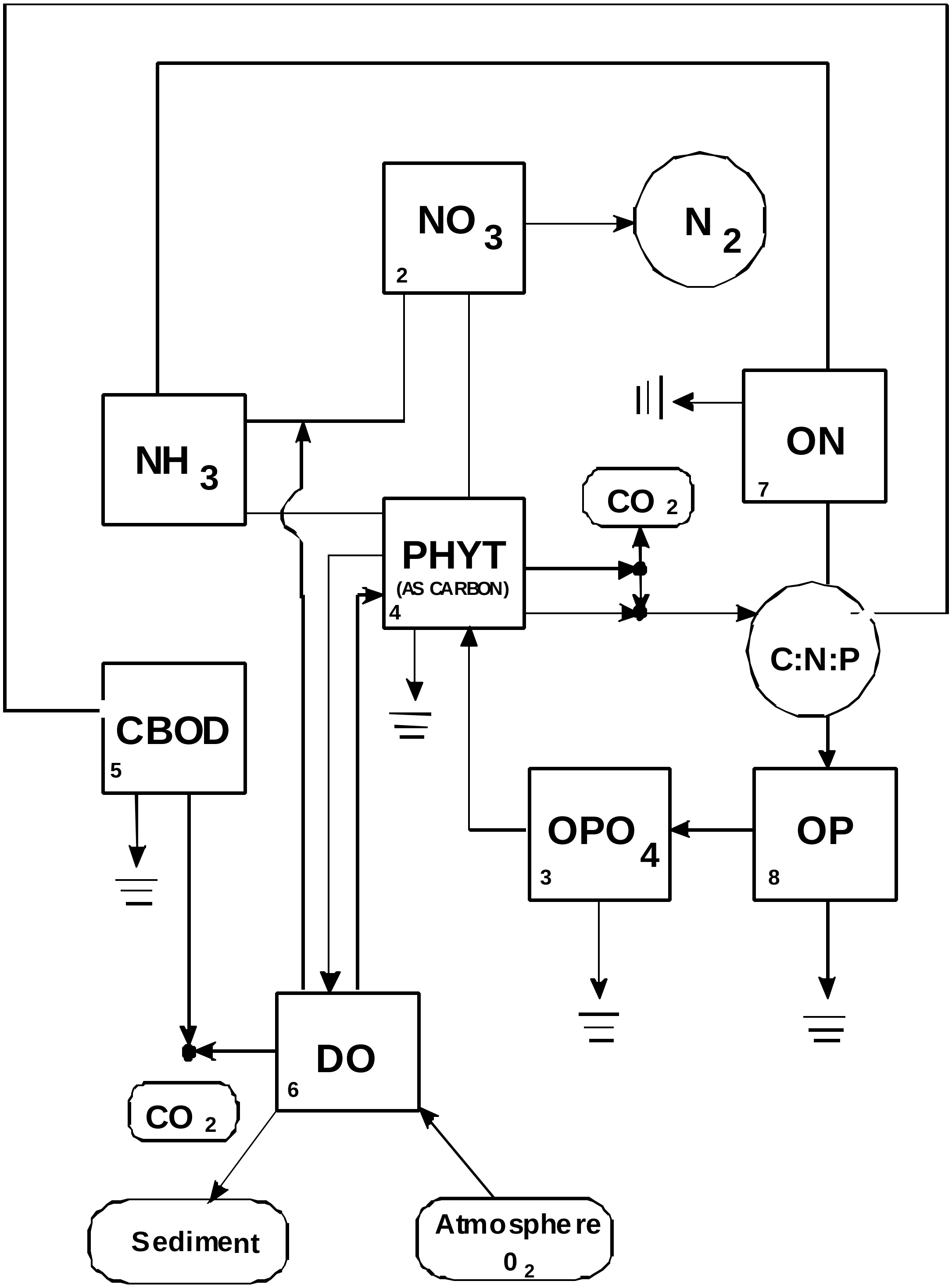

Figure A1: State Variables and Kinetic Interactions in EUTRO5

Table A1: Field and Laboratory Protocols

Parameter (units)	Dectection Limits	Method Reference
IN SITU:		
Flow	0.01 cfs	Meter (Marsh-McBirney or Pygmy Sampler)
Temperature	-5 deg. C	Linear thermistor network; Hydrolab System 8000 Water Quality Instrumentation Manual (1978) (HSWQIM)
Dissolved Oxygen (ppm)	0 ppm	Au/Ag polargraphic cell (Clark); HSWQIM
Conductivity (mmhos/cm)	0 mmhos/cm	Temperature-compensated, four electrode cell; HSWQIM
pH	1 pH	Glass electrode: Ag/AgCl reference electrode pair; HSWQIM
Secchi Depth	0.1 m	20.3 cm disk
GRAB SAMPLES:		
Total Alkalinity	0.01 mg/l	Filtration ** EPA No. 310
Total Organic Carbon (mg/l as C)	1 mg/l	Adapted from **EPA method No. 425.2
Turbidity	0.1 FTU	Light scatter **EPA No. 1979
Total Suspended Solids	1mg/l	Standard Methods for the Examination of Water and Wastewater (15th ed.) sect. 209D, p. 94
Total Kjeldahl Nitrogen unfiltered (mg/l as N)	0.2 mg/l	Technicon Industrial Method # 376-75W/b; #329-74W/B
Ammonia (mg/l as N)		Technicon Industrial Method # 154-71W/B
Nitrate (mg/l as N)		Technicon Industrial Method # 154-71W/B2
Nitrite (mg/l as N)		Technicon Industrial Method # 102-70W/C
Total Phosphorus (mg/l as P)		Technicon Industrial Method # 376-75W/B; #329-74/B
Ortho-phosphate (mg/l as P)		Technicon Industrial Method # 155-71W
Chlorophyll a (ug/l)	1 mg/cu. M	Standard Methods for the Examination of Water and Wastewater (15th ed.) #1002G. Chlorophyll. Pp 950-954.
BOD5	0.01 mg/l	Oxidation ** EPA No. 405

