MODELING FRAMEWORK

The computational framework chosen for the modeling of water quality of the Town Creek 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.*, 1993). EUTRO5.1 is the component of WASP5.1 that is applicable for modeling eutrophication, incorporating eight water quality constituents in the water column (Figure A2) and sediment bed. Town Creek Eutrophication Model (TCEM) is the Town Creek eutrophication model that was prepared and used for this TMDL analysis.

INPUT REQUIREMENTS [1]

Model Segmentation and Geometry

The spatial domain of the Town Creek Eutrophication Model (TCEM) extends from the confluence of the Tred Avon River and the Town Creek for about 1,930 meters (1.2 miles) to the creek's headwaters near the intersection of Maryland's Route 333 crossing. Following a review of the water quality monitoring locations for Town Creek, which will serve later as reference points for the model matching predicted and observed values. The creek was divided into 14 segments. Figure A8 shows the model segmentation for the development of the TCEM. Table A7 lists the volumes, characteristic lengths, and interfacial areas of the fourteen segments.

WATER QUALITY MONITORING

The Maryland Department of the Environment (MDE), Field Operations Program conducted intensive water quality surveys of Town Creek in July, and twice in August 1998 from a total of ten sampling locations. Eight of these monitoring locations are strategically positioned in Town Creek, one in the Tred Avon River, and one at the Wastewater Treatment Plant (WWTP) as shown in Figure A12. The July 8 data was used to calibrate the water quality model of Town Creek during low flow conditions, and the August 17 data was used to verify the calibrated

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. 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 |

model. Table A5 lists low flow water quality intensive survey data, and Figure A3 through Figure A7 present Town Creek water quality profiles.

Freshwater Flows

Town Creek is fed by relatively small headwater tributaries with low or zero flows during dry weather months. Freshwater flows were obtained using calculated run-off rate from the average 7-day, 10-year flows of two USGS gages #01489000 - Faulkner Branch, Federalsburg (drainage area equals 7.10 mi^2 and $7Q_{10}$ of 0.2 ft^3/s), and #01490000 - Chicamacomico River, Salem (drainage area equals 15 mi^2 and $7Q_{10}$ of 1.2 ft^3/s) located in the vicinity of the Town Creek Watershed. The Town Creek drainage basin was delineated into fourteen segments (Figure A8). Each segment drainage area was then multiplied by the run-off rate to obtain the background flow for the segments (See Tables A1 and A3).

Table A1: USGS Gage Stream flow Characteristics Data

USGS Gage	Drainage Area	7Q10 Low Flow	Winter Flow	Average Annual Flow
	mi^2	cfs	cfs	cfs
1489000	7.1	0.20	1.24	0.72
1490000	15.0	1.20	5.30	3.25
Average	11.05	0.7	3.27	1.98
Run-Off Rate		0.06335	0.2959	0.179

The delineated sub watershed shown in Figure A8 contributed a total of 0.059 cfs flows. Based on sub watershed drainage patterns (as illustrated in Figure A8), the flows are introduced into the model segments as shown in Table A3.

The TCEM was calibrated for the low flow conditions corresponding to the dry weather months of July, August, September and October when the water at the creek is expected to be at its lowest.

Table A2: Contribution of Flow from watershed Segments

Segment Number	Estimated Flows into Segments (Drainage Area x Run-Off Rates)					
	Summer Months Flow		Winter Months Flow		Average Annual Flow	
	CFS	M^3/S	CFS	M^3/S	CFS	M^3/S
1	0.0020	0.000056	0.009	0.0002656	0.00576	0.00016
2	0.0037	0.000104	0.017	0.0004866	0.01055	0.00030
3	0.0023	0.000064	0.011	0.0002991	0.00648	0.00018
4	0.0022	0.000061	0.010	0.0002852	0.00618	0.00017
5	0.0015	0.000042	0.007	0.0001990	0.00431	0.00012
6	0.0015	0.000042	0.007	0.0001977	0.00429	0.00012
7	0.0020	0.000054	0.009	0.0002554	0.00554	0.00016
8	0.0142	0.000396	0.066	0.0018529	0.04017	0.00112
9	0.0031	0.000086	0.014	0.0004028	0.00873	0.00024
10	0.0018	0.000049	0.008	0.0002329	0.00505	0.00014
11	0.0036	0.000102	0.017	0.0004769	0.01034	0.00029
12	0.0135	0.000376	0.063	0.0017601	0.03816	0.00107
13	0.0026	0.000072	0.012	0.0003407	0.00739	0.00021
14	0.0051	0.000144	0.024	0.0006729	0.01459	0.00041
	0.059	0.0016543	0.276	0.00773	0.167536	0.00469

Table A3: Watershed Background Flow Distribution into Model Segments

Watershed Background Flow Distribution	Low Flow		Average Annual Flow	
Model Segment	cfs	**(m^3/s)**	cfs	**(m^3/s)**
8	0.016	0.0004513	0.046	0.001280
9	0.009	0.0002539	0.026	0.000720
12	0.024	0.0006822	0.069	0.001934
14	0.010	0.0002668	0.027	0.000757
Total	**0.059**	**0.001654**	**0.168**	**0.00469**

Table A4: Nonpoint Source Concentrations for the Low Flow Model Calibration

Segment Number	NH4 *mg/l*	NO_{23} *mg/l*	PO_4 *mg/l*	CHL *a* *μg/l*	CBOD *mg/l*	DO *mg/l*	ON *mg/l*	OP *mg/l*
1	0.090	0.011	0.042	11.7	1.05	6.0	0.45	0.005
2	0.054	0.012	0.054	11.7	0.45	5.9	0.52	0.006
3	0.046	0.017	0.055	10.7	1.50	6.0	0.54	0.007
4	0.046	0.017	0.055	10.7	1.50	6.0	0.54	0.007
5	0.032	0.018	0.070	11.7	1.35	6.0	0.58	0.001
6	0.075	0.014	0.073	10.0	1.65	5.9	0.57	0.006
7	0.075	0.014	0.073	10.0	1.65	5.9	0.57	0.006
8	0.075	0.014	0.073	10.0	1.65	5.9	0.57	0.006
9	0.083	0.021	0.070	12.0	1.95	5.8	0.54	0.001
10	0.083	0.021	0.070	12.0	1.95	5.8	0.54	0.001
11	0.075	0.014	0.073	10.0	1.65	5.9	0.57	0.006
12	0.075	0.014	0.073	10.0	1.65	5.9	0.57	0.006
13	0.053	0.033	0.100	23.6	2.55	4.8	0.85	0.001
14	0.096	0.085	0.137	16.4	2.70	4.2	0.92	0.001

Point and Nonpoint Source Loadings

The Town of Oxford WWTP is the only point source contributing loads to Town Creek. Nonpoint source loadings were estimated for low flow conditions from the product of observed concentrations and the estimated respective segment flows. These loads account for all sources because they are observed loads. Concentrations (Table A4) used for the determination of loads for the low flow model calibration came from the observed in-stream water quality data within the Town Creek basin.

Data from station OXF8, located near the confluence of Town Creek with the Tred Avon River, was used as the boundary concentration for segment one, and data from station OXF1, near the WWTP was used as a boundary concentration for segment fourteen. The boundary concentrations for the remaining model segments were based on data associated with the corresponding monitoring station.

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_{23}), 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 algal growth, that can affect chlorophyll *a* levels and dissolved oxygen concentrations.

Environmental Conditions

Eight environmental parameters (see Table A9) were used for developing the Town Creek model: solar radiation and photoperiod (Table A8), temperature (T), extinction coefficient (K_e), salinity, sediment oxygen demand (SOD), sediment ammonia flux (FNH_3), and sediment phosphate flux (FPO_4). Initial values of SOD, FNH_3 and FPO_4 were estimated then refined through the calibration of the model. Different SOD values were estimated for different TCEM segments based on observed environmental conditions and literature values. The highest SOD values were assumed to occur in the upper headwater, near the Town of Oxford WWTP, where the dispersion coefficient is low and more sediment deposition would usually occur. A maximum SOD value of 1.6 g O_2/m^2day was used.

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

$$K_e = \frac{1.95}{D_s} = \frac{1.95}{0.4213} = 4.629$$

where:

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

Kinetic Coefficients

The water column kinetic coefficients are universal constants used in the TCEM model. They are formulated to characterize the kinetic interactions among the water quality constituents. The initial values were taken from past modeling studies of the 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 A10.

MODEL CALIBRATION & VERIFICATION

TCEM calibration and verification was accomplished using the observed stream water quality data. It consists of two phases: the exchange or transport, and water quality calibrations. The stream salinity data was employed for the exchange or transport calibration. Since the water quality parameter of primary concern for these TMDLs is the in-stream dissolved oxygen, it was decided to use the downstream dissolved oxygen concentrations for the water quality calibration phase. Prior to beginning the model calibrations, all the available water quality data were analyzed to select the ones that are good representative of the watershed system. A close comparison of the water quality data for the survey periods of July 8, August 17 and 26, 1998 shows the July 8, 1998 data to be a better representative of Town Creek System. In all three surveys, salinity gradient is most evident in the July 8, 1998 survey with a maximum concentration of 7.2 ppt reported at the mouth of Town Creek, which decreased to 6.8 ppt toward the headwaters. The water quality calibration phase was followed by verification, using the August 17 data. The salinity and kinetic calibration results are presented in Figure A9, Figure A10 and Figure A13 through Figure A18.

Dispersion Coefficients

The dispersion coefficients were calibrated using the TCEM and the in-stream water quality data for July 8, 1998. The TCEM was set up to simulate 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 at the tidal boundary at the mouth of the creek. For model execution, salinities at all boundaries except the tidal boundary were set to zero. Flows were obtained from two USGS gages near the basin (see section on freshwater flows for more detail). Figure A11 shows the results of the dispersion coefficients calibration for the low flow conditions, and are listed in Table A7.

SENSITIVITY ANALYSIS

Results of sensitivity runs (see Figure A27) showed that when TN is reduced 50% leaving TP alone, chlorophyll *a* value increases to the 48 µg mark. When the case is reversed, with TP reduced by 50% and leaving TN alone, chlorophyll *a* jumps to the 68 µg mark. Similarly, when TN is reduced 50%, minimum dissolved oxygen value of 4.48 mg/l is obtained. When TN is left alone and TP is reduced by 50%, minimum dissolved oxygen improves to 4.59 mg/l.

SYSTEM RESPONSE

The EUTRO5.1 model of Town Creek was applied to several different point and nonpoint sources loading conditions under low and average annual stream flow conditions to project the impacts on dissolved oxygen, nutrients and on algal production, represented by chlorophyll *a*. By simulating various stream flows, the analysis accounts for seasonality.

Model Run Descriptions

<u>Baseline Conditions</u>

The baseline investigation consists of two schemes (Low and Average Annual Flow) that represent Town Creek under critical steady-state conditions, with the WWTP discharging at permitted full capacity loadings.

Scenario 1 (Low Flow)**:** Represents the baseline conditions of the creek under current loading conditions during low flow. Assumes 7-day consecutive lowest flow expected to occur once every 10 years, which was estimated using two nearby USGS gages 01489000 and 01490000 (see computation details in Tables A1 and A2). Assumes current summertime monthly NPDES permitted flow of 208,000 gallons per day with loads based on BOD_5 = 30 mg/l, TN = 18 mg/l, TP = 2.0 mg/l and DO = 5.0 mg/l. Assumes nonpoint source loads as computed from the product of observed 1998 average water quality data concentrations and the estimated sub-watershed low flow. These loads account for all background and human-induced sources because they are based on observed concentrations. All environmental parameters used for scenario 1 remained the same as in the low flow calibration.

Scenario 2 (Average Annual Flow): Assumes average annual stream flow that was estimated using two nearby USGS gages 01489000 and 01490000 as described above. Assumes maximum plant design flow capacity of 208,000 gallons per day with loads based on BOD_5 = 30 mg/l, TN = 18 mg/l, TP = 2.0 mg/l and DO = 5.0 mg/l. Assumes nonpoint source loads as computed from the product of observed 1998 average water quality data concentrations and the estimated sub watershed average annual flow. All environmental parameters remain the same as in the low flow calibration.

Scenario 3 (Low Flow without WWTP): Represents the creek's natural conditions during low flow. WWTP loads were intentionally removed. Assumes 7-day consecutive lowest flow expected to occur once every 10 years, estimated by using two nearby USGS gages 01489000 and 01490000 as described above. Nonpoint source loads are the same as in Scenario 1, and based on MDE's 1998 observed data. All the environmental parameters remained the same. The initial condition values were assumed to be the same as for the Scenario 1.

Future Condition TMDL

In the creek's future conditions, three iterative model scenarios involving point source and nonpoint source loadings of BOD, TN and TP reductions were explored to determine the maximum allowable loads that will maintain 5.0 mg/l minimum dissolved oxygen standards and chlorophyll a concentrations below the 50 µg/l marks. Scenario 4 and Scenario 5 show the water quality responses in Town Creek for the maximum allowable loads for low and average annual flows respectively. Scenario 6 examines the impact of no WWTP discharge during average annual flows to see if there are water quality violations.

Scenario 4 (Low Flow): Represents improved conditions associated with the maximum allowable loads to the stream during critical low flow. The flow was the same as in Scenario 1. The point source (PS) loads were reduced by 50% and the nonpoint source (NPS) loads were reduced by 35% from the first scenario (baseline scenario) to meet the dissolved oxygen criterion of no less than 5.0 mg/l, and chlorophyll *a* concentration of no more than 50 µg/l. The WWTP's effluent DO was increased from 5.0 to 6.0 mg/l. A margin of safety 25% of the difference between the weekly and monthly (PS) limits, and 5% (NPS) were included in the load calculation. All environmental parameters and kinetic coefficients used for the calibration of the model remained the same as in Scenario 1.

<u>Scenario 5 (Average Annual Flow):</u> Represents improved conditions associated with the maximum allowable loads to the stream during average annual flow. The point source and nonpoint source loads reductions are the same as in Scenario 4 above. Point source (PS) and nonpoint source (NPS) margin of safety as computed in the Scenario 4 were included in the load calculation. All environmental parameters and kinetic coefficients used for the calibration of the model remained the same as in the Scenario 1.

<u>Scenario 6 (Average Annual Flow without WWTP):</u> Represents the creek's conditions associated with the average annual flow when the WWTP loads are intentionally removed. The point source loads are the same as Scenario 2, and are based on the 1998 observed water quality data. All environmental parameters and kinetic coefficients used for the calibration of the model remained the same as in the Scenario 1.

Model Results and Observations

Figure A19 through Figure A21 show low flow baseline conditions scenario results. The results indicate violations of water quality standards for dissolved oxygen and chlorophyll a concentrations.

Figure A22 through Figure A24 show average annual flow baseline conditions scenario results. The results also show violations of water quality standards for dissolved oxygen and chlorophyll a concentrations near the Town of Oxford WWTP.

Figure A25 shows future low flow TMDL scenario results, with low flow baseline scenario (solid lines) and low flow natural conditions scenario (dots connected lines) for comparisons. The results show that the required 5.0 mg/l minimum DO and chlorophyll a concentrations of less than 50 μg/l are met.

Figure A26 shows future average annual flow TMDL scenario results. Similarly, the results indicate that violations of water quality standards no longer exist downstream of the WWTP.

Table A13 on page A28 shows baseline (scenario 1) nonpoint source and point source mass loadings.

CHLOROPHYLL_A REDUCTION - RATIONALE CALCULATION

Observed Data- 7/8, 8/17 & 8/26 Average

SEG NO.	OP (Mg/l)	ORTH-P0_4 (Mg/l)	TP OP + ORTH-P0_4 (Mg/l)	TN (ON+NH_4+NO_{23}) (Mg/l)	NO_3 (Mg/l)	NO_2 (Mg/l)	NH_4 (Mg/l)	ON (Mg/l)
1	0.003	0.056	0.059	0.611	0.006	0.002	0.033	0.570
2	0.004	0.056	0.060	0.637	0.007	0.003	0.022	0.605
3	0.004	0.066	0.070	0.832	0.007	0.002	0.020	0.803
4	0.004	0.066	0.070	0.832	0.007	0.002	0.020	0.803
5	0.004	0.066	0.070	0.682	0.010	0.002	0.021	0.649
6-8	0.004	0.070	0.074	0.685	0.006	0.002	0.028	0.649
9-10	0.002	0.065	0.067	0.637	0.008	0.002	0.031	0.596
11-12	0.004	0.070	0.074	0.685	0.006	0.002	0.028	0.649
13	0.002	0.098	0.100	0.815	0.012	0.003	0.024	0.776
14	0.002	0.098	0.100	0.784	0.003	0.004	0.039	0.738

Ratio of Carbon-to-Chlorophyll_a = $\left[\frac{C}{Chla}\right]$ used in the model $\longrightarrow$ 50

Ratio of Chlorophyll_a to Nitrogen in phytoplankton = $\left[\frac{Chla}{N}\right]$ used in the model $\longrightarrow$ 0.25 mg/N/mgC

Ratio of Chlorophyll_a to Phosphorus in phytoplankton = $\left[\frac{Chla}{P}\right]$ used in the model $\longrightarrow$ 0.025 mg/P/mgC

Calculations

Potential Chlorophyll_a based on Nitrogen = $\left[\frac{N}{C}\right] \times \left[\frac{C}{Chla}\right]$

$\left[\frac{N}{Chla}\right] = 12.5$

$\left[\frac{Chla}{N}\right] = 0.08$

Potential Chlorophyll_a based on Total Phosphorus = $\left[\frac{P}{C}\right] \times \left[\frac{C}{Chla}\right]$

$\left[\frac{P}{Chla}\right] = 1.25$

$\left[\frac{Chla}{P}\right] = 0.8$

<u>FIRST SCENARIO</u> (baseline Low Flow Condition with maximum design flow)

Based on Nitrogen

SEG NO.	Potential (Chlorophyll_a) growth based on available Nitrogen (ug/l)	Potential (Chlorophyll_a) growth based on available Phosphorus (ug/l)	Difference in Chla concentration between baseline / reduced baseline runs	% Chla reduction from Segment boundaries
1	49	47	17.1	35
2	51	48	17.8	35
3	67	56	23.3	35
4	67	56	23.3	35
5	55	56	19.1	35
6-8	55	59	19.2	35
9-10	51	54	17.8	35
11-12	55	59	19.2	35
13	65	80	22.8	35
14	63	80	22.0	35

<u>Third SCENARIO</u> - Load Reduction 50% in (baseline Low Flow Condition with maximum plant design Flow)

Based on Phosphorus

SEG NO.	Potential (Chlorophyll_a) growth based on available Nitrogen (ug/l)	Potential (Chlorophyll_a) growth based on available Phosphorus (ug/l)	Difference in Chla concentration between baseline / reduced baseline runs	% Chla reduction from Segment boundaries
1	32	31	16.5	35
2	33	31	16.8	35
3	43	36	19.6	35
4	43	36	19.6	35
5	35	36	19.6	35
6-8	36	38	20.7	35
9-10	33	35	18.8	35
11-12	36	38	20.7	35
13	42	52	28.0	35
14	41	52	28.0	35