** EPA Chemical Analysis for Water and Wastes (March, 1979). EPA-600/79-020

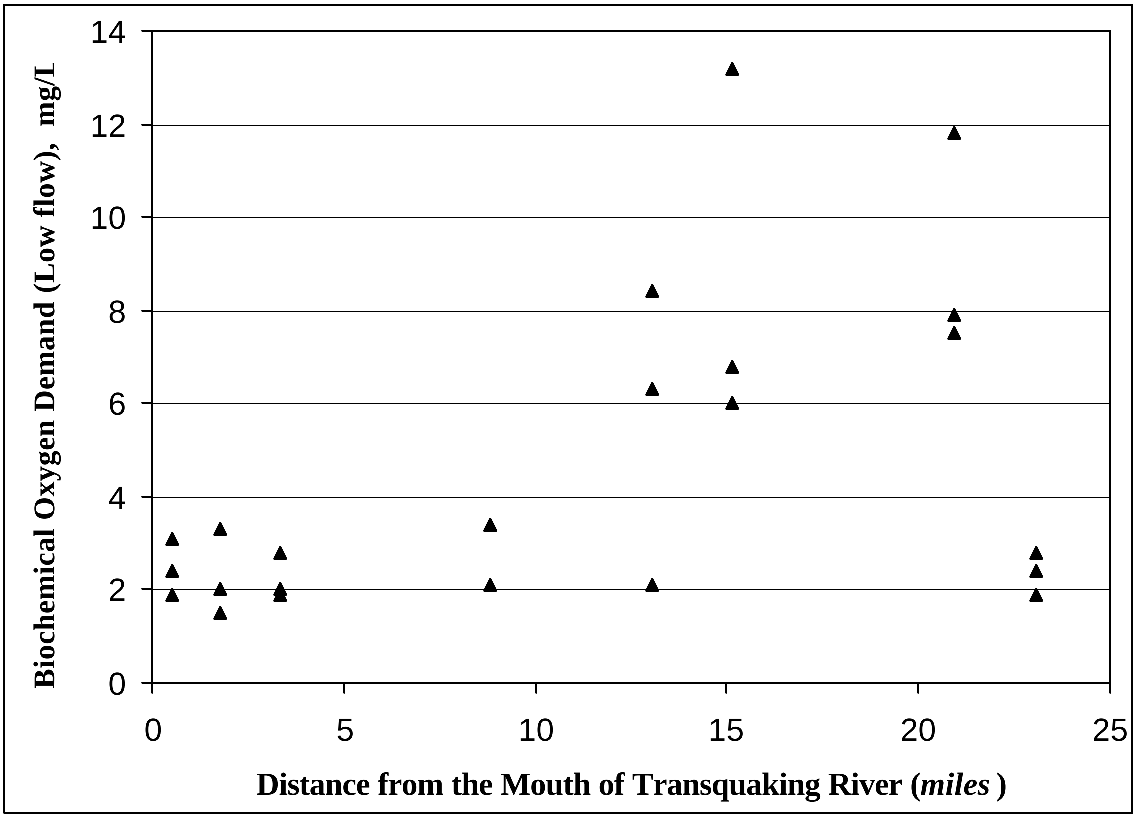

Figure A2: Longitudinal Profile of BOD Data

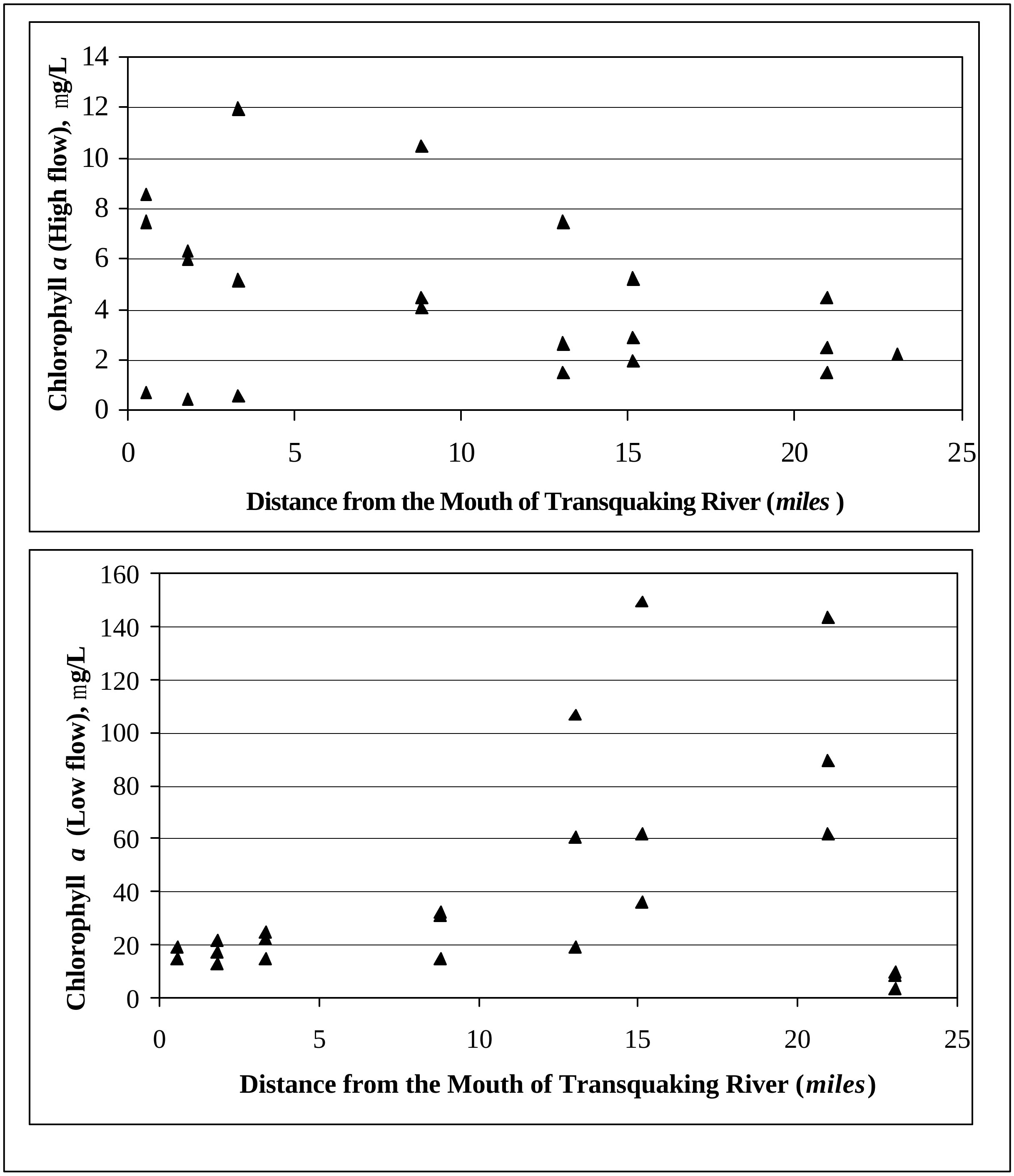

Figure A3: Longitudinal profile of Chlorophyll *a* data

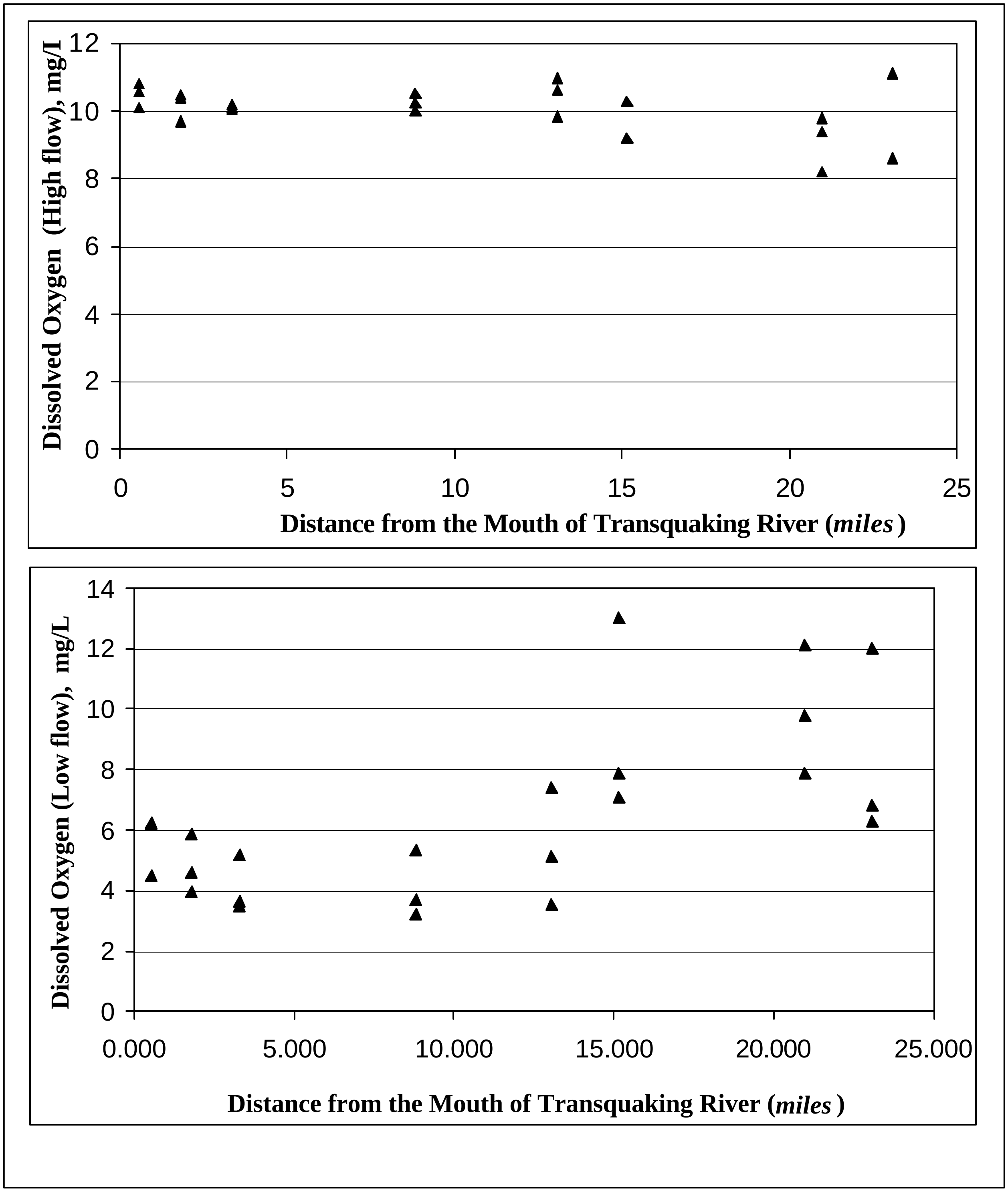

Figure A4: Longitudinal Profile of Dissolved Oxygen Data

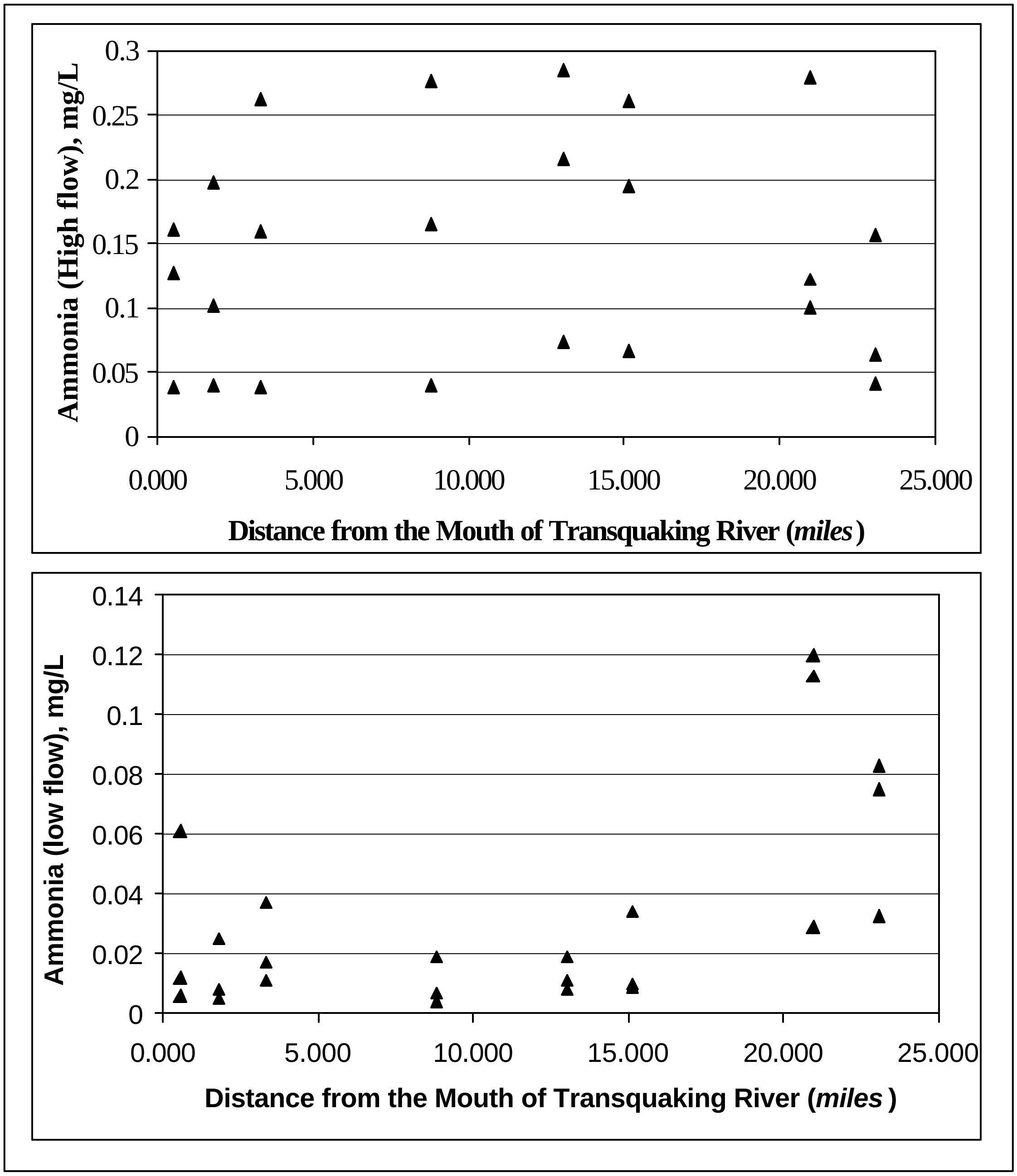

Figure A5: Longitudinal Profile of Ammonia Data

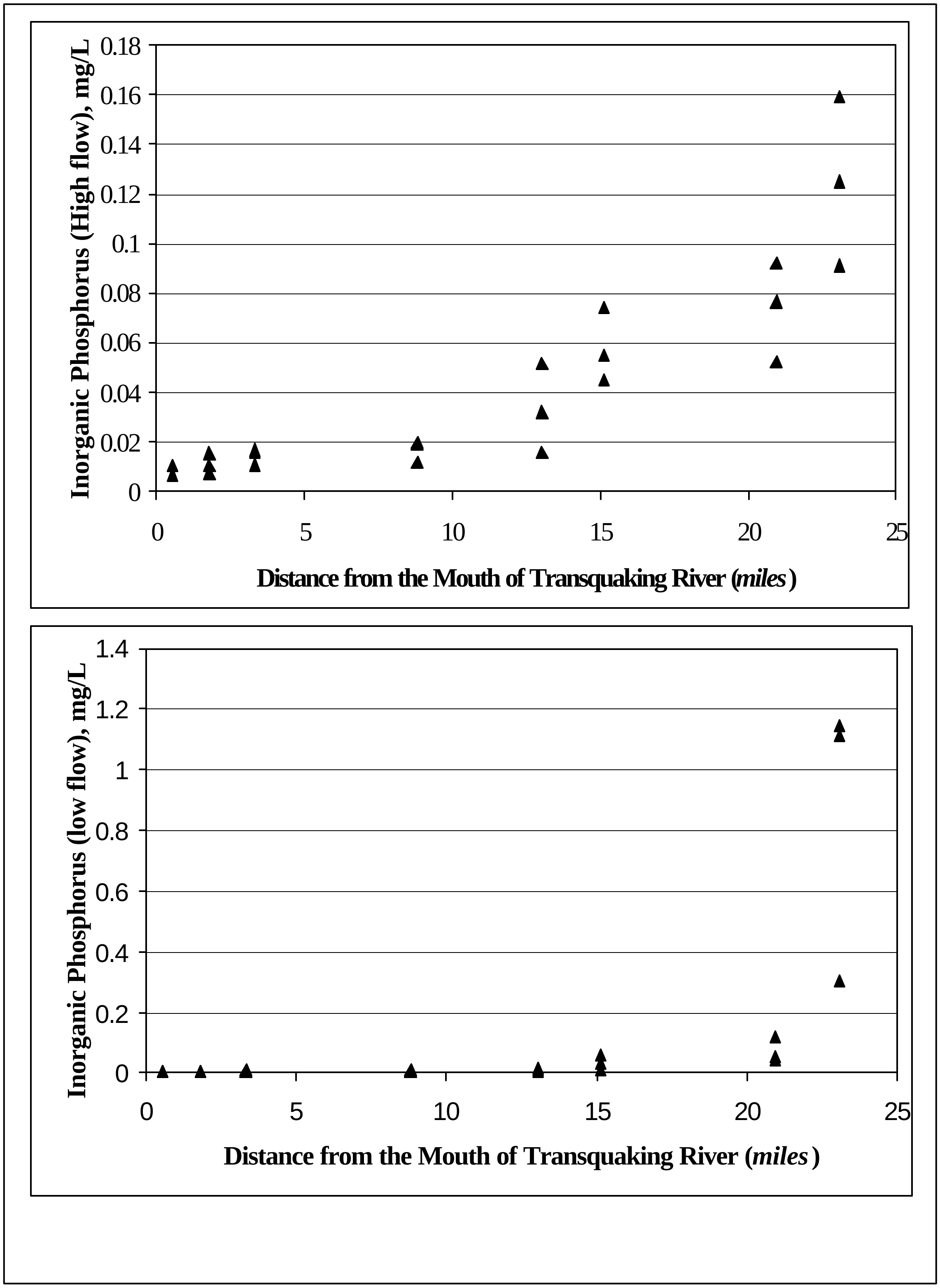

Figure A6: Longitudinal Profile of Inorganic Phosphorus data

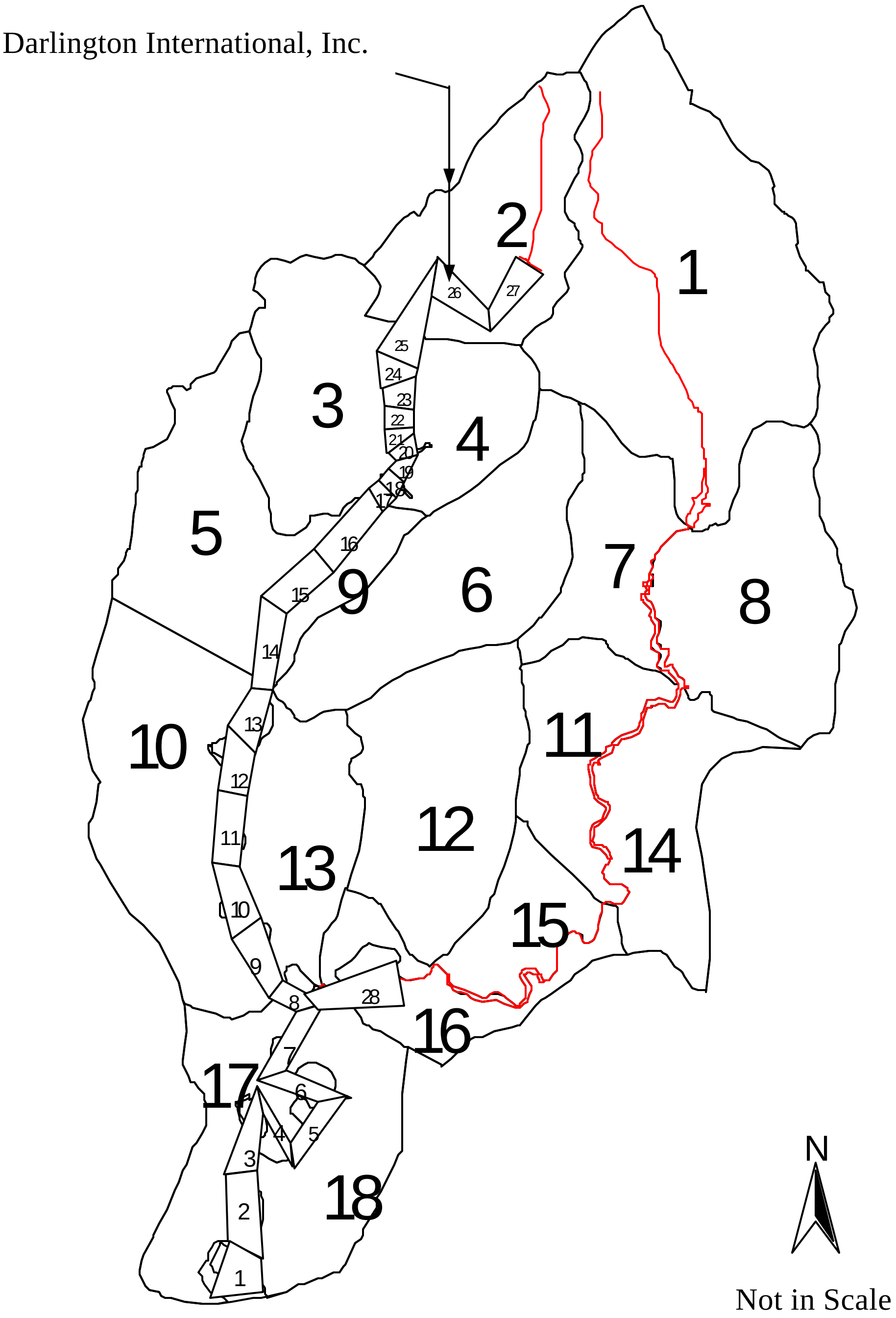

Figure A7: Model Segmentation, including Subwatersheds and Location of point Source

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

Segment No.	Volume (m3)	Characteristic Length (m)	Interfacial Area (m2)
1	559062	2020	135.1
2	283673	2205	123.03
3	191605.3	2110	64.81
4	153842	2259	71.73
5	170076.1	2336	73.93
6	164762	2200	76
7	176027.8	2038	97.23
8	135705.4	2029	34.9
9	75705.54	2168	34.94
10	77025.71	2201	35.06
11	68745.56	2134	29.3
12	56452.02	2138	23.43
13	46680.42	2315	17.08
14	28055.01	1970	11.67
15	16512.2	1794	6.75
16	8791.42	2485	0.15
17	183748.8	2130	90.2
18	155612.4	2360	83.04
19	90720.04	2172	49.28
20	69987.43	2128	35.39
21	51753.09	1790	30.84
22	56371.04	2305	27
23	37370.93	1880	22.07
24	36420.91	2352	18.04
25	25788.44	2540	13.01
26	10037.35	1776	7.57
27	3241.75	1712	3.77
28	2040.00	1712	97.23

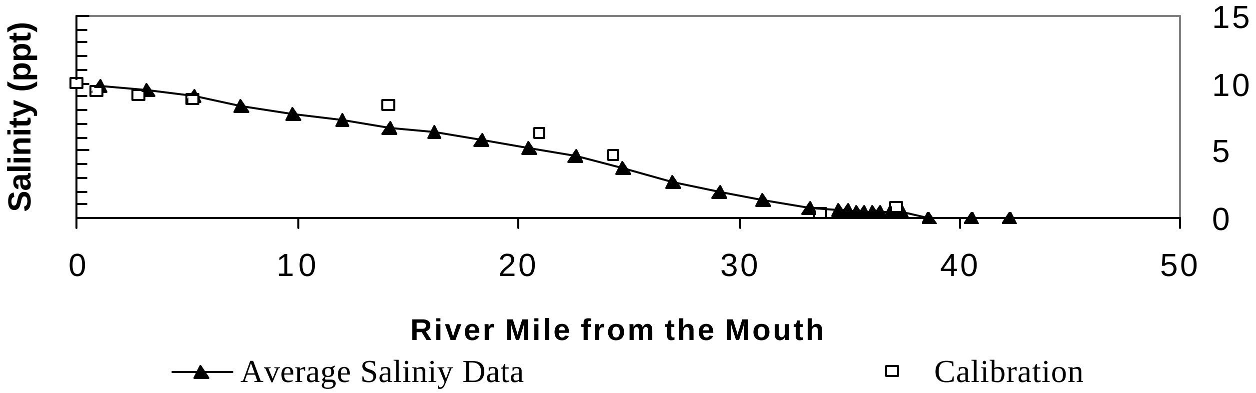

Figure A8: Results of the Calibration of Exchange Coefficients for Low Flow

Table A3: Dispersion Coefficients used in the TREM

Segment Nos	Dispersion coefficients (m^2/Sec)
1	150
2	140
3	140
4	140
5	140
6	140
7	140
8	130
9	100
10	90
11	70
12	45
13	35
14	25
15	20
16	15
17	10
18	5
19	5
20	5
21	5
22	5
23	5
24	5
25	0
26	0
27	0
28	65