Figure A1: Chlorophyll a Reduction – Rationale Calculation

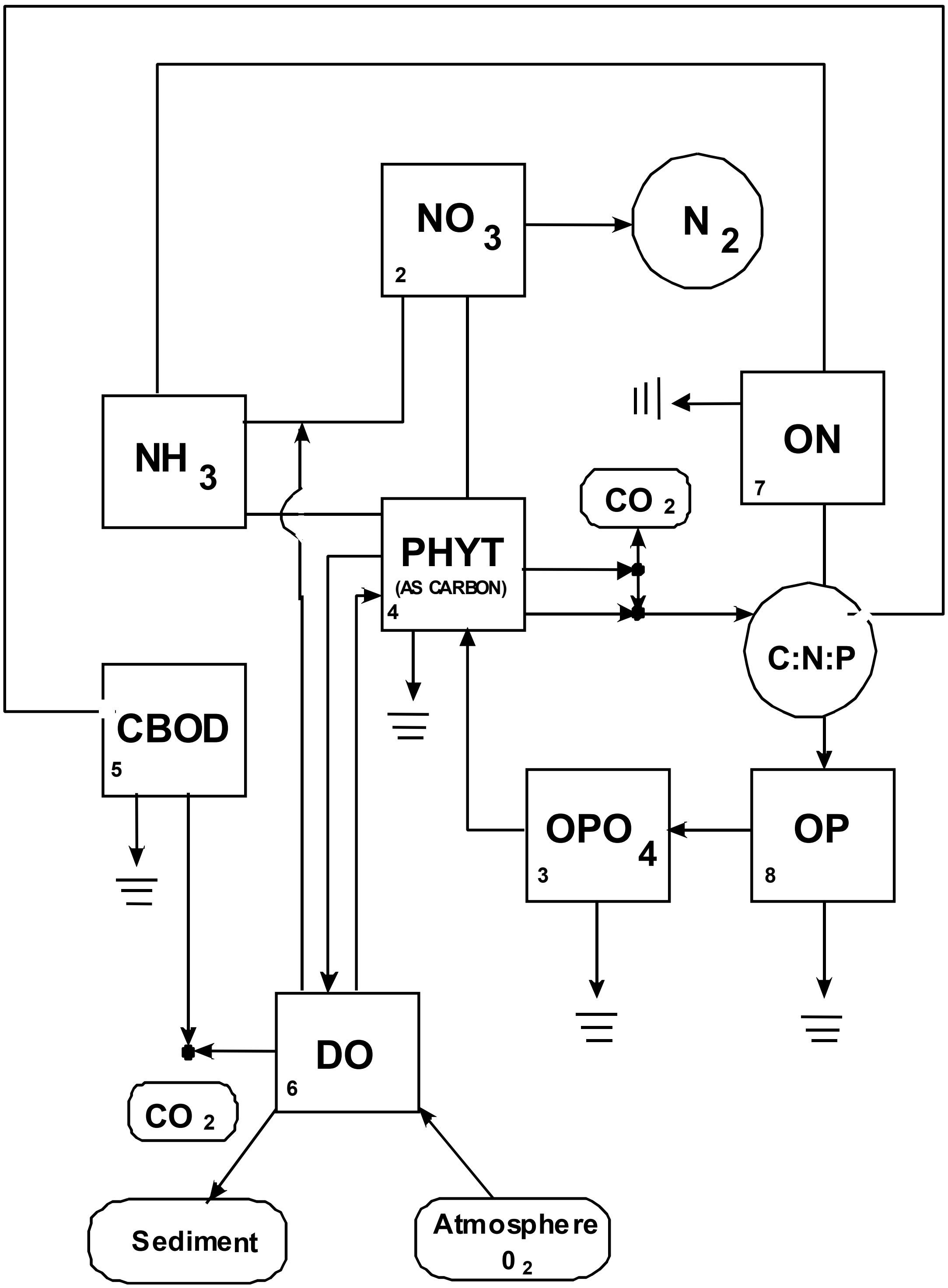


Figure A2: State Variables and Kinetic Interactions in EUTRO5

Table A5: Town Creek Field Observed Water Quality Data

AVG. W Q DATA- OXFORD 7/08, 08/17 & 08/26 1998											ON		NO_2 /		NO_3			Ortho - PO_4
Sample Station		Water Temp °C	Depth Meters	Secchi Depth (M)	Salinity	DO Mg/l	BOD_5 Mg/l	TN Mg/l	NH_4 Mg/l	WTKN Mg/l	(WTKN - NH_4)	CHLA_A Ug/l	NO_3 Mg/l	NO_2 Mg/l	(NO_2/NO_3) -NO_2 Mg/l	OP Mg/l	TP Mg/l	(TP-OP) Mg/l
OXF1	07/08/1998	26.0	1.0		6.8	4.20	1.80	1.113	0.096	1.020	0.924	16.4	0.093	0.008	0.085	0.000	0.137	0.137
14	08/17/1998	27.7	0.8	0.04	9.9	4.95	1.60	0.517	0.008	0.510	0.502	15.0	0.007	0.002	0.005	0.003	0.073	0.070
	08/26/1998	26.7	0.9	0.30	10.0	3.40	0.80	0.810	0.012	0.800	0.788	12.2	0.010	0.002	0.008	0.003	0.090	0.087
	AVG.	**26.8**	**0.9**	**0.17**	**8.9**	**4.18**	**1.40**	**0.813**	**0.039**	**0.777**	**0.738**	**14.5**	**0.037**	**0.004**	**0.033**	**0.002**	**0.100**	**0.098**
OXF2	07/08/1998	25.5	0.9		6.9	4.80	1.70	0.940	0.053	0.900	0.847	23.6	0.040	0.007	0.033	0.000	0.100	0.100
13	08/17/1998	27.8	0.8	0.40	9.9	6.20	1.00	0.705	0.008	0.700	0.692	16.1	0.005	0.002	0.003	0.003	0.100	0.097
	08/26/1998	26.9	0.9	0.30	10.1	4.40	1.90	0.802	0.012	0.800	0.788	19.2	0.002	0.001	0.001	0.003	0.100	0.097
	AVG.	**26.7**	**0.9**	**0.35**	**9.0**	**5.13**	**1.53**	**0.816**	**0.024**	**0.800**	**0.776**	**19.6**	**0.016**	**0.003**	**0.012**	**0.002**	**0.100**	**0.098**
OXF3	07/08/1998	26.0	1.4		7.1	6.00	0.90	0.631	0.032	0.610	0.578	11.7	0.021	0.003	0.018	0.000	0.070	0.070
5, 10	08/17/1998	27.9	1.0	0.50	9.8	6.13	2.40	0.593	0.029	0.580	0.551	14.1	0.013	0.003	0.010	0.009	0.070	0.061
	08/26/1998	27.2	1.1	0.40	10.1	4.90	1.20	0.804	0.003	0.800	0.797	11.2	0.004	0.001	0.003	0.003	0.070	0.067
	AVG.	**27.0**	**1.2**	**0.45**	**9.0**	**5.68**	**1.50**	**0.676**	**0.021**	**0.663**	**0.642**	**12.3**	**0.013**	**0.002**	**0.010**	**0.004**	**0.070**	**0.066**
OXF4	07/08/1998	26.0	1.0		7.0	5.80	1.30	0.644	0.083	0.620	0.537	12.0	0.024	0.003	0.021	0.000	0.070	0.070
9	08/17/1998	27.8	1.0	0.60	9.8	6.90	1.20	0.576	0.008	0.570	0.562	14.7	0.006	0.003	0.003	0.002	0.070	0.068
	08/26/1998	27.5	1.0	0.40	10.1	5.30	1.00	0.690	0.002	0.690	0.688	14.2	0.000	0.000	0.000	0.003	0.060	0.057
	AVG.	**27.1**	**1.0**	**0.50**	**9.0**	**6.00**	**1.17**	**0.637**	**0.031**	**0.627**	**0.596**	**13.6**	**0.010**	**0.002**	**0.008**	**0.002**	**0.067**	**0.065**
OXF5	07/08/1998	26.0	0.9		7.1	5.90	1.10	0.657	0.075	0.640	0.565	10.0	0.017	0.003	0.014	0.006	0.079	0.073
6-8,11,12	08/17/1998	28.9	0.8	0.50	9.8	8.75	1.10	0.675	0.008	0.670	0.662	13.8	0.005	0.002	0.003	0.002	0.078	0.076
	08/26/1998	27.6	1.0	0.30	10.1	5.50	0.70	0.720	0.001	0.720	0.719	11.9	0.000	0.000	0.000	0.003	0.063	0.060
	AVG.	**27.5**	**0.9**	**0.40**	**9.0**	**6.72**	**0.97**	**0.684**	**0.028**	**0.677**	**0.649**	**11.9**	**0.007**	**0.002**	**0.006**	**0.004**	**0.073**	**0.070**
OXF6	07/08/1998	25.9	1.4		7.1	6.00	1.00	0.611	0.046	0.590	0.544	10.7	0.021	0.004	0.017	0.007	0.062	0.055
3, 4	08/17/1998	27.9	1.0	0.50	9.9	6.63	2.00	0.696	0.008	0.690	0.682	15.6	0.006	0.002	0.004	0.002	0.085	0.083
	08/26/1998	27.5	1.0	0.40	10.1	5.90		1.190	0.007	1.190	1.183	9.5	0.000	0.000	0.000	0.003	0.063	0.060
	AVG.	**27.1**	**1.1**	**0.45**	**9.0**	**6.18**	**1.50**	**0.832**	**0.020**	**0.823**	**0.803**	**11.9**	**0.009**	**0.002**	**0.007**	**0.004**	**0.070**	**0.066**
OXF7	07/08/1998	26.0	1.4		7.1	5.90	0.30	0.586	0.054	0.570	0.516	11.7	0.016	0.004	0.012	0.006	0.060	0.054
2	08/17/1998	28.3	1.2	0.60	9.6	7.30	1.40	0.656	0.008	0.650	0.642	21.2	0.006	0.002	0.004	0.002	0.070	0.068
	08/26/1998	27.3	1.0	0.40	10.1	5.70	0.50	0.666	0.004	0.660	0.656	8.7	0.006	0.002	0.004	0.003	0.050	0.047
	AVG.	**27.2**	**1.2**	**0.50**	**8.9**	**6.30**	**0.73**	**0.636**	**0.022**	**0.627**	**0.605**	**13.9**	**0.009**	**0.003**	**0.007**	**0.004**	**0.060**	**0.056**
OXF8	07/08/1998	26.1	1.9		7.2	6.00	0.70	0.555	0.090	0.540	0.450	11.7	0.015	0.004	0.011	0.005	0.047	0.042
1	08/17/1998	28.2	1.2	0.60	9.9	7.57	1.40	0.736	0.008	0.730	0.722	16.1	0.006	0.002	0.004	0.002	0.080	0.078
	08/26/1998	27.4	1.0	0.50	10.0	5.90	0.60	0.545	0.002	0.540	0.538	9.2	0.005	0.001	0.004	0.003	0.050	0.047
	AVG.	**27.2**	**1.4**	**0.55**	**9.0**	**6.49**	**0.90**	**0.612**	**0.033**	**0.603**	**0.570**	**12.3**	**0.009**	**0.002**	**0.006**	**0.003**	**0.059**	**0.056**
TRED AVON RIVER																		
OXF9	07/08/1998	26.5	2.4		7.2	6.00	1.00	0.593	0.044	0.580	0.536	10.8	0.013	0.003	0.010	0.005	0.049	0.044
	08/17/1998	27.6	2.1	0.70	9.9	6.56	4.00	1.258	0.008	1.250	1.242	41.5	0.008	0.002	0.006	0.002	0.129	0.127
	08/26/1998	27.5	2.1	0.50	10.2	6.20	0.60	0.586	0.005	0.580	0.575	9.7	0.006	0.002	0.004	0.003	0.048	0.045
	AVG.	**27.2**	**2.2**	**0.60**	**9.1**	**6.25**	**1.87**	**0.812**	**0.019**	**0.803**	**0.784**	**20.7**	**0.009**	**0.002**	**0.007**	**0.003**	**0.075**	**0.072**
OXFORD WWTP																		
	07/08/1998	24.6	0.01		0.9	6.80	6.80	4.068	0.047	4.050	4.003	10.1	0.018	0.006	0.012	0.335	1.100	0.765
	08/17/1998	28.0	0.1		1.4	6.90	5.60	4.515	0.042	4.490	4.448	19.9	0.025	0.006	0.019	0.242	0.944	0.702
	08/26/1998	28.3	0.1		0.9	5.00	4.80	2.033	0.041	2.010	1.969	0.5	0.023	0.001	0.022	0.004	0.176	0.172
	AVG.	**27.0**	**0.1**		**1.1**	**6.2**	**5.7**	**3.539**	**0.043**	**3.5**	**3.5**	**10.2**	**0.022**	**0.004**	**0.018**	**0.194**	**0.7**	**0.5**