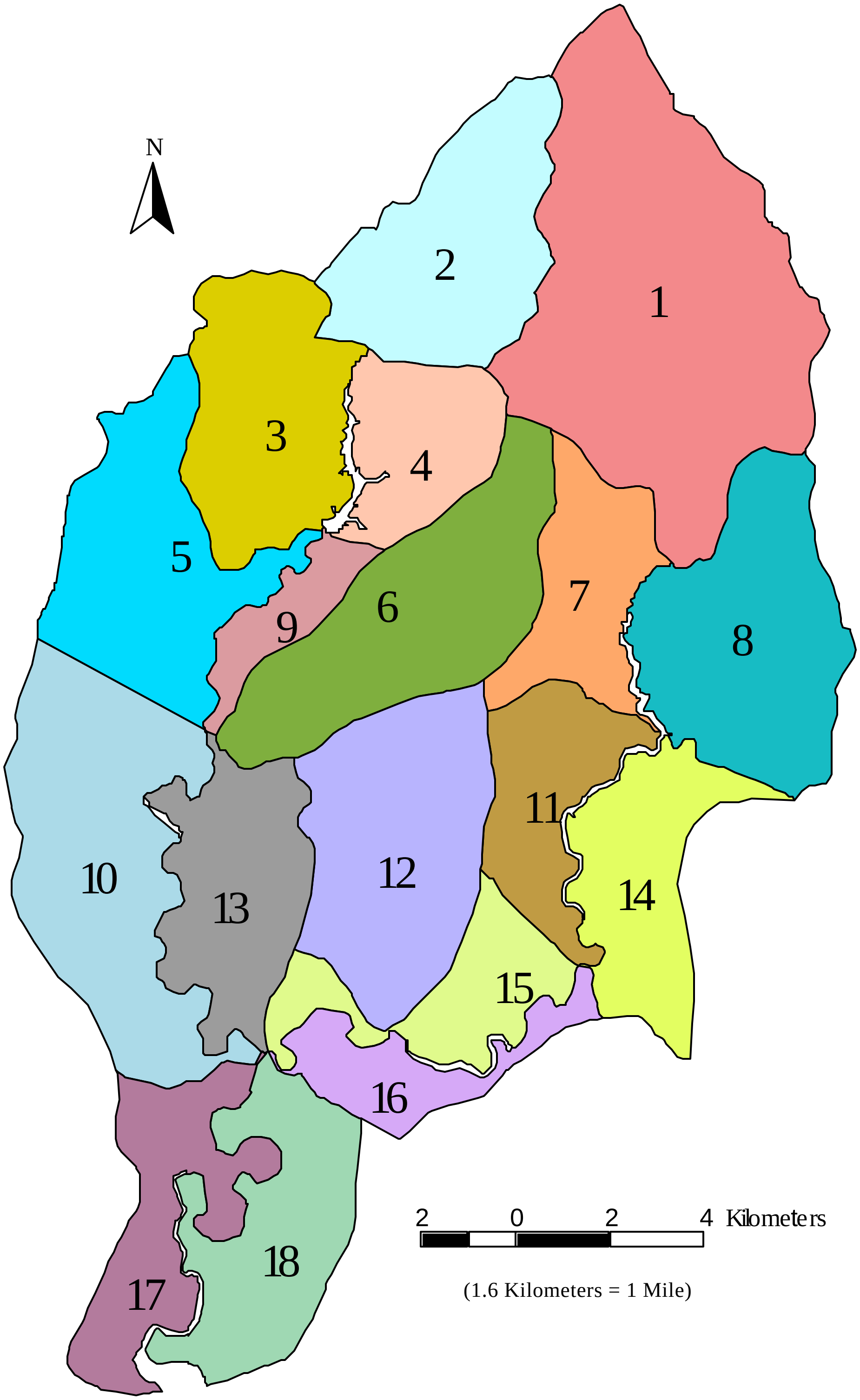

Figure A9: The Eighteen Subwatersheds of the Transquaking River Drainage Basin

Table A4: Subwatersheds flow for low, high, and average conditions

Subwatershed Nos.	Flow Symbols	Low flow (m^3/sec)	High flow (m^3/sec)	Average flow (m^3/sec)
1	Q_1	0.336	2.993	0.573
2	Q_2	0.117	1.234	0.236
3	Q_3	0.108	1.155	0.221
4	Q_4	0	0.666	0.127
5	Q_5	0.125	1.296	0.248
6	Q_6	0.142	1.432	0.274
7	Q_7	0.055	0.734	0.141
8	Q_8	0.144	1.447	0.277
9	Q_9	0	0.319	0.061
10	Q_{10}	0	1.716	0.329
11	Q_{11}	0.054	0.720	0.138
12	Q_{12}	0.142	1.432	0.274
13	Q_{13}	0	0.977	0.187
14	Q_{14}	0	0.902	0.173
15	Q_{15}	0	0.665	0.127
16	Q_{16}	0	0.484	0.093
17	Q_{17}	0	0.868	0.166
18	Q_{18}	0	1.056	0.202

Table A5: Point source loadings for the calibration of models

Parameters	**Unit**	**Load from Rendering Plant**
Flow	m^3/sec	0.0108
NH_4	kg/day	.0978
NO_{23}	kg/day	376.541
PO_4	kg/day	2.5643
CHL*a*	kg/day	0
CBOD	kg/day	3.2589
DO	kg/day	6.1939
ON	kg/day	593.72
OP	kg/day	2.6986

Table A6: Environmental Parameters for the Calibration of the Model

Segment	Ke (m^{-1})		T (^{0}C)		Salinity (gm/L)		SOD (g O_2/m^2 day)		FNH4 (mg NH_4-N/m^2 day)		FPO4 (mg PO_4-P/m^2 day)	
nos.	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	9.75	5.091	7.0	29.2	1.55	8.5	0.5	3.5	0	140	0	14
2	9.75	5.091	7.0	29.2	0.6	8.1	0.5	3.5	0	140	0	14
3	9.75	5.091	7.0	29.2	0.35	7.7	0.5	3.0	0	140	0	14
4	11.5	5.091	7.0	29.2	0.31	6.9	0.5	3.0	0	140	0	14
5	11.5	3.801	7.0	29.2	0.28	6.2	0.5	3.0	0	140	0	14
6	11.5	3.801	7.0	29.2	0.24	5.7	0.5	3.0	0	140	0	14
7	11.5	3.801	7.0	29.2	0.2	5.2	0.5	3.0	0	140	0	14
8	11.5	3.801	7.0	29.2	0.13	4.8	0.5	3.0	0	140	0	14
9	11.5	3.801	7.0	29.2	0.07	4.5	0.5	3.0	0	140	0	14
10	11.5	3.801	7.0	29.2	0	4	0.5	2.5	0	140	0	14
11	11.5	3.801	7.0	29.2	0	3.5	0.5	2.5	0	140	0	14
12	11.5	3.801	7.0	29.2	0	2.8	0.5	2.5	0	140	0	14
13	11.5	3.801	7.0	29.2	0	1.9	0.5	2.5	0	140	0	14
14	11.5	3.801	7.0	29.2	0	1.1	0.5	2.0	0	140	0	14
15	11.5	3.801	7.0	29.2	0	0.6	0.5	1.5	0	140	0	14
16	11.5	3.801	7.0	29.2	0	0.2	0.5	1.5	0	140	0	14
17	11.5	3.801	7.0	27.0	0	0.01	0.5	2.0	0	140	0	14
18	11.5	3.801	7.0	27.0	0	0.01	0.5	2.0	0	140	0	14
19	11.5	3.801	7.0	27.0	0	0.01	0.5	2.0	0	140	0	14
20	11.5	3.801	7.0	27.0	0	0.01	0.5	2.0	0	140	0	14
21	11.5	3.801	7.0	27.0	0	0.01	0.5	2.0	0	140	0	14
22	11.5	3.801	7.0	27.0	0	0.01	0.5	2.0	0	140	0	14
23	11.5	3.801	7.0	27.0	0	0.01	0.5	2.0	0	140	0	14
24	11.5	3.801	7.0	27.0	0	0.01	0.5	2.0	0	140	0	14
25	11.5	3.801	7.0	27.0	0	0	0.5	0.5	0	0	0	0
26	11.5	3.801	8.6	27.0	0	0	0.5	0.5	0	0	0	0
27	11.5	3.801	8.6	27.0	0	0	0.5	0.5	0	0	0	0
28	11.5	3.801	7.0	29.2	0.13	4	0.5	3.0	0	140	0	14

Table A7: EUTRO5 Kinetic Coefficients

Constant	Code	Value
Nitrification rate	K12C	0.15 *day* -1 at 20^{o} C
temperature coefficient	K12T	1.04
Denitrification rate	K20C	0.08 *day* -1 at 20^{o} C
temperature coefficient	K20T	1.045
Saturated growth rate of phytoplankton	K1C	2.0 *day* -1 at 20^{o} C
temperature coefficient	K1T	1.066
Endogenous respiration rate	K1RC	0.11 *day* -1 at 20^{o} C
temperature coefficient	K1RT	1.08
Nonpredatory phytoplankton death rate	K1D	0.09 *day* -1
Phytophankton Stoichometry		
Oxygen-to-carbon ratio	ORCB	2.67 *mg* O_2 */ mg C*
Carbon-to-chlorophyll ratio	CCHL	35
Nitrogen-to-carbon ratio	NCRB	0.25 *mg N/mg C*
Phosphorus-to-carbon ratio	PCRB	0.025 *mg* PO_4*-P/ mg C*
Half-saturation constants for phytoplankton growth		
Nitrogen	KMNG1	0.005 *mg* N / L
Phosphorus	KMPG1	0.001 *mg* P / P
Phytoplankton	KMPHY	0.0 *mg* C/ *L*
Grazing rate on phytoplankton	K1G	0.0 *L / cell-day*
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	500. *Ly/day*
BOD deoxygenation rate	KDC	0.20 *day* -1 at 20^{o} C
temperature coefficient	KDT	1.047
Half saturation const. for carb. deoxygenation	KBOD	0.0
Reaeration rate constant	k2	0.26 *day* -1 at 20^{o} C
Mineralization rate of dissolved organic nitrogen	K71C	0.005 *day*-1
temperature coefficient	K71T	1.08
Mineralization rate of dissolved organic phosphorus	K58C	0.20 *day* -1
temperature coefficient	K58T	1.08
Phytoplankton settling velocity		0.233 *m/day*
Inorganics settling velocity		0.052 *m/day*

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

Water quality Segments	Subwatershed contributions	Low flow m^3/sec	High flow m^3/sec	Average flow m^3/sec
S2	17+18	0.0000	0.8129	0.1557
S3	22	0.0000	0.3037	0.0582
S5	17+18	0.0000	0.4036	0.0773
S6	18	0.0000	0.1056	0.0202
S7	17+18	0.0000	0.2791	0.0535
S9	10+13	0.0000	0.7102	0.1360
S10	10+13	0.0000	0.4528	0.0867
S11	10+13	0.0000	0.6244	0.1196
S12	10+13	0.0000	0.4409	0.0844
S13	6+10	0.0568	1.7751	0.3400
S14	5+9	0.0000	0.1287	0.0246
S15	5+9	0.0313	1.2626	0.2418
S16	3+5+9	0.0405	0.9126	0.1748
S20	4	0.0000	0.4659	0.0892
S22	3+4	0.0000	0.3642	0.0698
S25	2+3+4	0.0146	0.6464	0.1238
S26	2	0.0000	0.1743	0.0355
S27	2	0.0117	0.4936	0.0845
S28	1+7+8+11+12+14+15+16	0.1785	9.7543	1.8682

Table A9: Nonpoint Source Loadings for the Calibration of the Model for Low flow

Segment Nos.	NH4 mg/l	NO_{23} mg/l	PO_4 mg/l	CHL a mg/l	CBOD mg/l	DO mg/l	ON mg/l	OP mg/l
1	0.0153	0.0023	0.0388	15.5169	3.7222	6.52	1.0893	0.0309
27	0.0323	0.243	0.1207	0.4237	3.333	8.27	0.1305	0.0690
13	0.0323	0.243	0.1207	0.4237	3.333	8.27	0.1305	0.0690
15	0.0323	0.243	0.1207	0.4237	3.333	8.27	0.1305	0.0690
16	0.0323	0.243	0.1207	0.4237	3.333	8.27	0.1305	0.0690
25	0.0323	0.243	0.1207	0.4237	3.333	8.27	0.1305	0.0690
28	0.007	0.0061	0.0396	29.9705	4.9000	5.22	1.5993	0.0492

Table A10: Nonpoint Source Loadings for the Calibration of the Model for High flow

Segment Nos.	**NH4** *mg/l*	**NO23** *mg/l*	**PO4** *mg/l*	**CHL *a*** *mg/l*	**CBOD** *mg/l*	**DO** *mg/l*	**ON** *mg/l*	**OP** *mg/l*
1	0.0765	0.2555	0.0478	6.7284	2.0000	11.385	0.6709	0.0497
2	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
3	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
5	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
6	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
7	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
9	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
10	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
11	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
12	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
13	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
14	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
15	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
16	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
20	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
22	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
25	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
26	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
27	0.0775	0.1067	0.0371	1.3083	2.0000	8.7	0.5253	0.0245
28	0.124	0.571	0.0385	2.8145	2.0000	10.01	0.923	0.0479

Low Flow Calibration

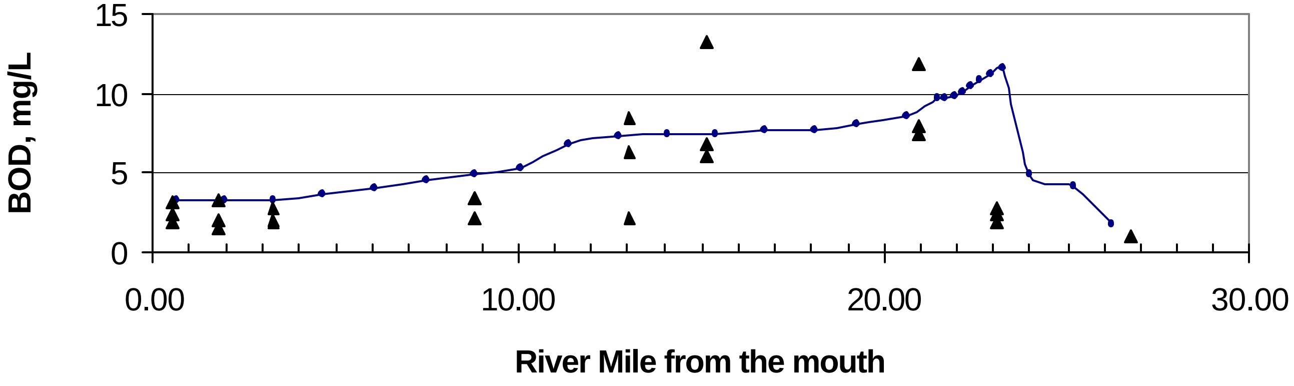

Figure A10: BOD vs. River Mile for the Calibration of the Model (Low flow)

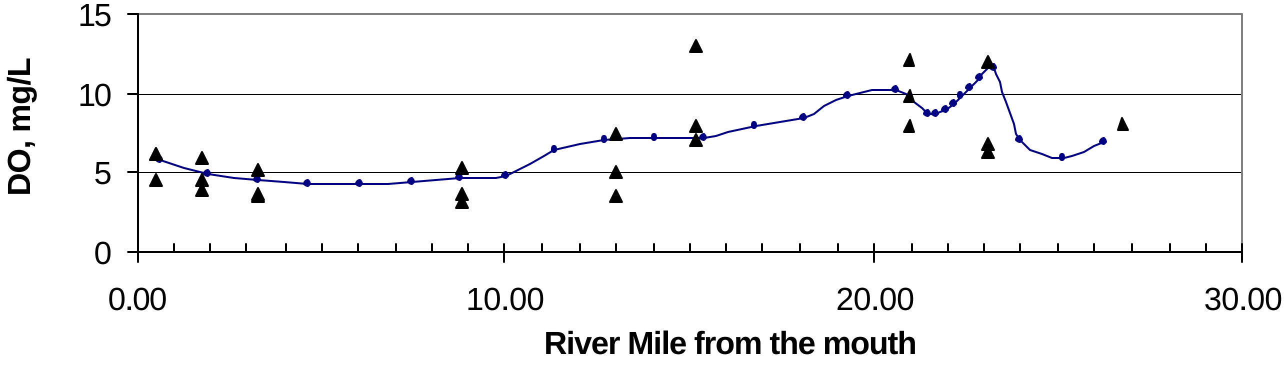

Figure A11: Dissolved Oxygen vs. River Mile for the Calibration of the Model (Low flow)