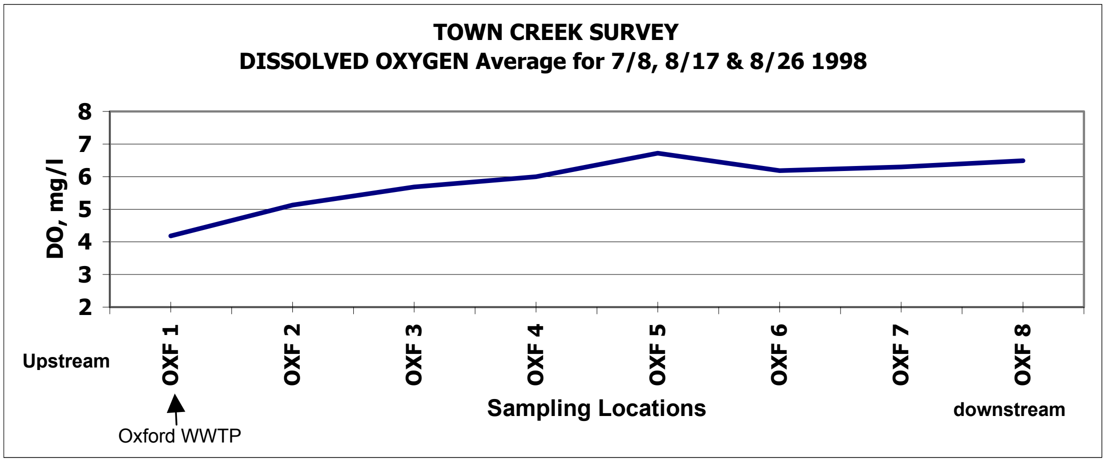


Figure A3: Longitudinal profile of Dissolved Oxygen data

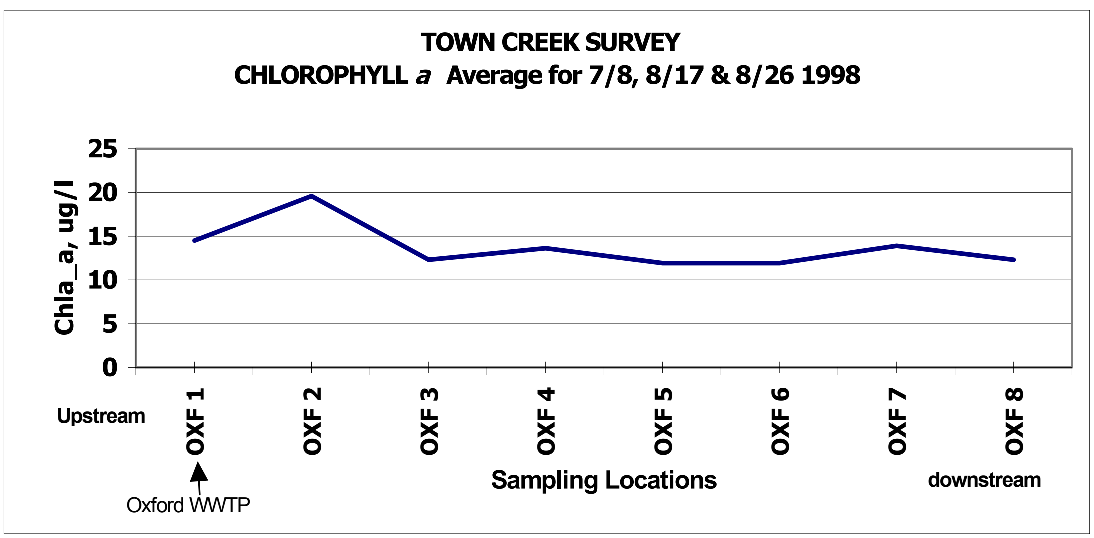


Figure A4: Longitudinal profile of Chlorophyll *a* data

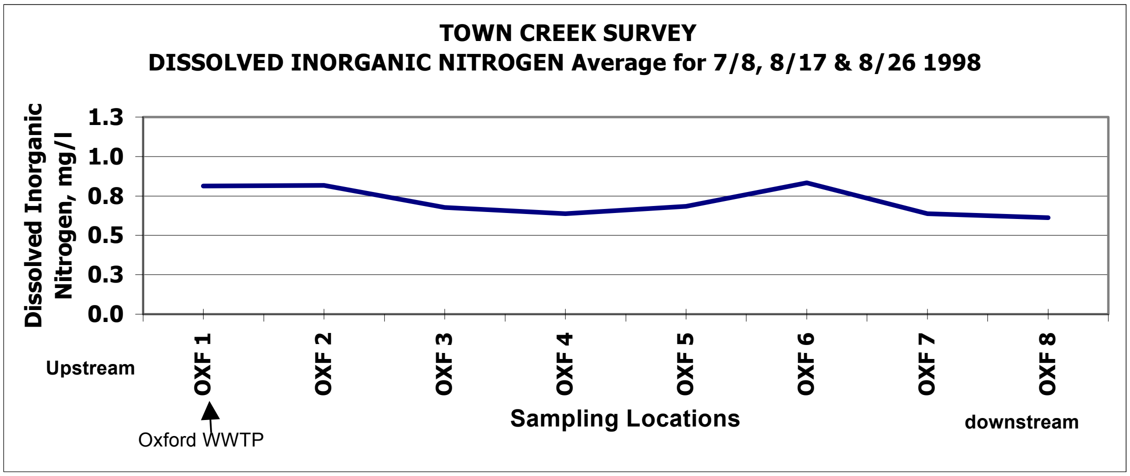


Figure A5: Longitudinal Profile of Total Nitrogen Data

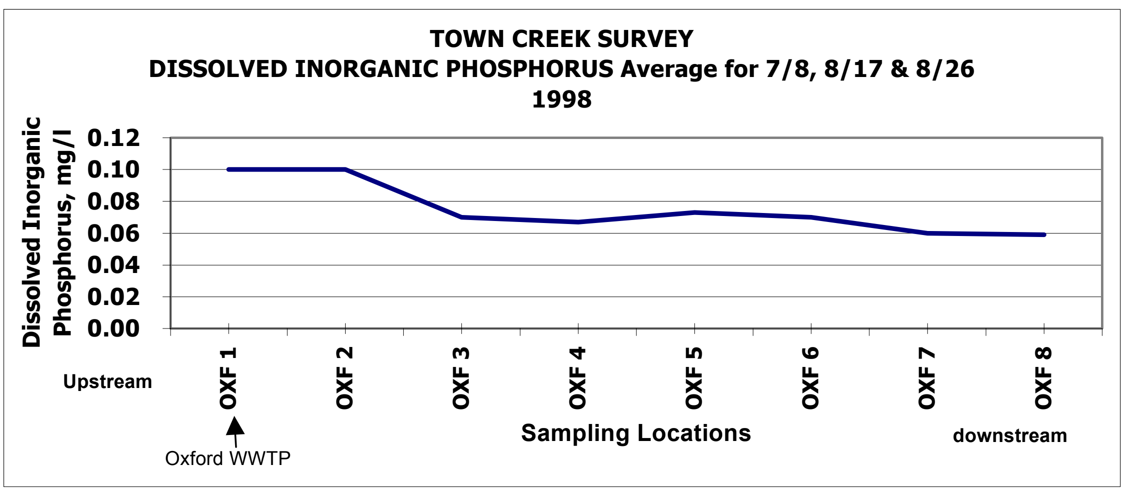


Figure A6: Longitudinal Profile of Phosphorus Data

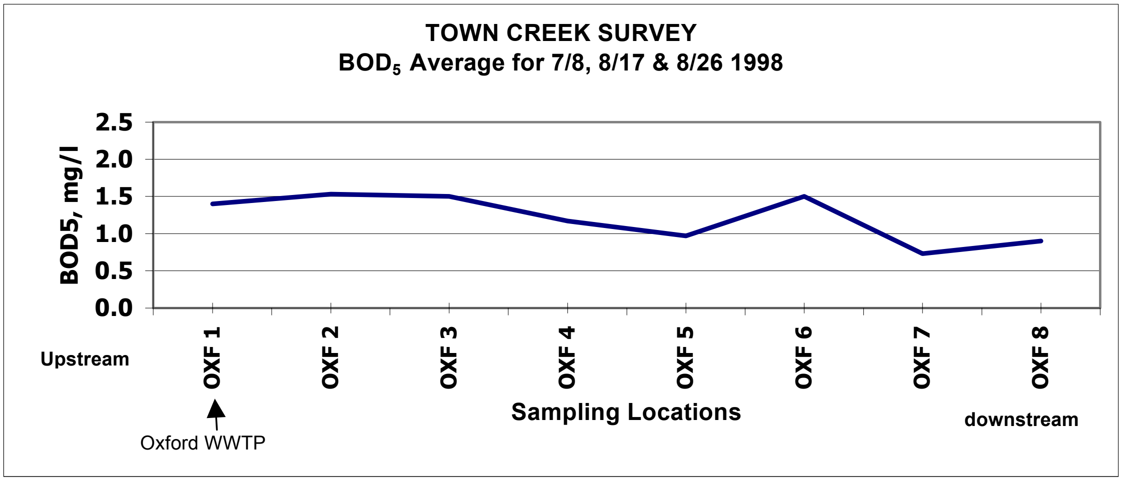


Figure A7: Longitudinal profile of Biochemical Oxygen Demand data

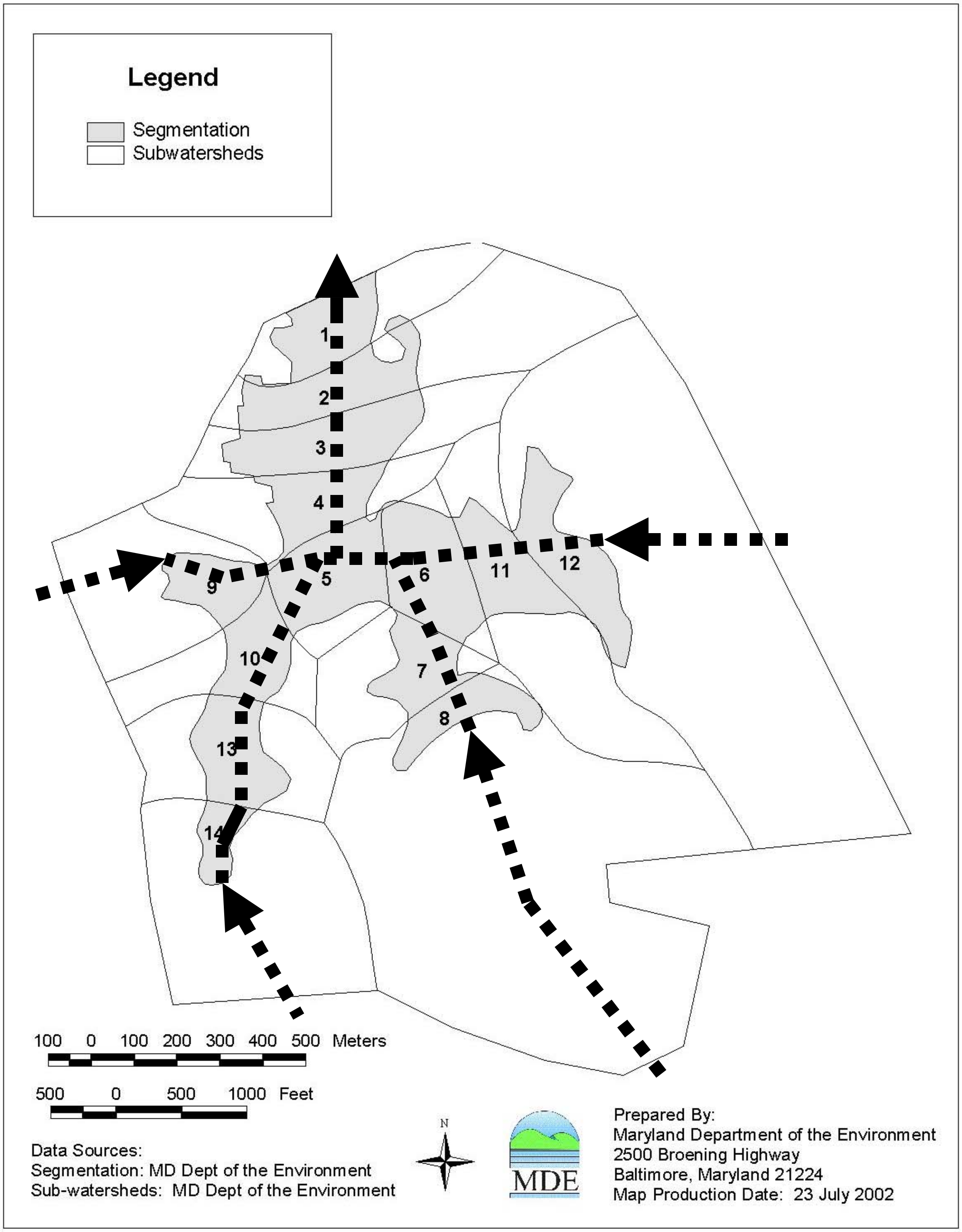


Figure A8: Model Segmentation, including Sub watersheds Drainage

Table A6: Volumes, Characteristic Lengths, Interfacial Areas used in the TCEM

Segment No.	Volume m^3
1	64,251
2	105,119
3	83,592
4	35,421
5	66,393
6	50,953
7	41,665
8	78,821
9	40,410
10	74,148
11	73,785
12	124,754
13	103,392
14	53,141

Segment Pair	Characteristic Length m	Interfacial Area m^2
0-1	144.0	202.0
1-2	149.0	194.0
2-3	162.0	186.0
3-4	142.0	156.0
4-5	167.0	192.0
5-6	218.0	229.0
6-7	187.5	169.0
7-8	137.5	124.0
10-9	160.5	177.0
5-10	187.0	224.0
6-11	196.5	177.0
11-12	159.5	144.0
10-13	222.5	234.0
13-14	267.0	240.0

Table A7: Dispersion Coefficients used in TCEM (Main Channel)

Segment Pair	Dispersion Coefficient (m^2/sec)
0-1	0.25
1-2	0.25
2-3	0.25
3-4	0.20
4-5	0.15
9-10	0.15
12-13	0.10
13-14	0.10

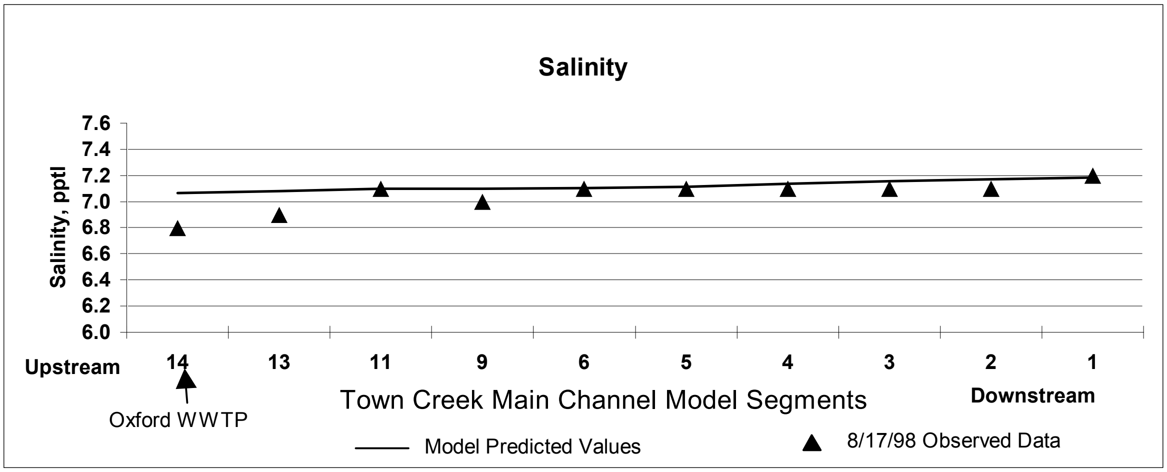


Figure A9: Salinity Model Calibration (Low Flow)

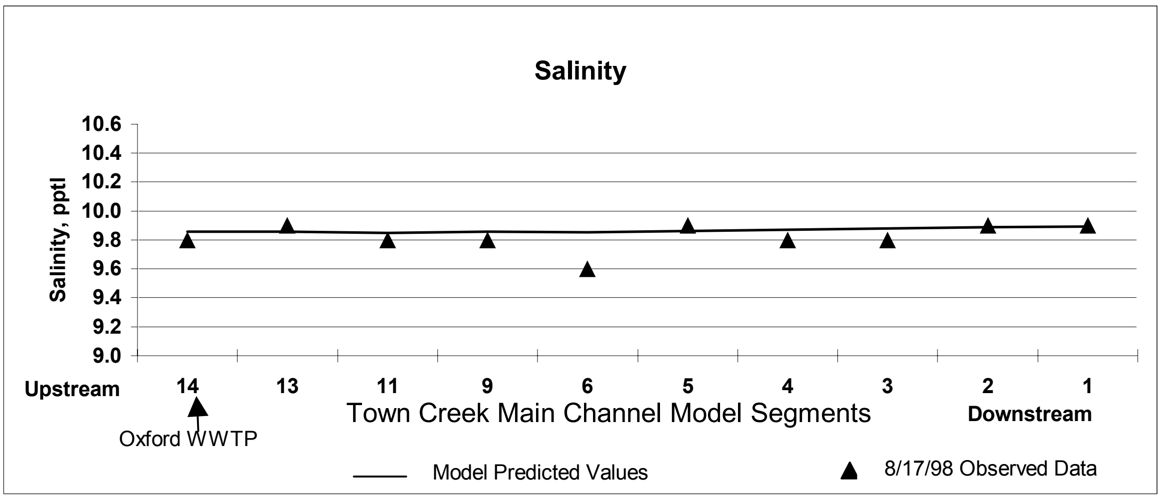


Figure A10: Salinity Model Verification (Low Flow)