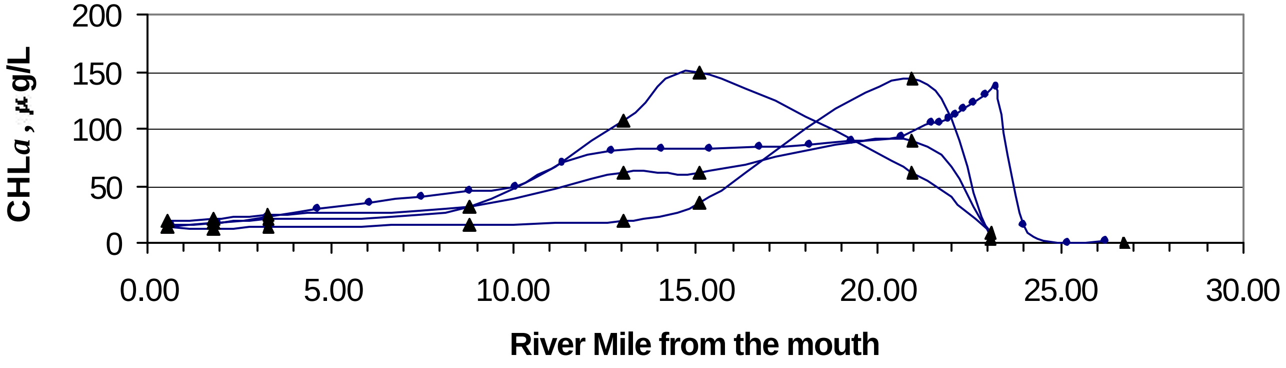

Figure A12: Chlorophyll *a* vs. River Mile for the Calibration of the Model (Low flow)

? **Monitoring Data** ___ **Calibration**

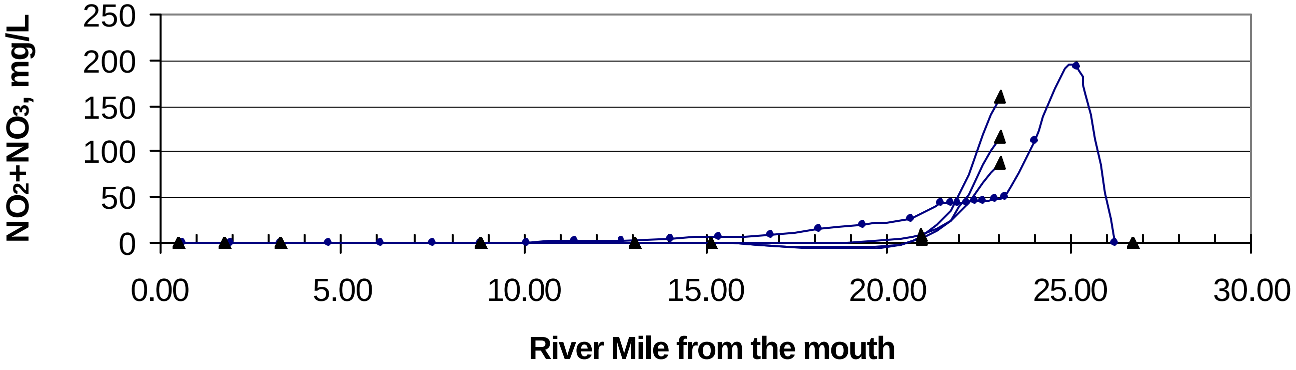

Figure A13: Nitrate (plus Nitrite) vs. River Mile for the Calibration of the Model (Low flow)

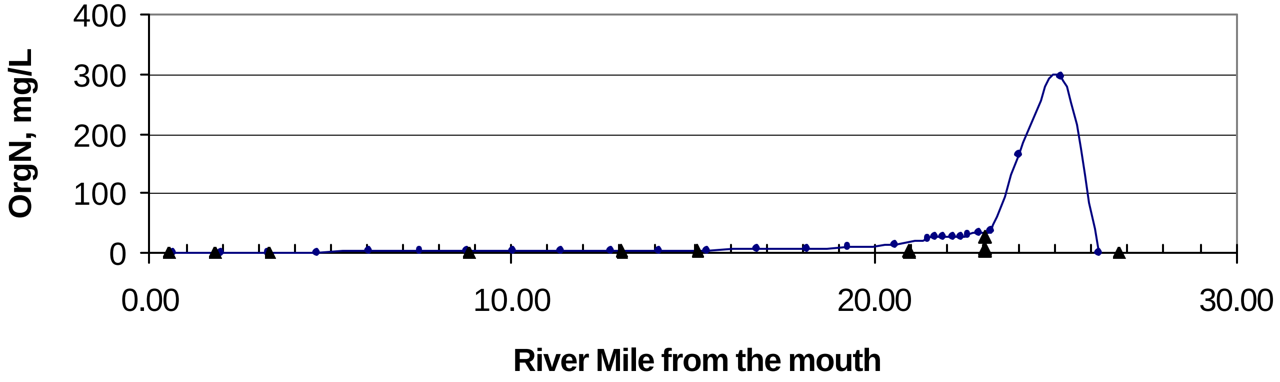

Figure A14: Organic Nitrogen vs. River Mile for the Calibration of the Model (Low flow)

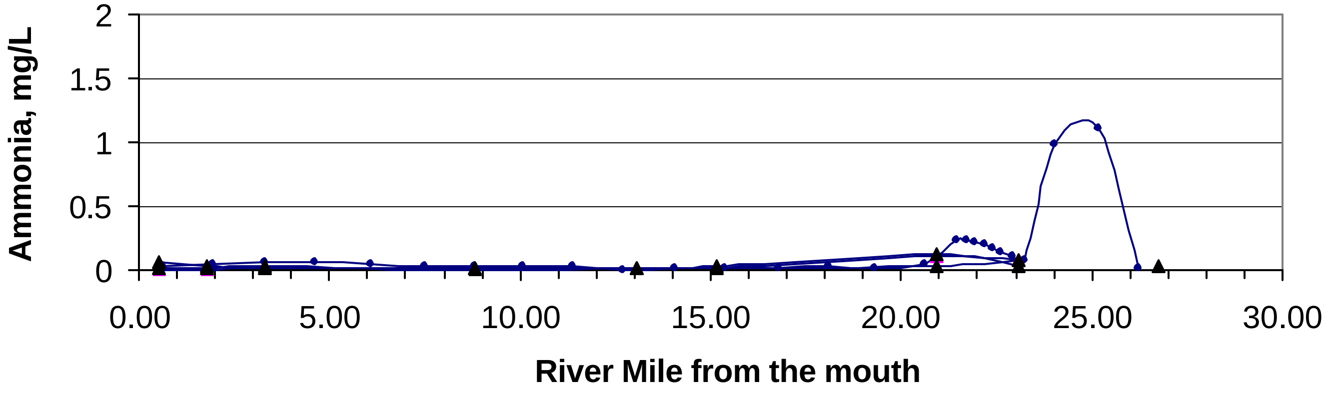

Figure A15: Ammonia vs. River Mile for the Calibration of the Model (Low flow)

? **Monitoring Data** ___ **Calibration**

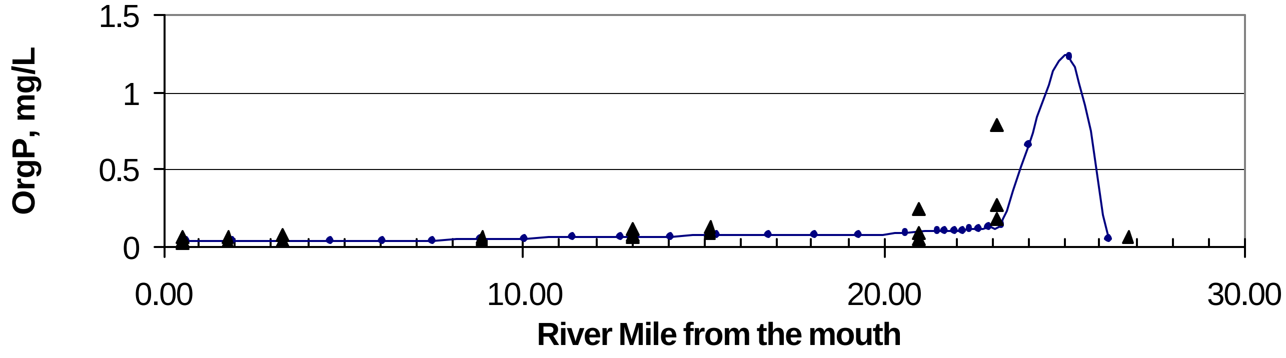

Figure A16: Organic Phosphorus vs. River Mile for the Calibration of the Model (Low flow)

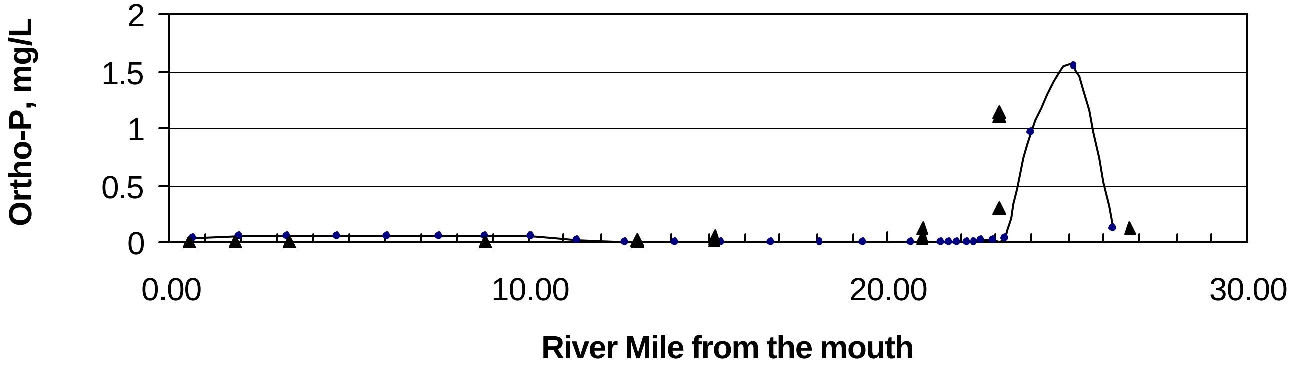

Figure A17: Ortho-Phosphate vs. River Mile for the Calibration of the Model (Low flow)

? **Monitoring Data** ___ **Calibration**

High Flow Calibration

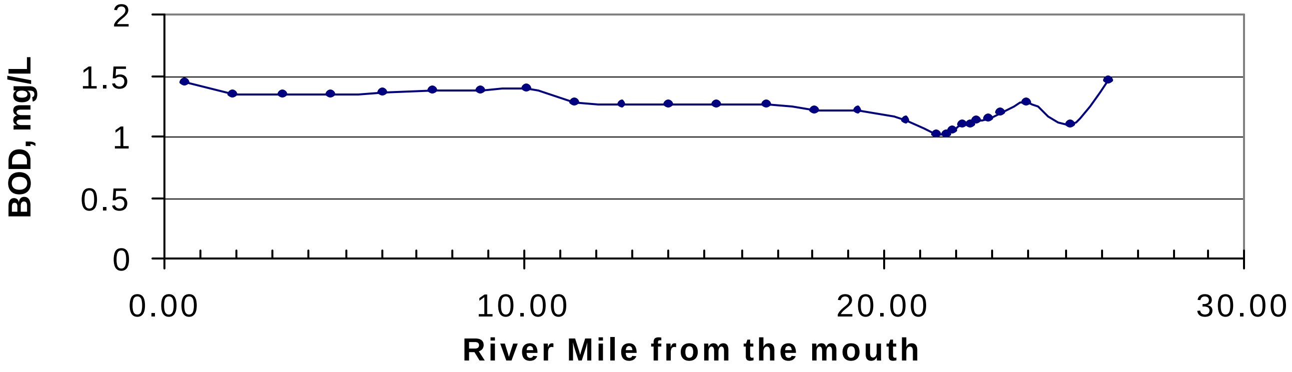

Figure A18: BOD vs. River Mile for the Calibration of the Model (High flow)

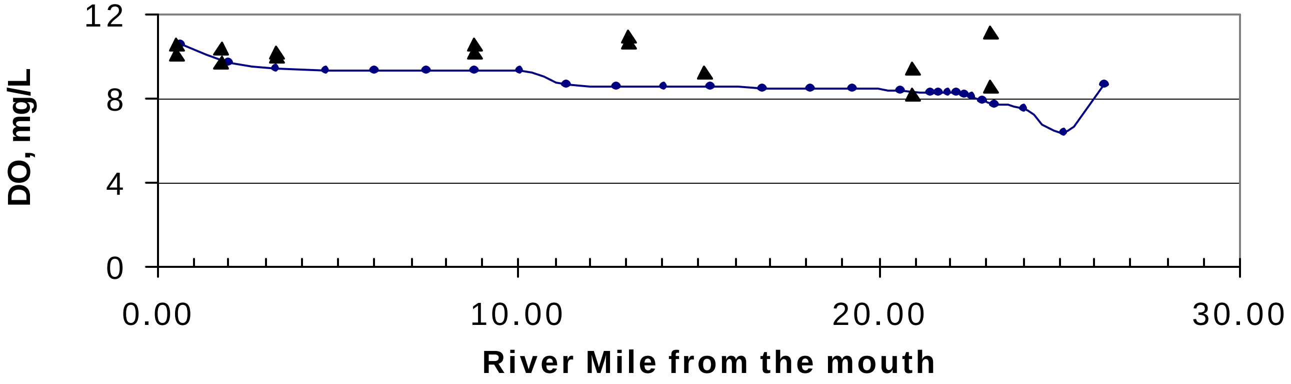

Figure A19: Dissolved Oxygen vs. River Mile for the Calibration of the Model (High Flow)

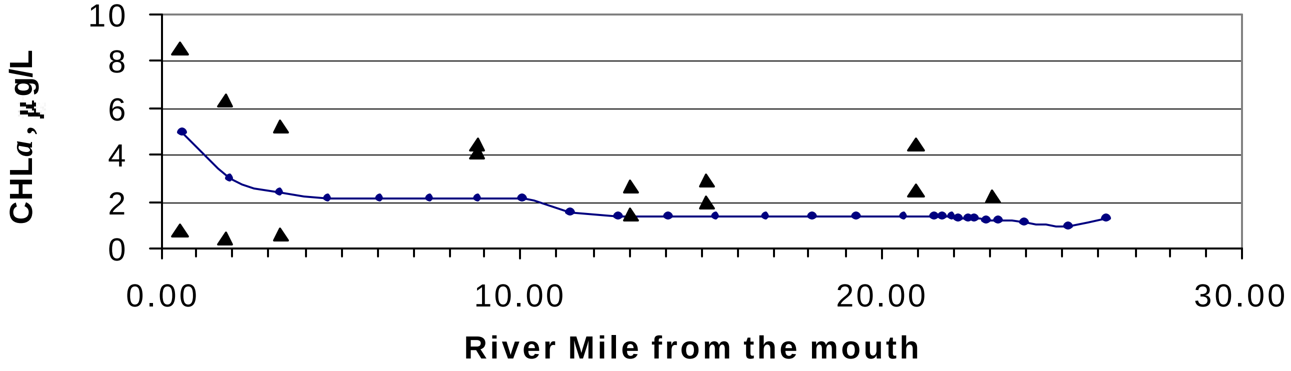

Figure A20: Chlorophyll *a* vs. River Mile for the Calibration of the Model (High flow)

? **Monitoring Data** ___ **Calibration**

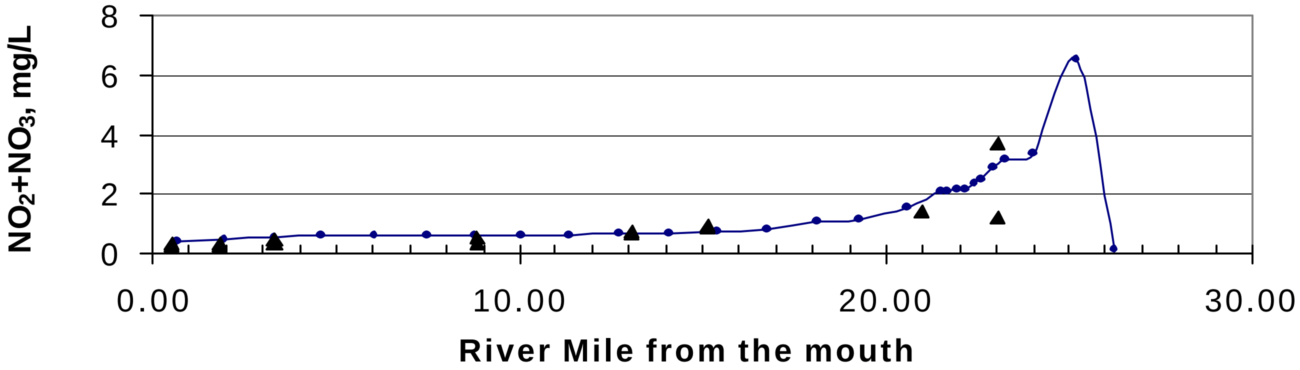

Figure A21: Nitrate (plus Nitrite) vs. River Mile for the Calibration of the Model (High flow)

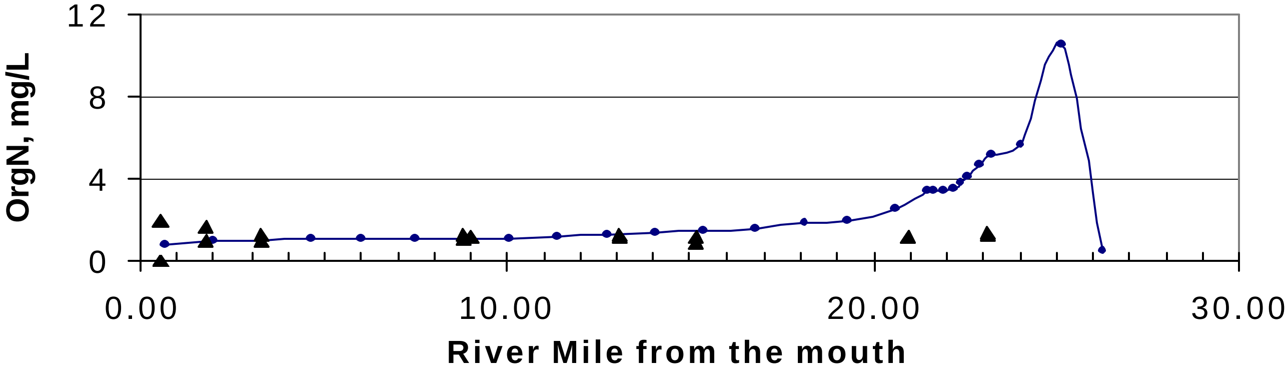

Figure A22: Organic Nitrogen vs. River Mile for the Calibration of the Model (High flow)

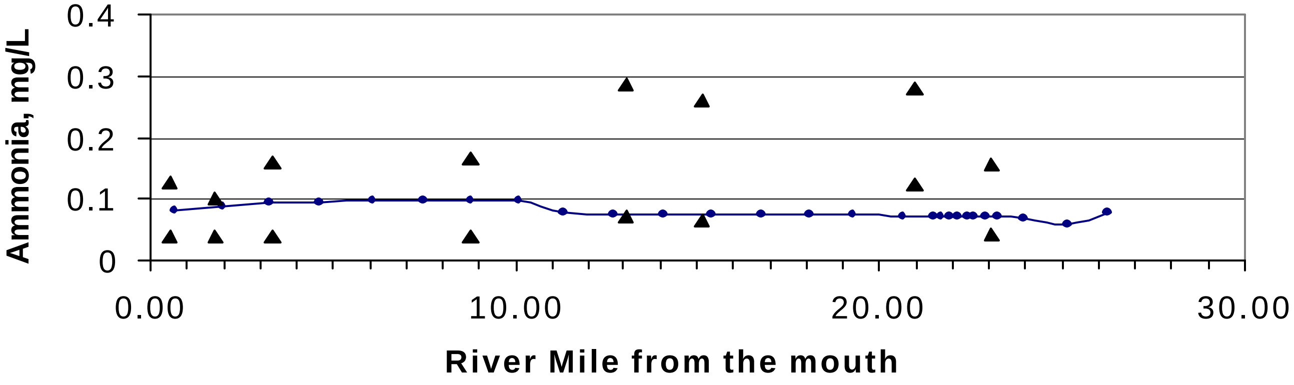

Figure A23: Ammonia vs. River Mile for the Calibration of the Model (High flow)

? Monitoring Data **___ Calibration**

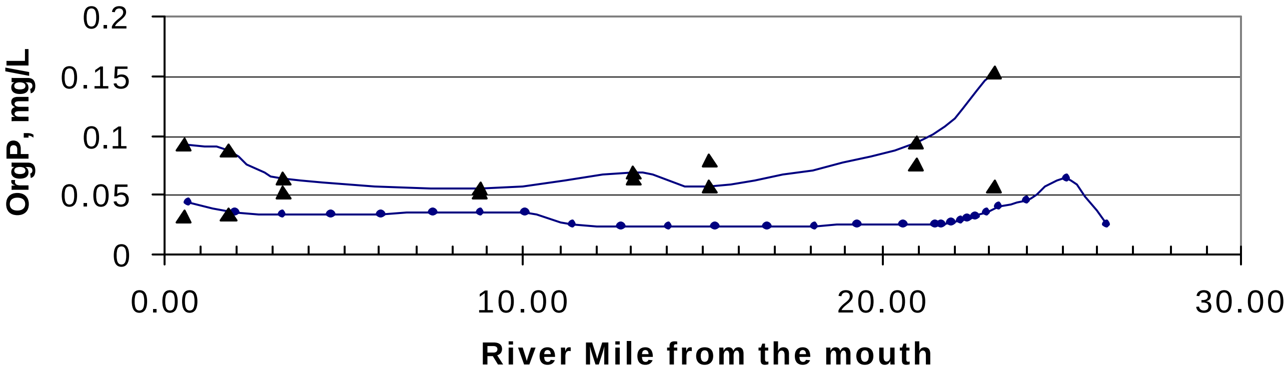

Figure A24: Organic Phosphorus vs. River Mile for the Calibration of the Model (High flow)

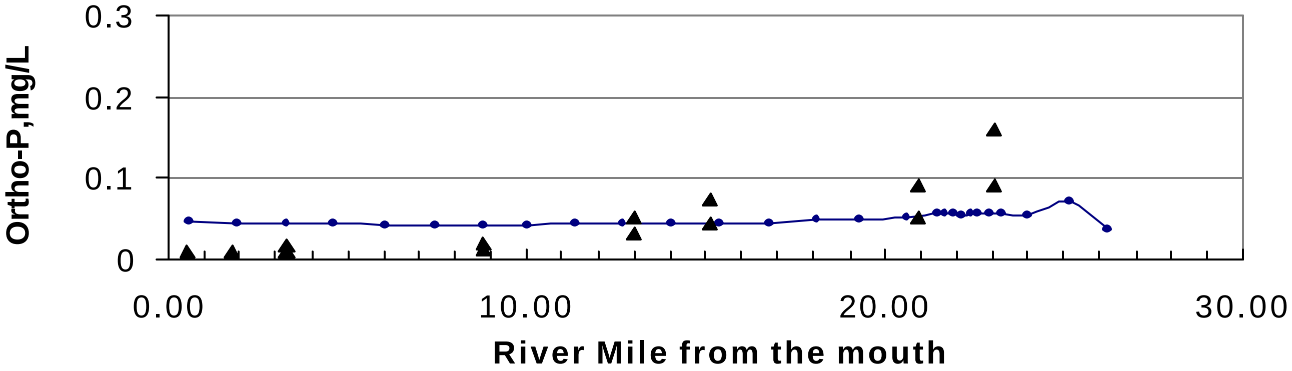

Figure A25: Ortho-Phosphate vs. River Mile for the Calibration of the Model (High flow)

? **Monitoring Data** ___ **Calibration**

Table A11: Nonpoint Source Loadings for the Expected Low Flow condition

Segment Nos.	NH4 mg/l	NO_{23} mg/l	PO_4 mg/l	CHL a mg/l	CBOD mg/l	DO mg/l	ON mg/l	OP mg/l
1	0.0153	0.0023	0.0388	15.52	3.72	6.52	1.0893	0.0309
27	0.0323	0.243	0.1207	0.42	3.33	8.27	0.1305	0.0690
13	0.0323	0.243	0.1207	0.42	3.33	8.27	0.1305	0.0690
15	0.0323	0.243	0.1207	0.42	3.33	8.27	0.1305	0.0690
16	0.0323	0.243	0.1207	0.42	3.33	8.27	0.1305	0.0690
25	0.0323	0.243	0.1207	0.42	3.33	8.27	0.1305	0.0690
28	0.007	0.0061	0.0396	29.97	4.90	5.22	1.5993	0.0492

Table A12: Nonpoint Source Loadings for the Expected Average Flow Condition

Segment Nos.	NH4 mg/l	NO23 mg/l	PO4 mg/l	CHL a mg/l	CBOD mg/l	DO mg/l	ON mg/l	OP mg/l
1	0.0153	0.0023	0.0388	15.52	3.72	6.52	1.0893	0.0309
2	0.0707	0.4184	0.0111	0.42	3.33	8.27	0.3031	0.0172
3	0.0677	0.3982	0.0103	0.42	3.33	8.27	0.2989	0.0162
5	0.0723	0.4287	0.0115	0.42	3.33	8.27	0.3053	0.0177
6	0.0735	0.4371	0.0119	0.42	3.33	8.27	0.3070	0.0180
7	0.0718	0.4258	0.0114	0.42	3.33	8.27	0.3047	0.0175
9	0.1760	0.8808	0.0442	0.42	3.33	8.27	0.8406	0.0855
10	0.1699	0.8087	0.0414	0.42	3.33	8.27	0.8181	0.0829
11	0.1745	0.8634	0.0435	0.42	3.33	8.27	0.8352	0.0849
12	0.1780	0.9055	0.0452	0.42	3.33	8.27	0.8484	0.0864
13	0.2479	0.8171	0.0717	0.42	3.33	8.27	1.2855	0.1445
14	0.3595	0.9626	0.1014	0.42	3.33	8.27	1.8755	0.2154
15	0.2842	0.8294	0.0982	0.42	3.33	8.27	1.4782	0.1700
16	0.2367	0.9433	0.0625	0.42	3.33	8.27	1.1629	0.1293
20	0.2338	1.2792	0.0656	0.42	3.33	8.27	1.0391	0.1133
22	0.2261	1.0764	0.0586	0.42	3.33	8.27	1.0589	0.1162
25	0.1986	1.0875	0.0545	0.42	3.33	8.27	0.9576	0.0999
26	0.1941	1.0893	0.0539	0.42	3.33	8.27	0.9410	0.0972
27	0.1941	1.0893	0.0539	0.42	3.33	8.27	0.9410	0.0972
28	0.2011	0.8883	0.0500	29.97	4.90	5.22	0.9677	0.1041

Expected Low Flow Scenario

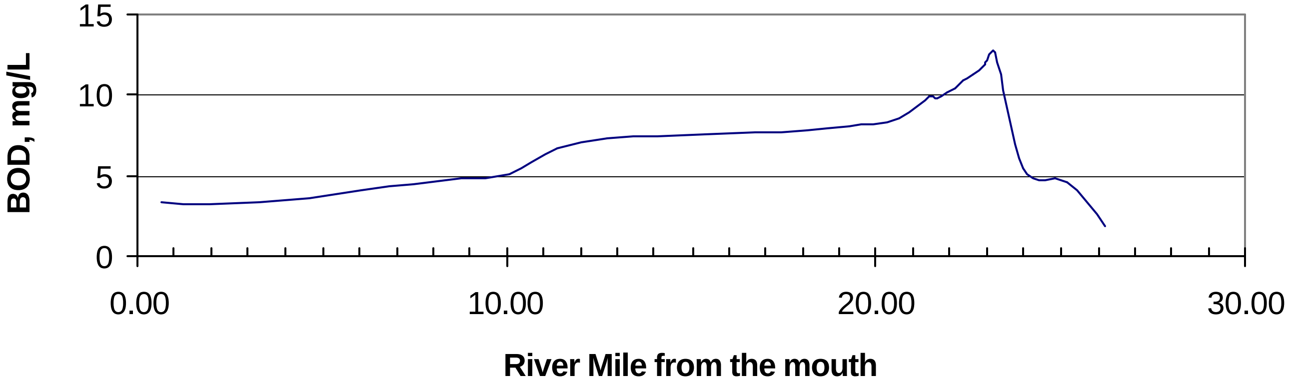

Figure A26: BOD vs. River Mile for the Expected Low Flow Scenario

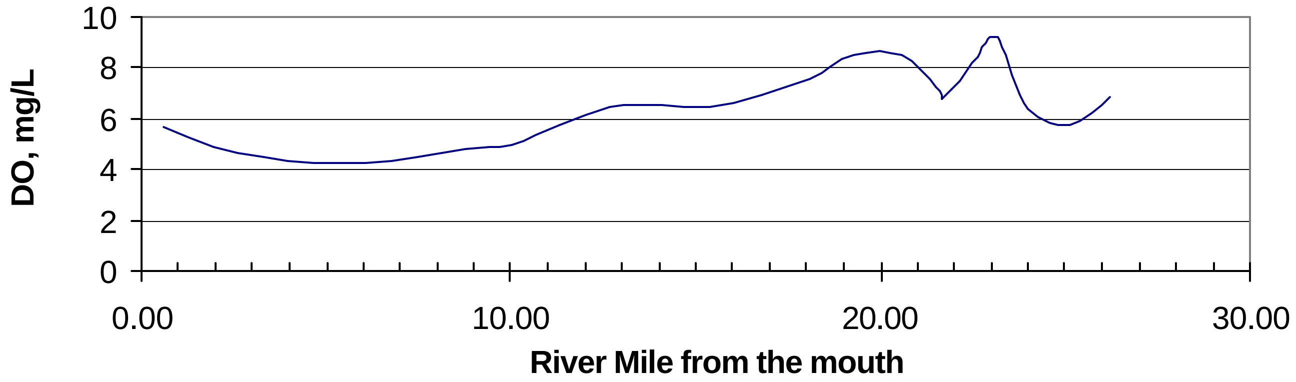

Figure A27: Dissolved Oxygen vs. River Mile for the Expected Low Flow Scenario

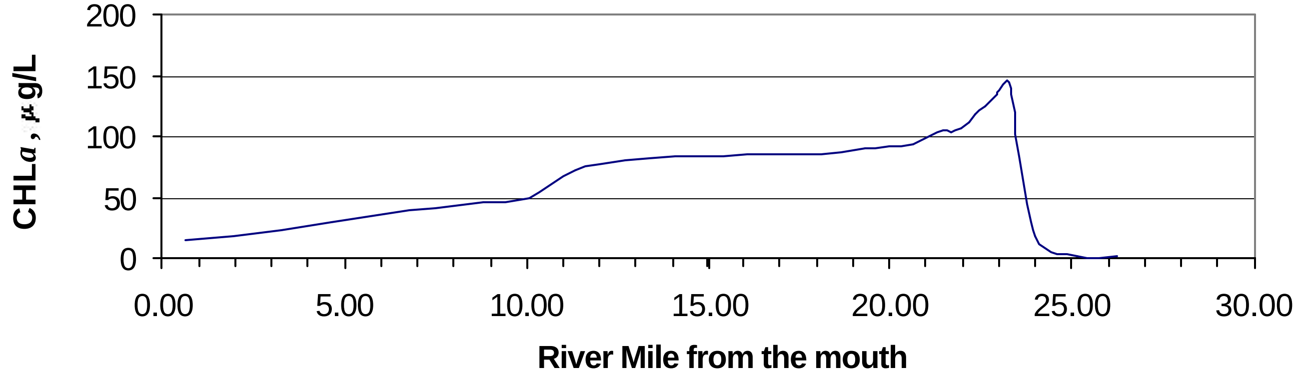

Figure A28: Chlorophyll *a* vs. River Mile for the Expected Low Flow Scenario

_____ Expected low flow condition

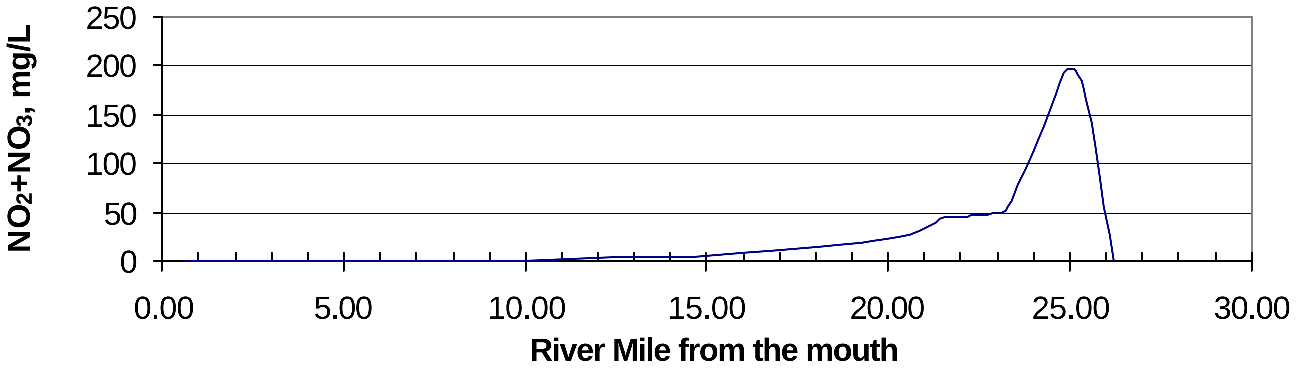

Figure A29: Nitrate (plus Nitrite) vs. River Mile for the Expected Low Flow Scenario