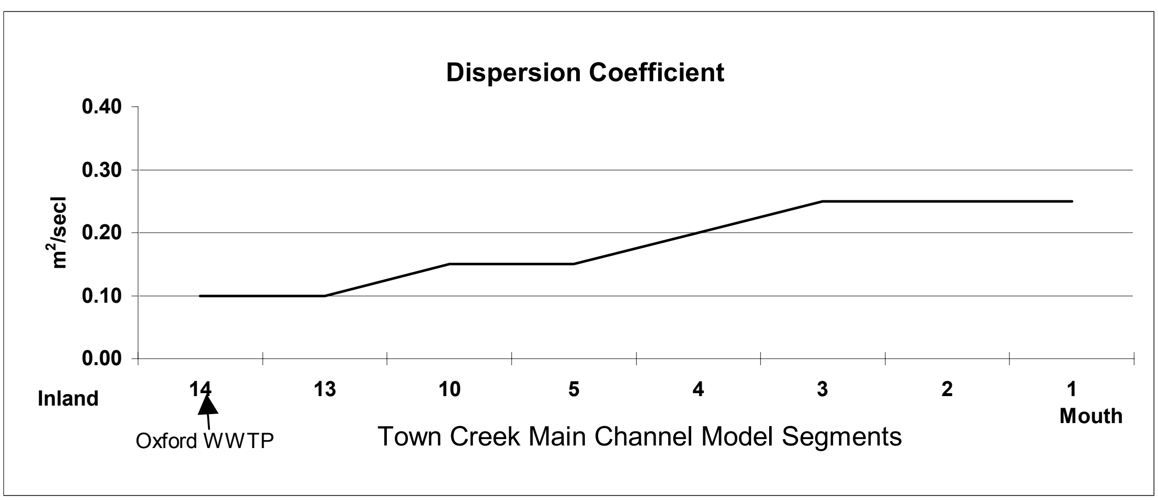


Figure A11: Dispersion Coefficient Results for the Calibration

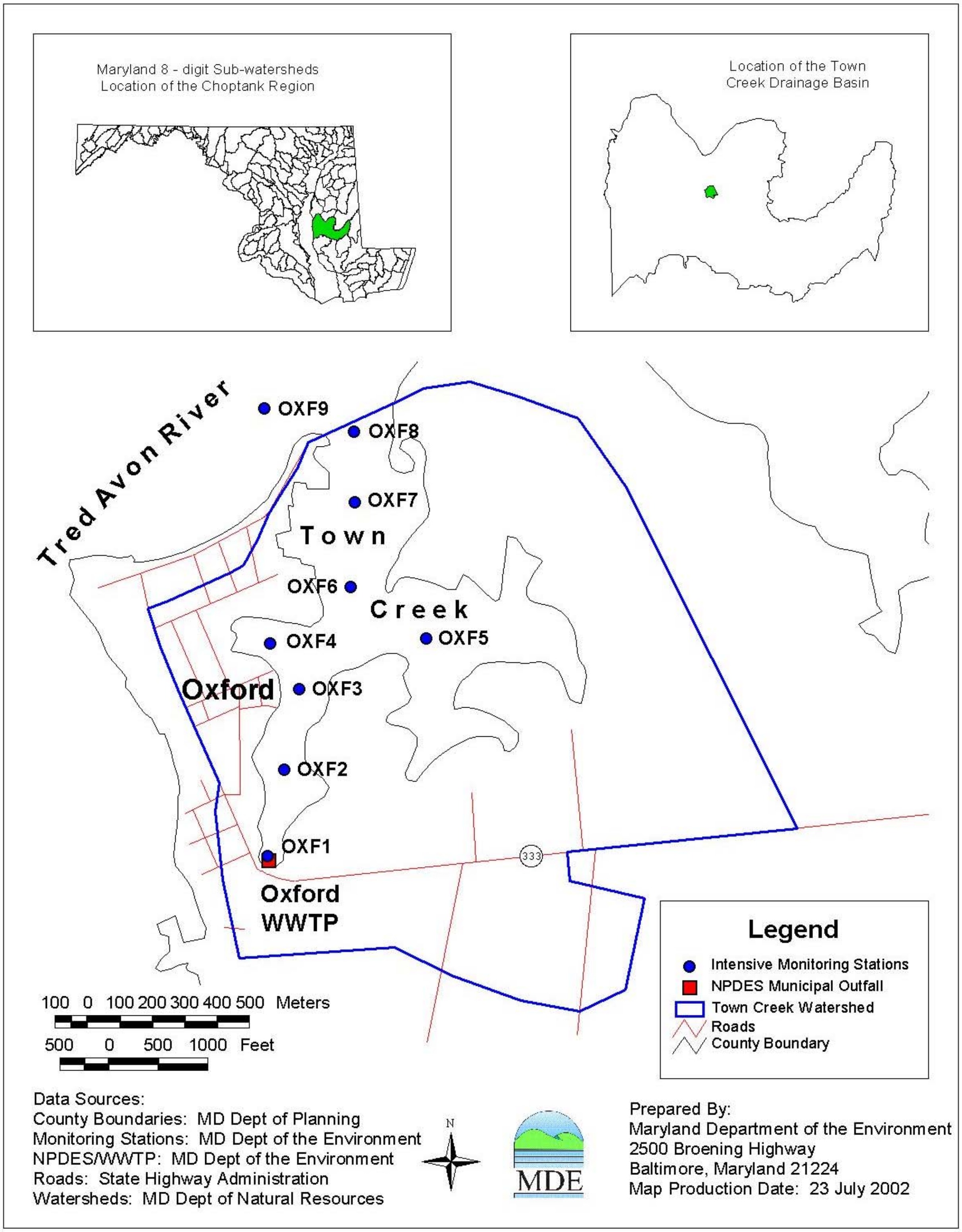


Figure A12: Town Creek Water Quality Monitoring Stations

Table A8: Solar Radiation and Photoperiod used in the Calibration of the Model.

Parameter	Unit	Low Flow (July, August)
Solar Radiation	*Langleys*	422
Photoperiod	*Fraction of a day*	0.56

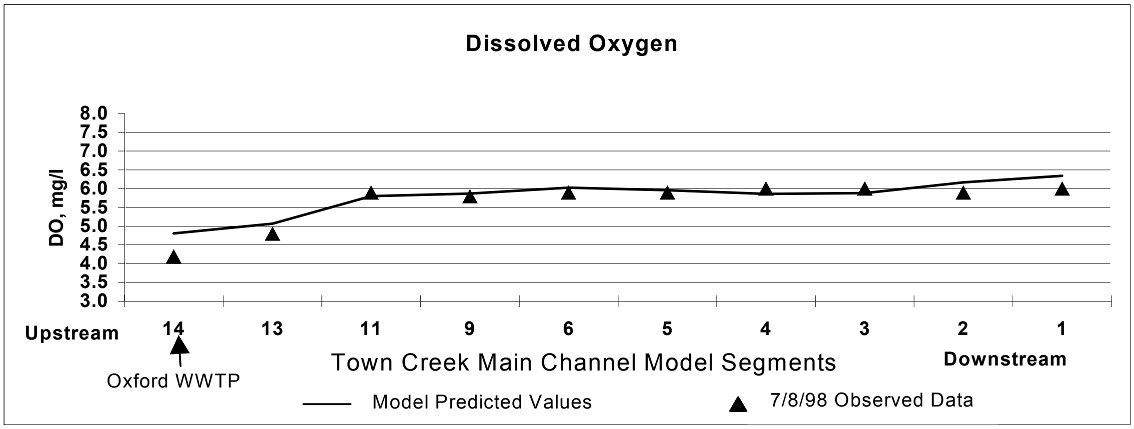
Table A9: Environmental Parameters for the Calibration of the Model

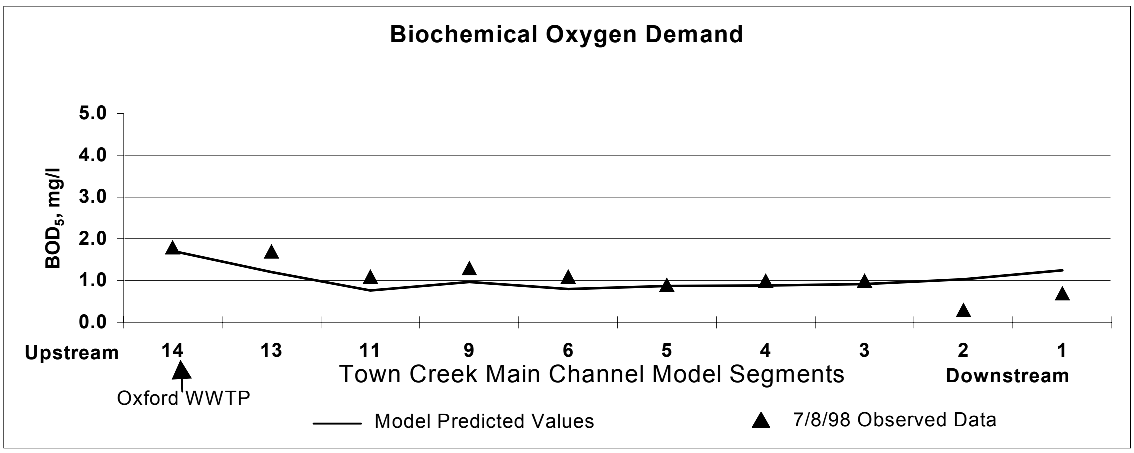
Segment	Ke (m^{-1})		T (^oC)		Salinity (mg/L)		SOD (g O_2/m^2 day)		FNH_4 (mg NH_4-N/m^2 day)		FPO_4 (mg PO_4-P/m^2 day)	
Number		Low flow		Low flow		Low flow		Low flow		Low flow		Low flow
1		1.0		26.1		7.2		1.1		0.5		0.4
2		1.0		26.0		7.1		1.1		0.5		0.2
3		1.0		25.9		7.1		1.3		0.5		0.2
4		1.0		25.9		7.1		1.3		0.5		0.2
5		1.0		26.0		7.1		1.3		0.5		0.2
6		1.0		26.0		7.1		0.9		0.5		0.2
7		1.0		26.0		7.1		0.8		0.5		0.2
8		1.0		26.0		7.1		1.2		0.5		0.2
9		1.0		26.0		7.0		1.2		0.5		0.2
10		1.0		26.0		7.1		1.1		0.5		0.2
11		1.0		26.0		7.1		1.1		0.5		0.1
12		1.0		26.0		7.1		1.1		0.5		0.1
13		1.0		25.5		6.9		1.5		0.5		0.1
14		1.0		26.0		6.8		1.6		0.0		0.1

Table A10: EUTRO5 Kinetic Coefficients used in the Model

Code	PARAMETER DESCRIPTION	Value	
K12C	Nitrification rate	0.15	day^{-1} at 20^0 C
K12T	Temperature coefficient for K1320C.	1.08	
KNIT	Half-saturation constant for nitrification-oxygen limitation	0.5	mg 0_2/L
K20C	Dentrification rate	0.09	day^{-1} at 20^0 C
K20T	Temperature coefficient for K140C.	1.08	
KNO3	Half-saturation constant for denitrification-oxygen limitation	0.5	mg 0_2/L
K1C	Saturated growth rate of phytoplankton	1.7	day^{-1} at 20^0 C
K1T	Temperature coefficient.	1.08	
LGHTS	Light formulation switch; LGHTS=1, use Di Toro et al	1.0	
PHIMX	Maximum quantum yield constant	720	mg C/mole
XKC	Chlorophyll extinction coefficient	0.017	(mg chla/$m^3)^{-1}$/m
CCHL	Carbon-to-chlorophyll ratio	50	mg carbon/mg
IS1	Saturated light intensity for phytoplankton	300	Ly/day
KMNG1	Nitrogen half-saturation constant for nitrogen for phytoplankton growth	0.025	mg-N/L
KMPG1	Phosphorus half-saturation constant for phytoplankton growth	0.001	mg PO_4-P/L
K1RC	Endogenous respiration rate of phytoplankton	0.1	day^{-1} at 20^0 C
K1RT	Temperature coefficient for phytoplankton respiration	1.045	
K1D	Non-predatory phytoplankton death rate	0.01	day^{-1}
K1G	Grazing rate on phytoplankton per unit zooplankton population	0	L/cell-day
NUTLIM	Nutrient limitation option	0	
KPZDC	Decomposition rate constant for phytoplankton in the sediment	0.02	day^{-1} at 20^0 C
KPZDT	Temperature coefficient for decomposition of phytoplankton in the sediment	1.0	
PCRB1	Phosphorus -to-carbon ratio in phytoplankton	0.025	mg P/mg C.
NCRB1	Nitrogen-to-carbon ratio in phytoplankton	0.25	mg N/mg C.
KMPHYT	Half-saturation constant for phytoplankton	0	
KDC	BOD deoxygenation rate	0.1	day^{-1} at 20^0 C
KDT	Temperature coefficient for carbonaceous deoxygenation in water column.	1.05	
KDSC	Decomposition rate of carbonaceous BOD in the sediment	0	day^{-1} at 20^0 C
KDST	Temperature coefficient for carbonaceous deoxygenation in the sediment.	1.0	
KBOD	Half-saturation constant for carbonaceous deoxygenation oxygen limitation.	0.5	
OCRB	Oxygen to carbon ratio in phytoplankton	2.67	mg 0_2/mg C.
K2	Reaeration rate constant at 20^0C for entire water body	0.5	day^{-1} at 20^0 C
K71C	Mineralization rate of dissolved organic nitrogen	0.02	per day
K71T	Temperature coefficient for K1013C.	1.08	
KONDC	Decomposition rate constant for organic nitrogen in the sediment	0	day^{-1} at 20^0 C
KONDT	Temperature coefficient for decomposition of organic nitrogen in the sediment.	1.0	
FON	Fraction of dead and respired phytoplankton nitrogen recycled to organic nitrogen.	1.0	
K58	Mineralization rate of dissolved organic phosphorus	0.15	per day
K58T	Temperature coefficient for K58C.	1.08	
KOPDC	Decomposition rate constant of organic phosphorus in the sediment	0	day^{-1} at 20^0 C
KOPDT	Temperature coefficient for decomposition of organic phosphorus in the sediment.	1.0	
FOP	Fraction of dead and respired phytoplankton phosphoru recycled to organic phosphorus.	0.5	