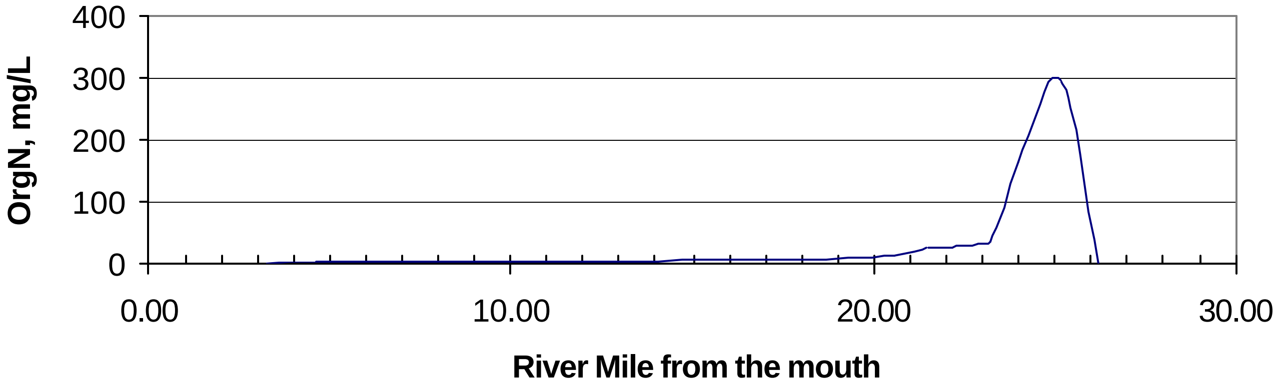

Figure A30: Organic Nitrogen vs. River Mile for the Expected Low Flow Scenario

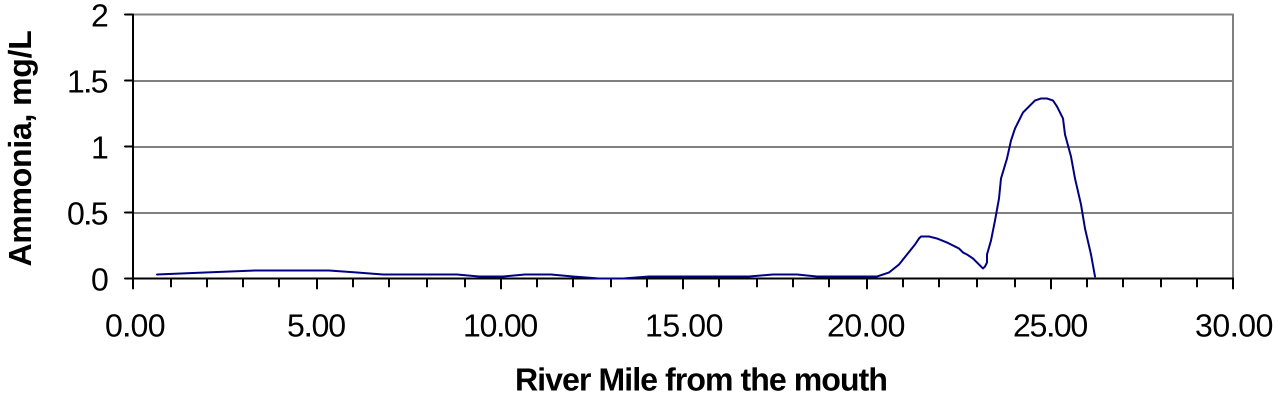

Figure A31: Ammonia vs. River Mile for the Expected Low Flow Scenario

_____ Expected low flow condition

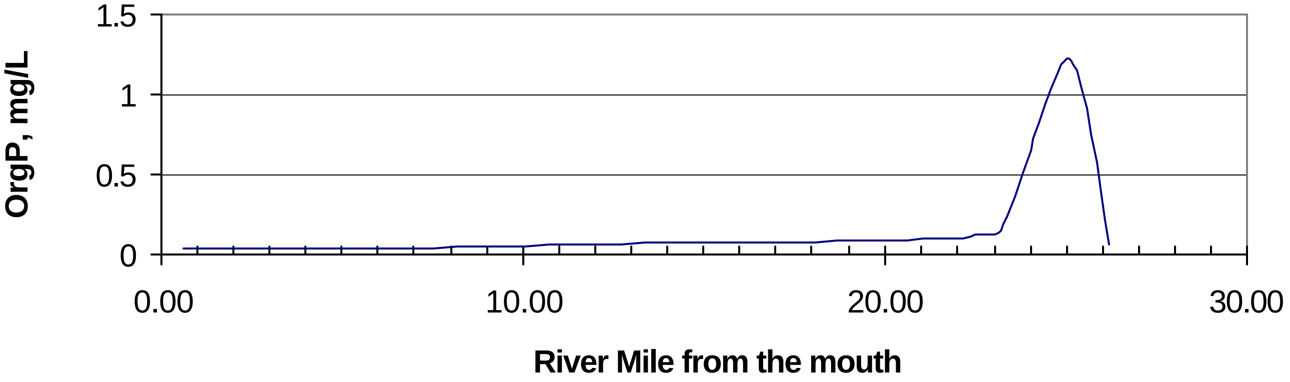

Figure A32: Organic Phosphorus vs. River Mile for the Expected Low Flow Scenario

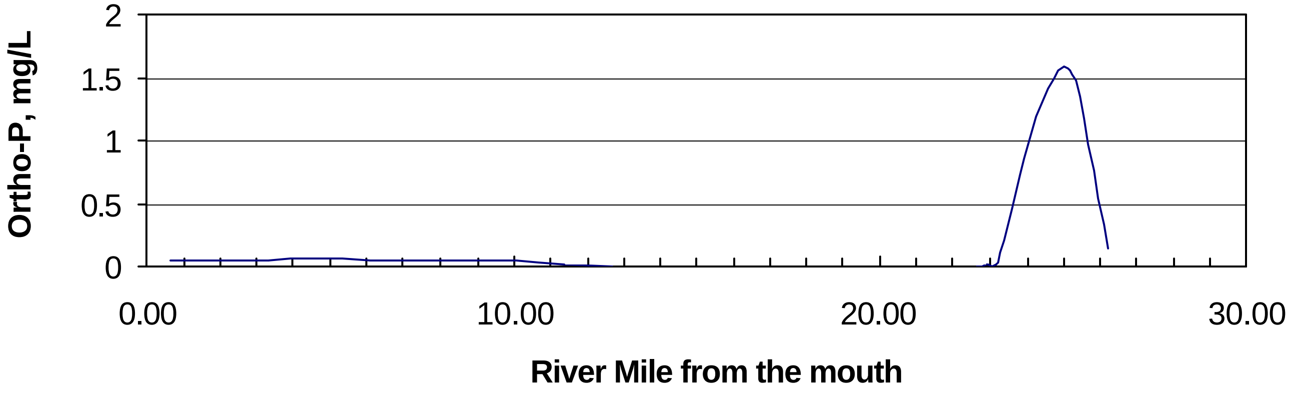

Figure A33: Ortho-Phosphorus vs. River Mile for the Expected Low Flow Scenario

_____ Expected low flow condition

Expected Average Flow Scenario

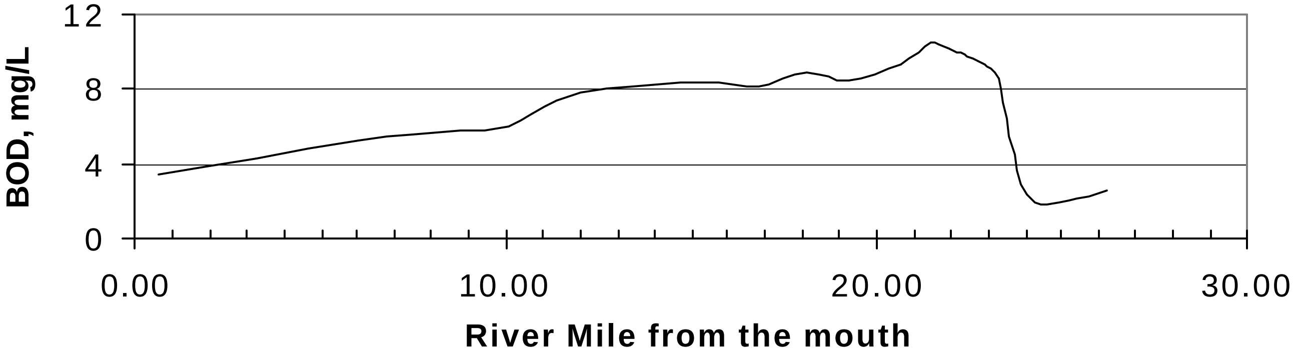

Figure A34: BOD vs. River Mile for the Expected Average Flow Scenario

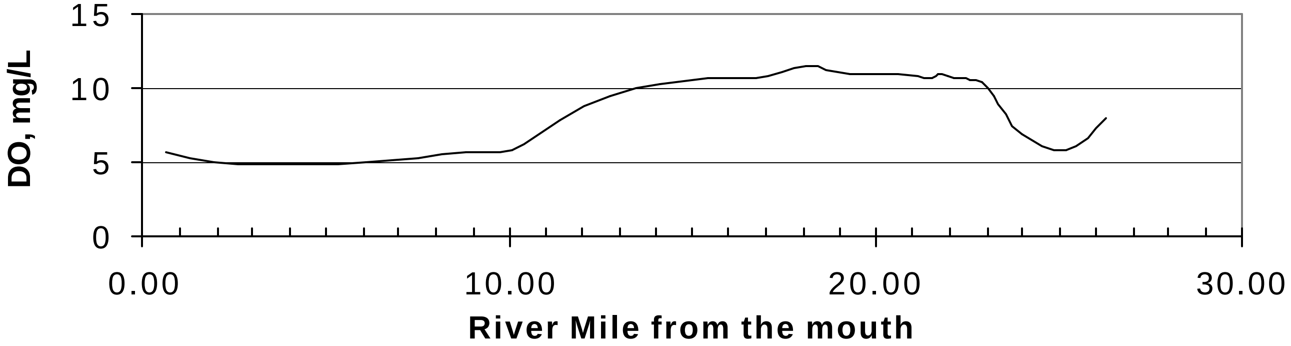

Figure A35: Dissolved Oxygen vs. River Mile for the Expected Average Flow Scenario

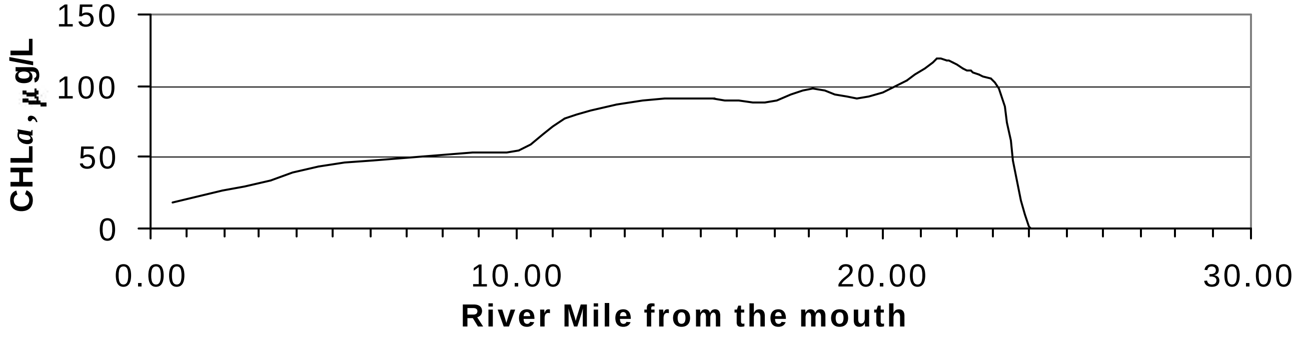

Figure A36: Chlorophyll *a* vs. River Mile for the Expected Average Flow Scenario

———— Expected average flow condition

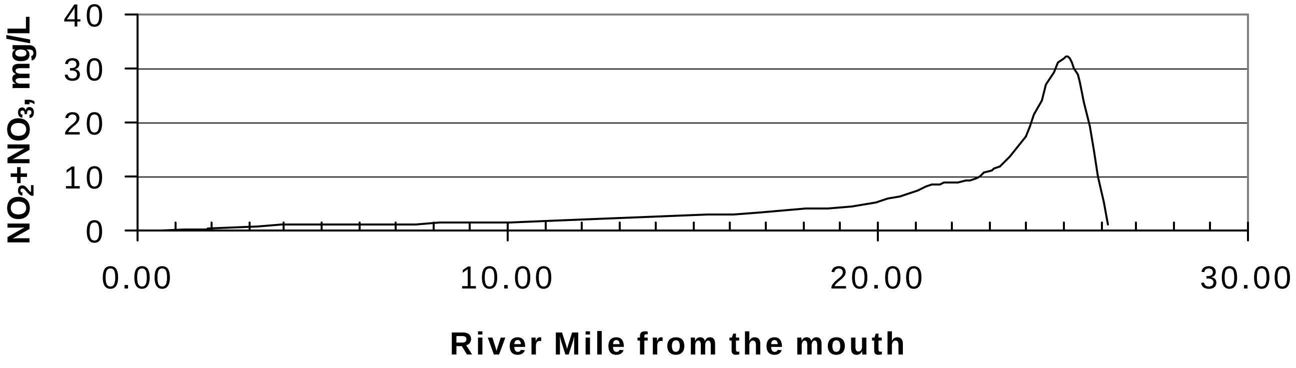

Figure A37: Nitrate (plus Nitrite) vs. River Mile for the Expected Average Flow Scenario

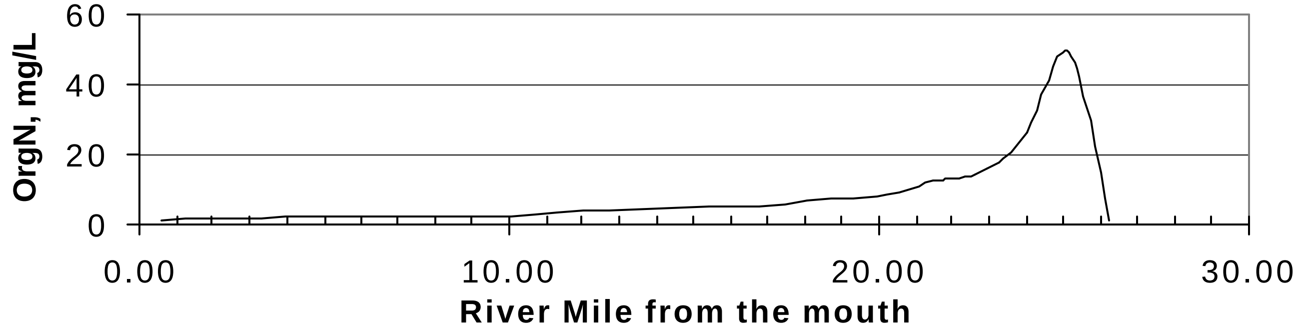

Figure A38: Organic Nitrogen vs. River Mile for the Expected Average Flow Scenario