Low Flow Calibration





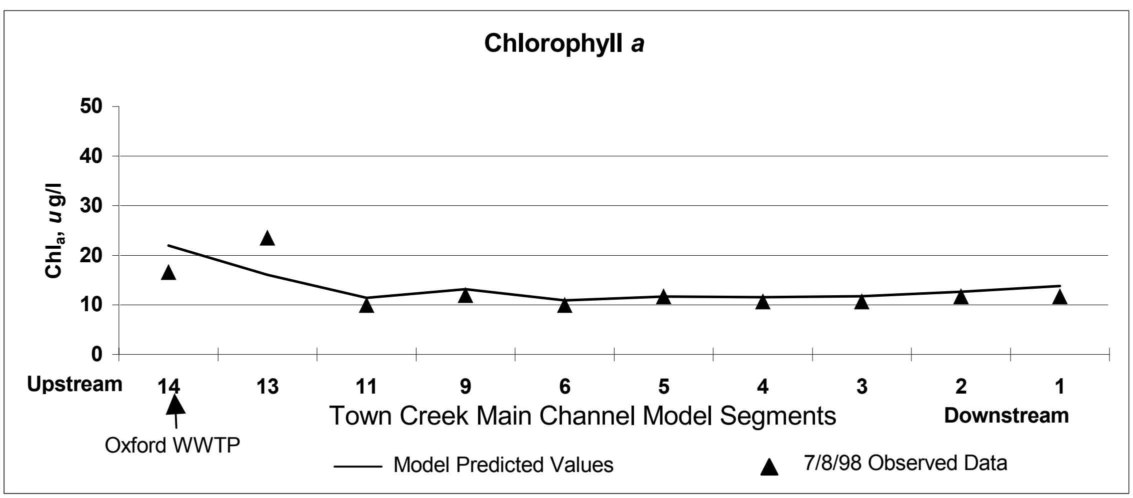


Figure A13: Low Flow Calibration Results

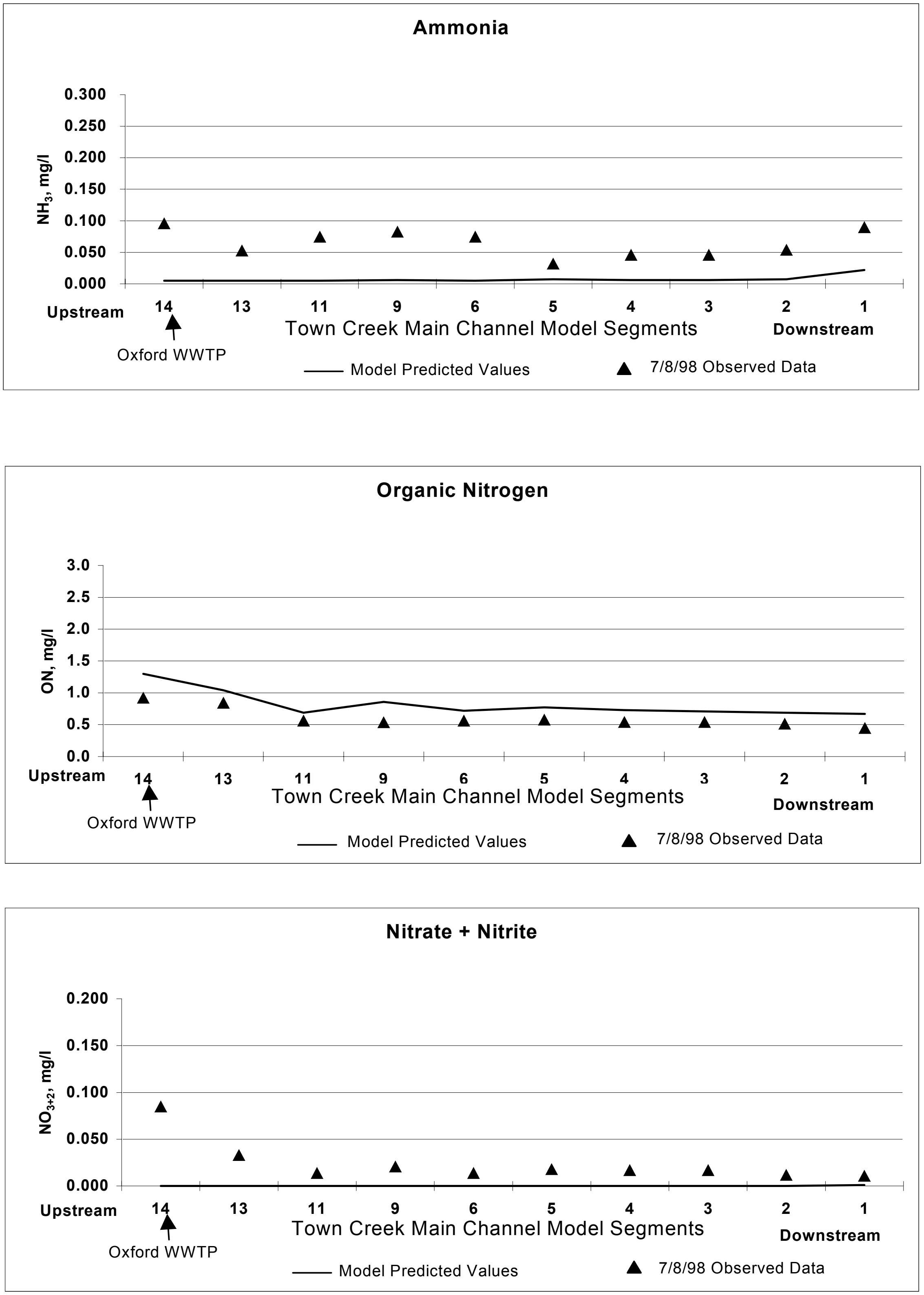


Figure A14: Low Flow Calibration Results

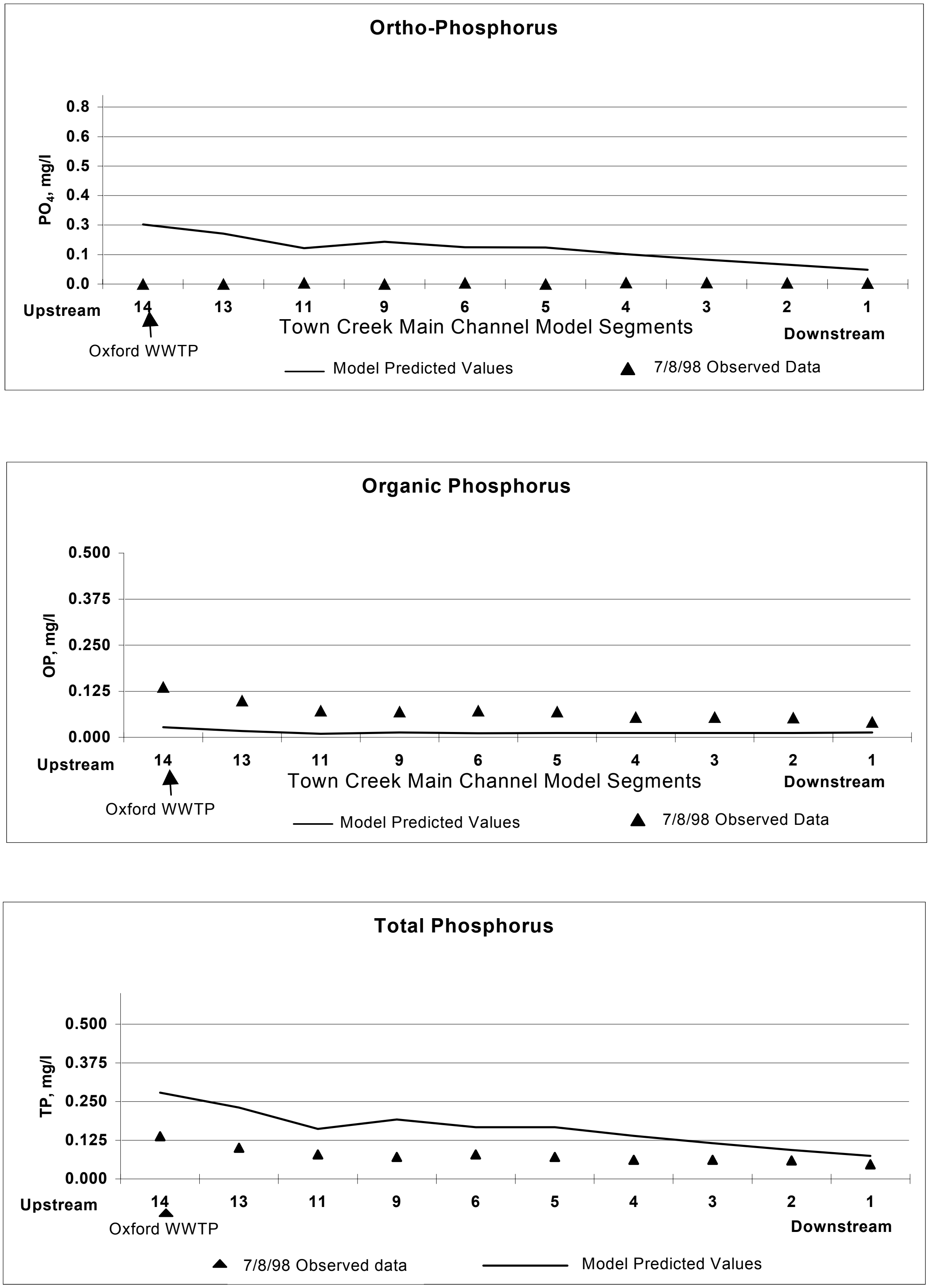


Figure A15: Low Flow Calibration Results

Low Flow Verification

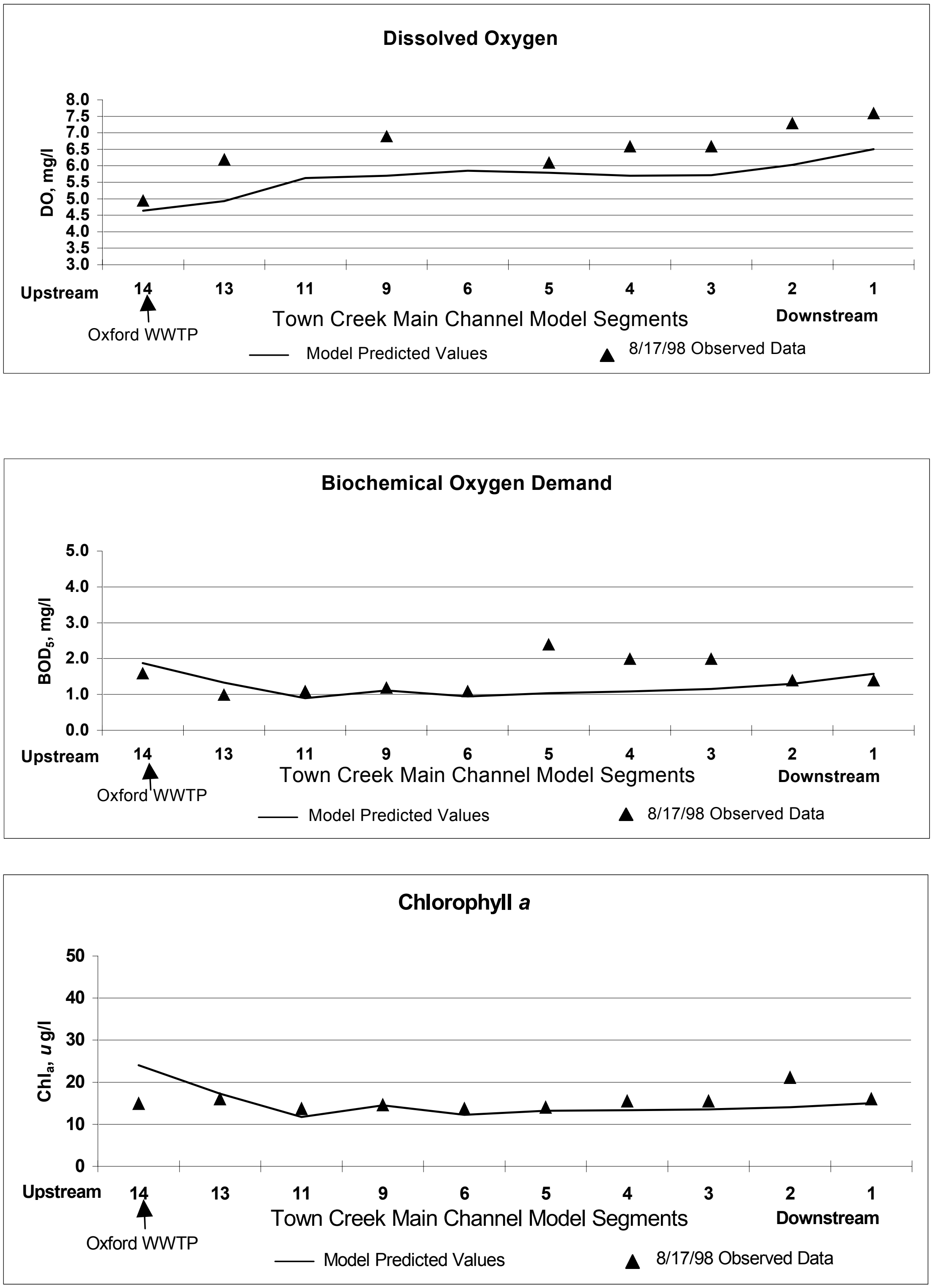