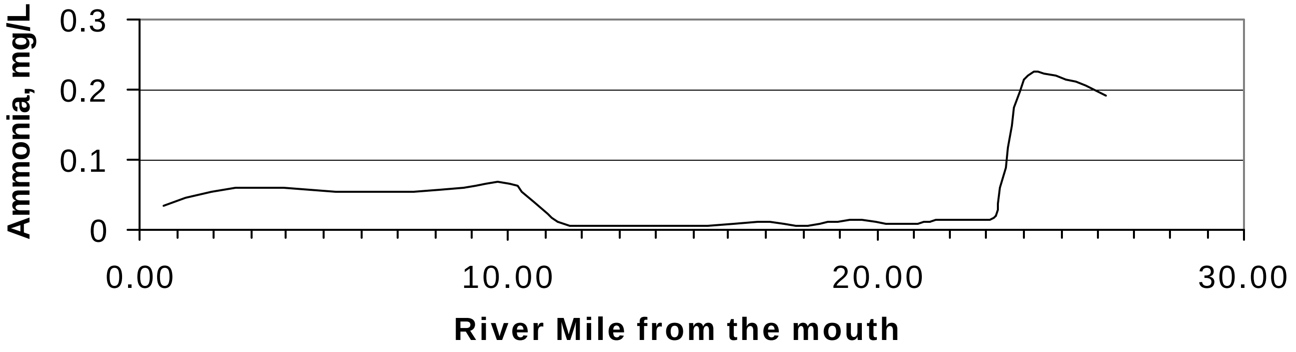

Figure A39: Ammonia vs. River Mile for the Expected Average Flow Scenario

____________ Expected average flow condition

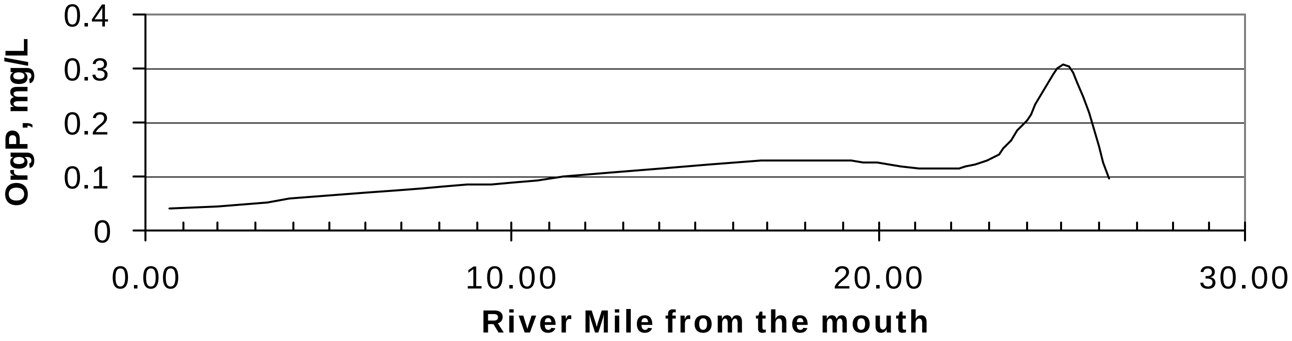

Figure A40: Organic Phosphorus vs. River Mile for the Expected Average Flow Scenario

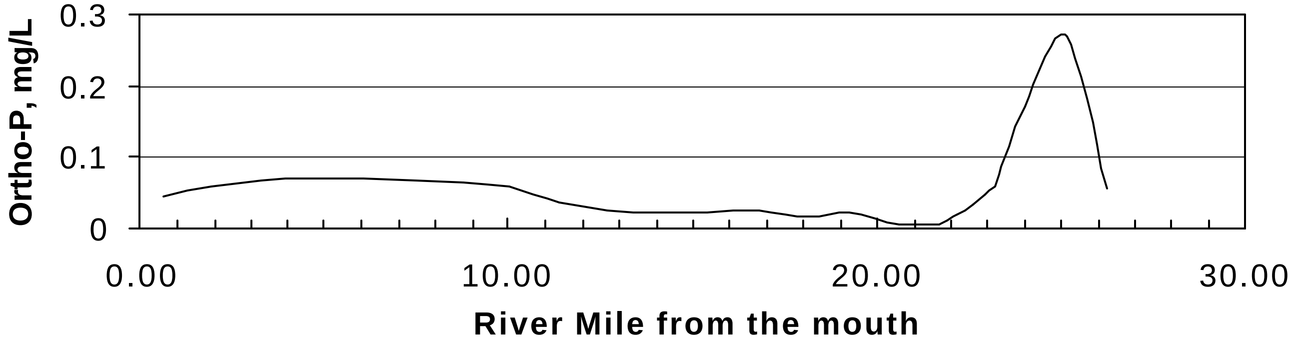

Figure A41: Ortho-Phosphorus vs. River Mile for the Expected Average Flow Scenario

____________ Expected average flow condition

Low Flow TMDL Scenario Results

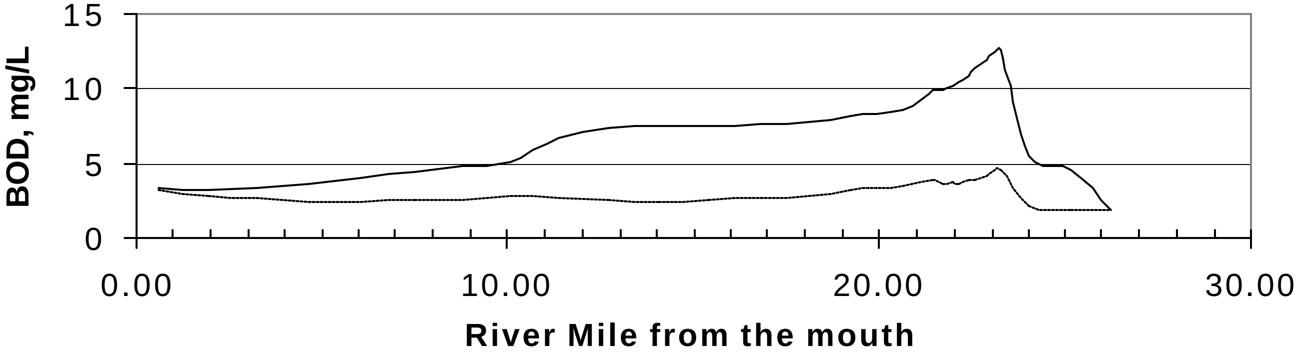

Figure A42: BOD vs. River Mile for the Low flow TMDL scenario

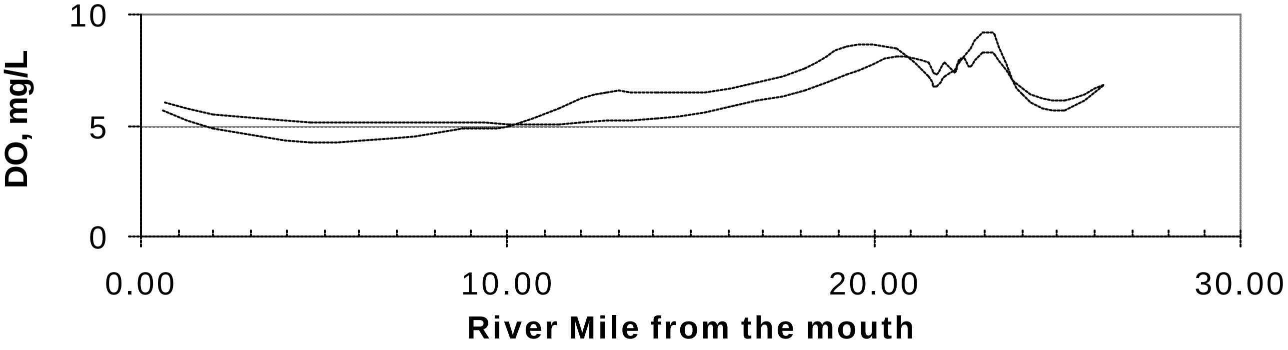

Figure A43: Dissolved Oxygen vs. River Mile for the Low Flow TMDL Scenario

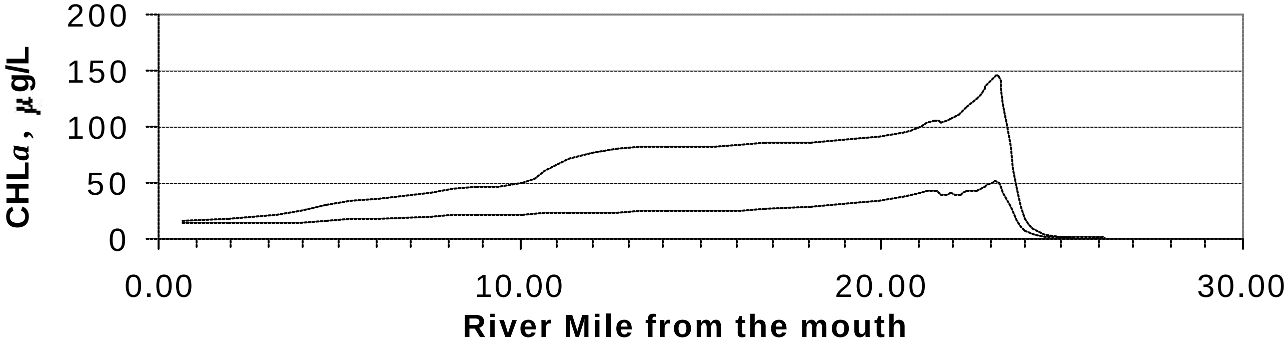

Figure A44: Chlorophyll *a* vs. River Mile for the Low Flow TMDL scenario

___ Low flow Expected condition **……..Low flow TMDL condition**

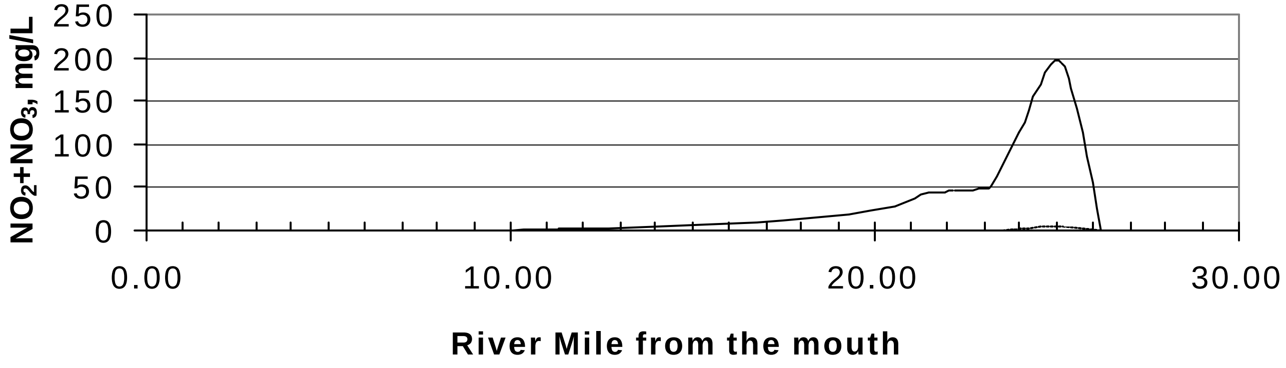

Figure A45: Nitrate (plus Nitrite) vs. River Mile for the Low flow TMDL Scenario

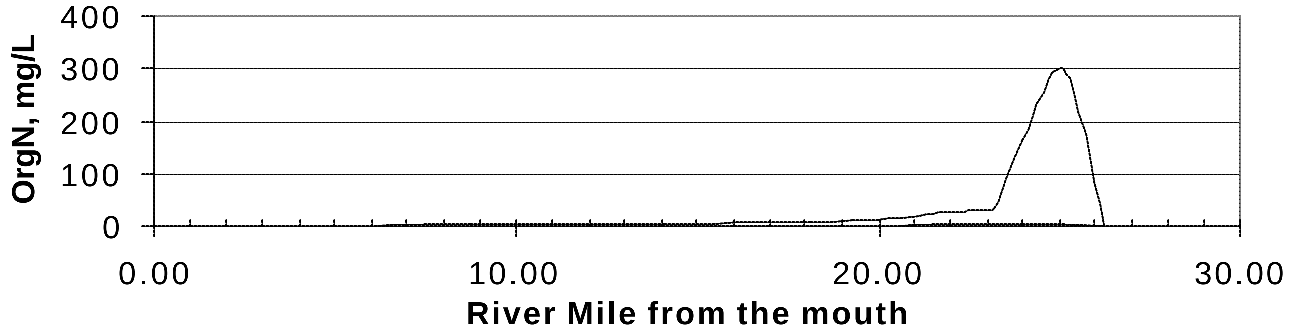

Figure A46: Organic Nitrogen vs. River Mile for the Low Flow TMDL Scenario

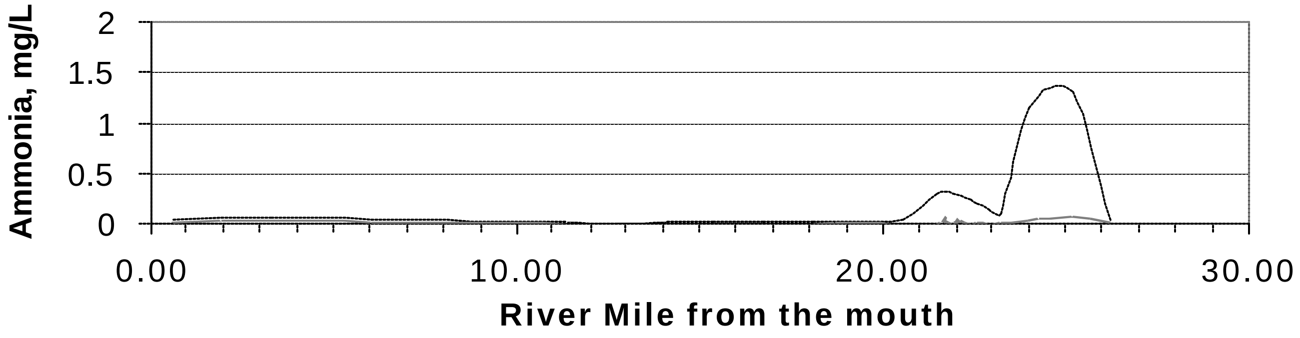

Figure A47: Ammonia vs. River Mile for the Low Flow TMDL Scenario

___ Low flow Expected condition **……..Low flow TMDL condition**

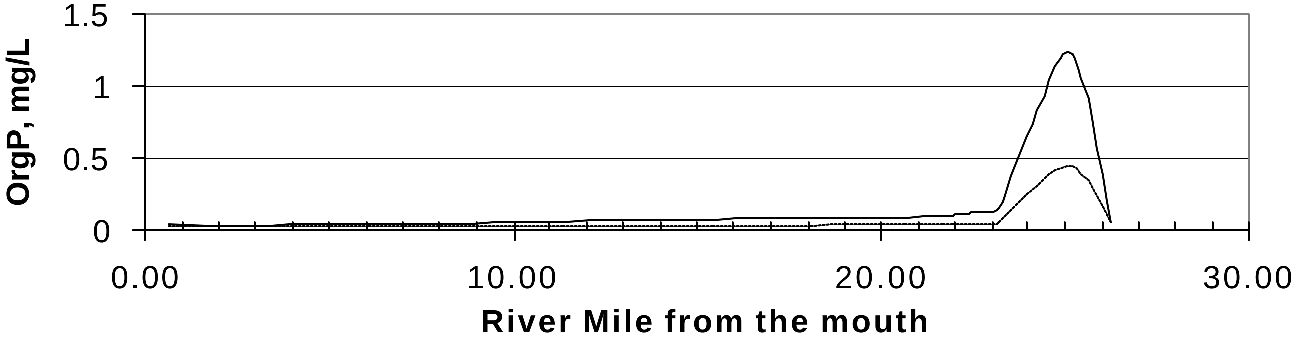

Figure A48: Organic Phosphorus vs. River Mile for the Low Flow TMDL Scenario

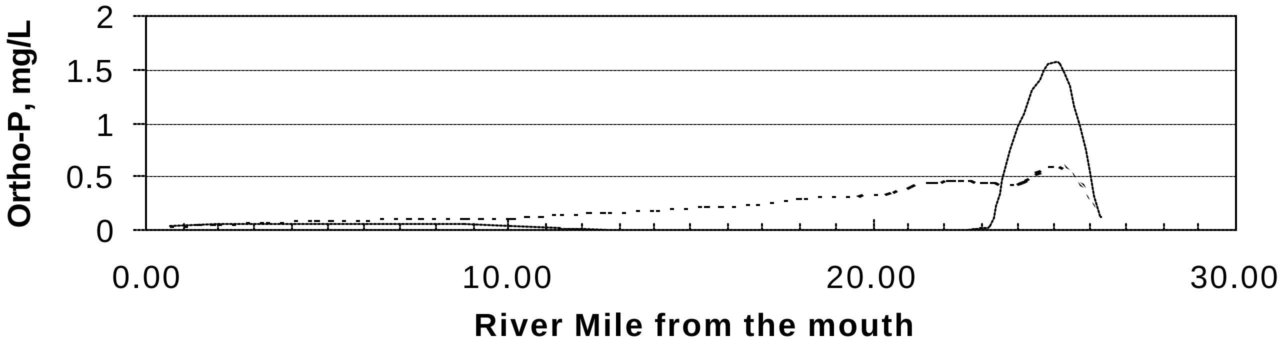

Figure A49: Ortho-Phosphate vs. River Mile for the Low Flow TMDL Scenario

___ Low flow Expected condition **……..Low flow TMDL condition**

Average Flow TMDL Scenario Results

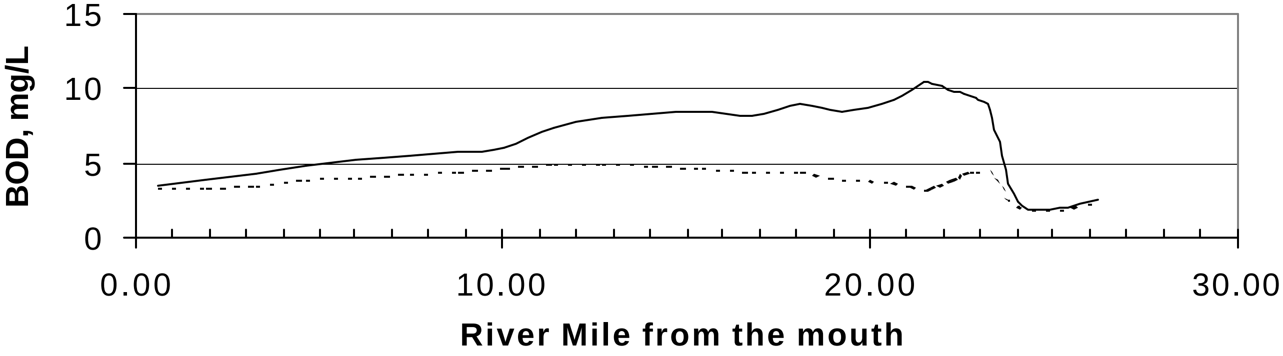

Figure A50: BOD vs. River Mile for the Average Flow TMDL Scenario

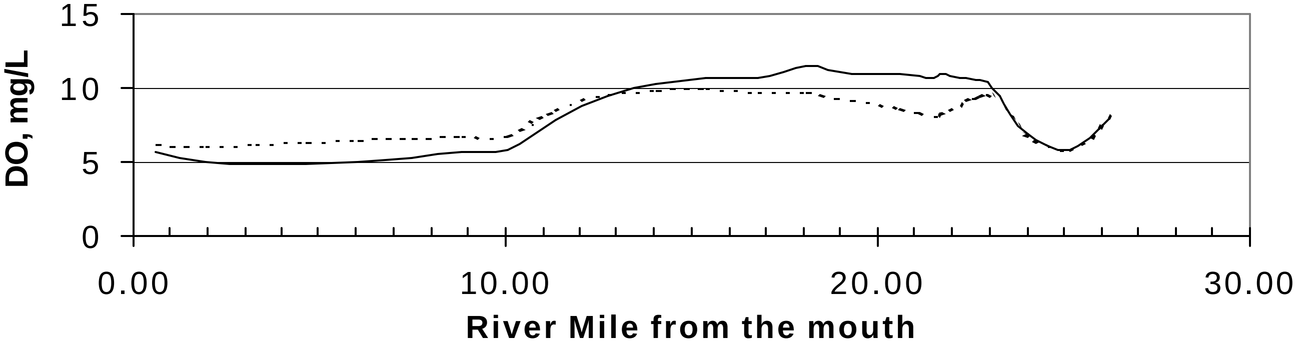

Figure A51: Dissolved Oxygen vs. River Mile for the Average Flow TMDL Scenario

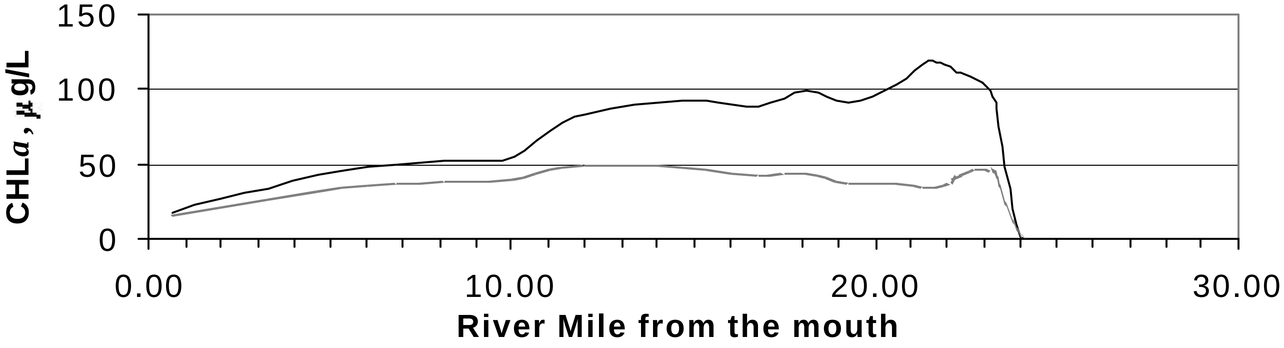

Figure A52: Chlorophyll *a* vs. River Mile for the Average Flow TMDL Scenario

___ Average flow Expected condition **……. Average flow TMDL condition**

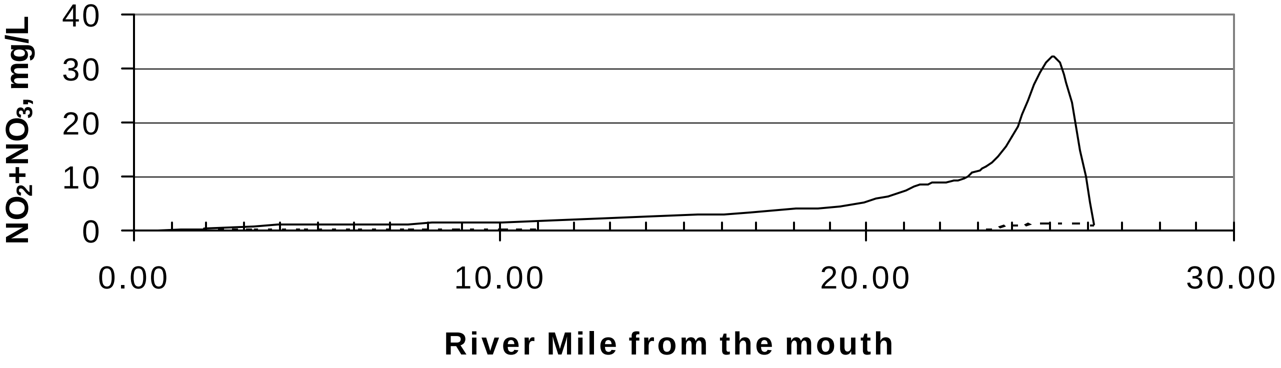

Figure A53: Nitrate (plus Nitrite) vs. River Miles for the Average Flow TMDL Scenario

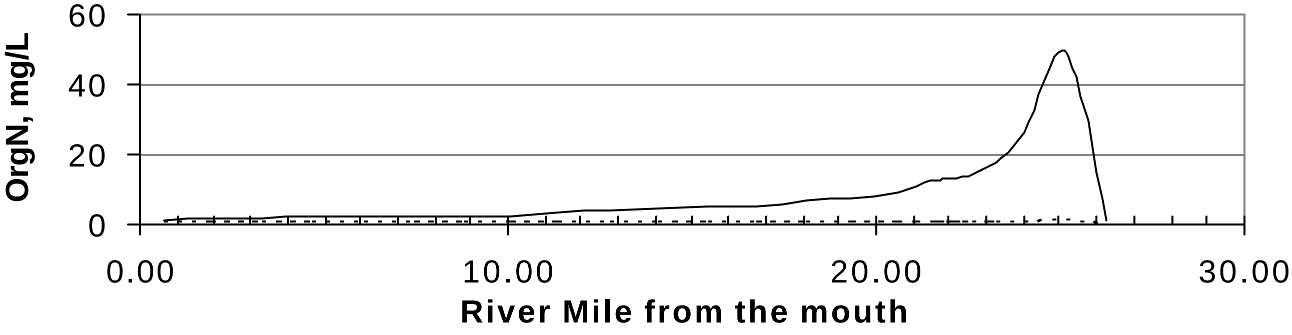

Figure A54: Organic Nitrogen vs. River Mile for the Average Flow TMDL Scenario

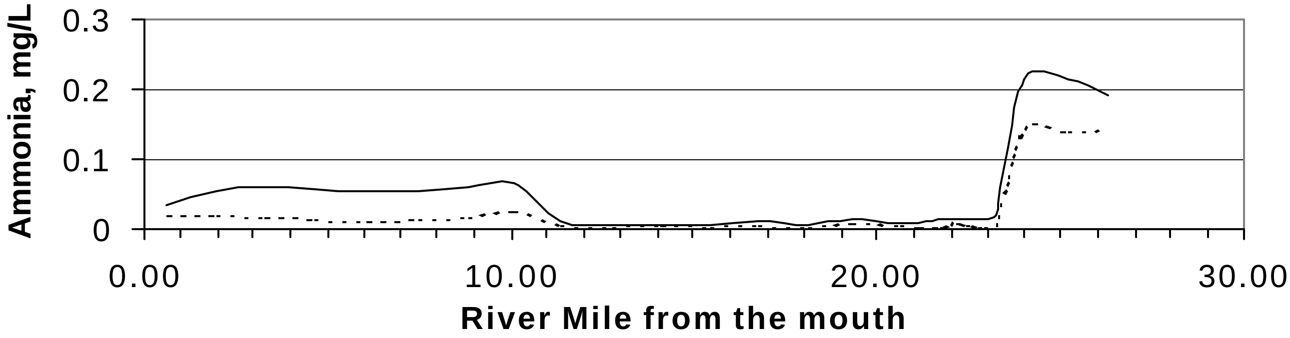

Figure A55: Ammonia vs. River Mile for the Average Flow TMDL Scenario

___ Average flow Expected condition **……. Average flow TMDL condition**

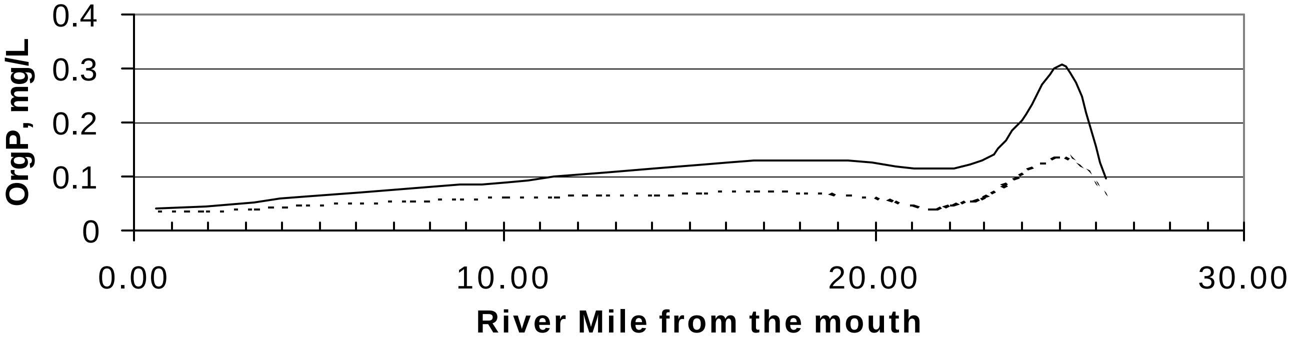

Figure A56: Organic Phosphorus vs. River Mile for the Average Flow TMDL Scenario

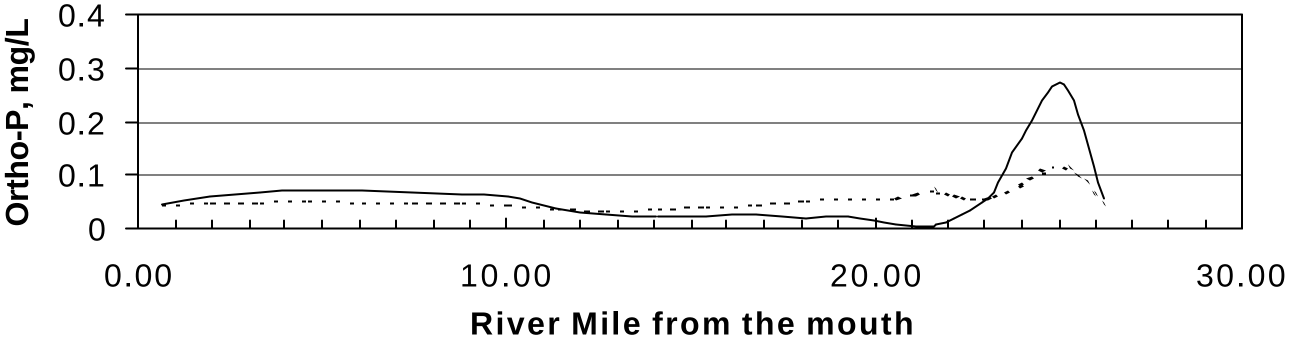

Figure A57: Ortho-Phosphate vs. River Mile for the Average Flow TMDL Scenario

___ Average flow Expected condition **……. Average flow TMDL condition**

REFERENCES

Ambrose, Robert B., Tim A. Wool, John P. Connolly, Robert W. Schanz. *WASP4, a Hydrodynamic and Water Quality Model: Model Theory, User's Manual, and Programmer's Guide*. Environmental Research Laboratory, Office of Research and Development, EPA 600/3-87/039, Athens, GA. 1988.

Cerco, Carl F. *Water Quality in a Virginia Potomac Embayment: Gunston Cove.* College of William and Mary, Virginia Institute of Marine Science, Glouster Point, Virginia. April 1985.

Clark L. J., and S. E. Roesh, *Assessment of 1977 Water Quality Conditions in the Upper Potomac Estuary*. U.S. EPA Annapolis Field Office, Annapolis Maryland. EPA 903/9-78-008, 1978.

Di Toro, D.M., J.J. Fitzpatrick, and R.V. Thomann. *Documentation for Water Quality Analysis Simulation Program (WASP) and Model Verification Program (MVP).* EPA/600/3-81-044. 1983.

Domotor, Diana K., Michael S. Haire, Narendra N. Panday, and Harry V. Wang. *Mattawoman Creek Water Quality Model*. Technical Report No. 64, Maryland Department of the Environment, Water Management Administration, Modeling and Analysis Division. October 1987.

Lung, W. S. *Water Quality Modeling of the Patuxent Estuary*. Final Report to the Maryland Department of the Environment, Water Management Administration, Chesapeake Bay and Special Projects Program, Baltimore, MD. 1993.

Haire, M. S., and N. N. Panday, "Quality Assurance/ Quality Control Plan: Water Quality Assessment of the Mattawoman Creek and nearby Potomac Estuary," Office of Environmental Programs, State of Maryland, April 1985.

Maryland Department of the Environment, Maryland Point Source Database, January, 1998.

Panday, Narendra N., and Michael S. Haire. *Water Quality Assessment of Mattawoman Creek and the Adjacent Potomac River: Summer 1985.* Technical Report No. 52, Water Management Administration, Modeling and Analysis Division, Maryland Office of Programs, Department of Health and Mental Hygiene. September 1986.

Thomann, Robert V., John A. Mueller. *Principles of Surface Water Quality Modeling and Control.* HarperCollins Publisher Inc., New York, 1987.

Thomann R. V., and J. J. Fitzpatrick. *Calibration and Verification of a Mathematical Model of the Eutrophication of the Potomac Estuary*. HydroQual, Inc. Final Report Prepared for the D.C. Department of Environmental Services, 1982.

U.S. EPA Chesapeake Bay Program. *Chesapeake Bay Program: Watershed Model Application to Calculate Bay Nutrient Loadings: Final Findings and Recommendations*. and Appendicies, 1996.

U.S. EPA. *Technical Guidance Manual for Developing Total Maximum Daily Loads, Book 2: Streams and Rivers, Part 1: Biochemical Oxygen demand Dissolved Oxygen and Nutrients/Eutrophication.* OW/OWEP and OWRS, Washington, D.C., March, 1997.