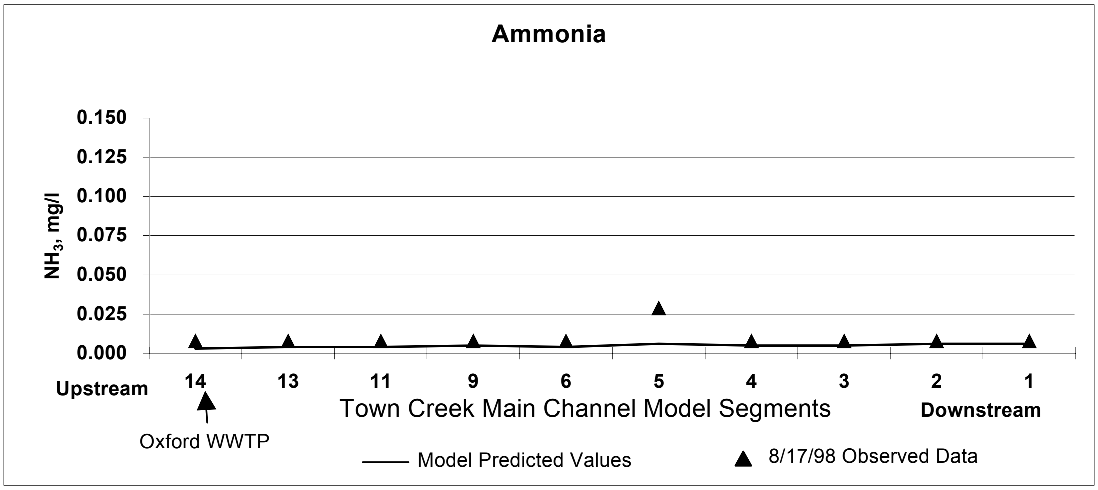
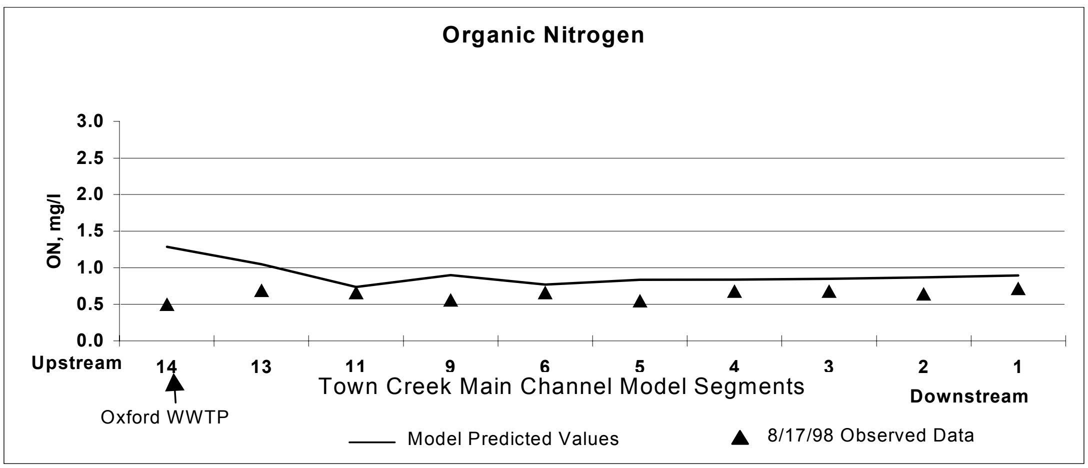


Figure A16: Model verification (Low flow)





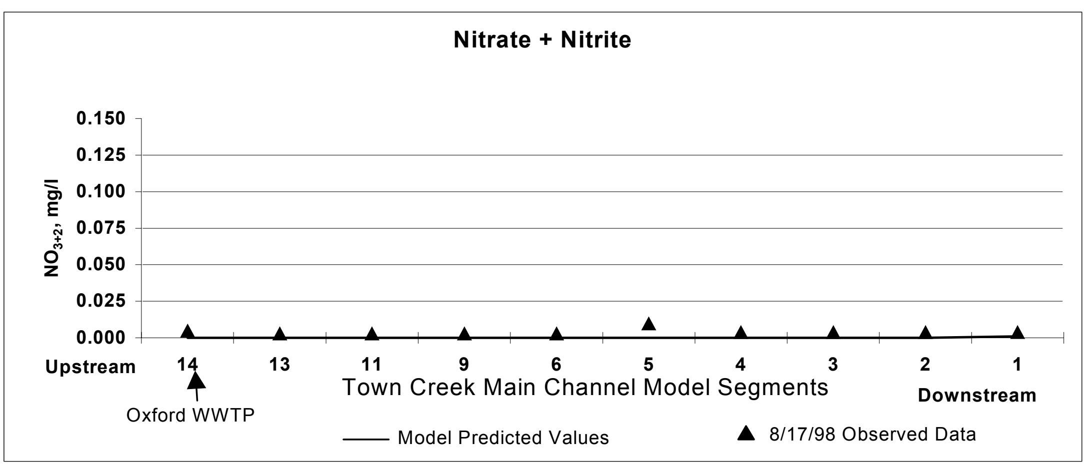
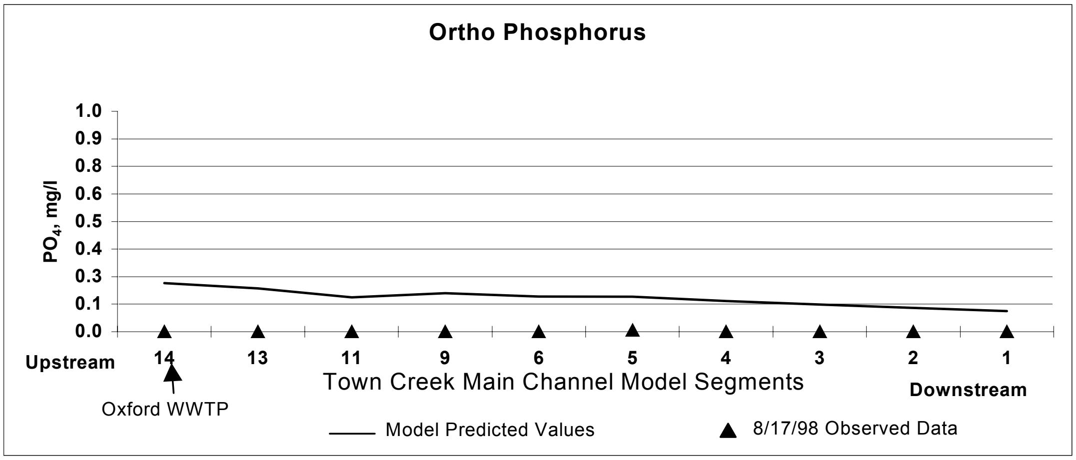
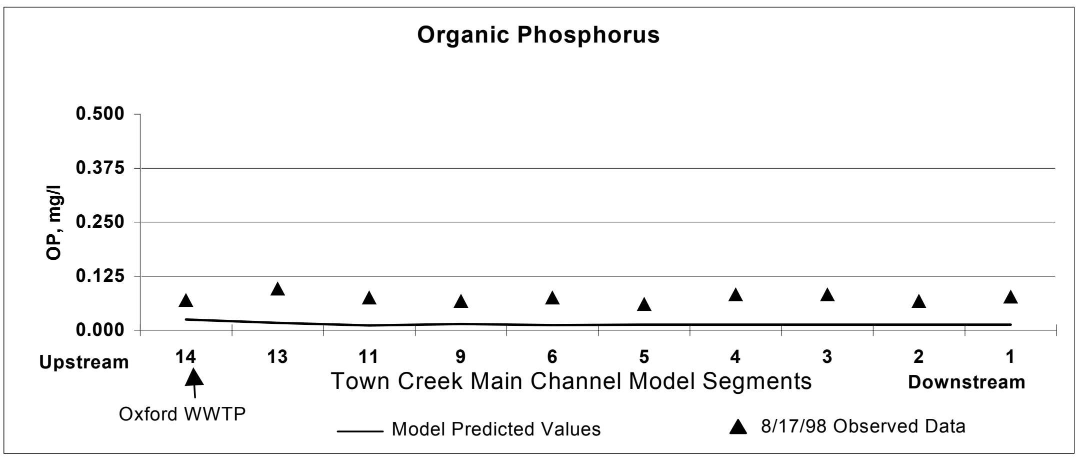


Figure A17: Model verification (Low flow)


Ortho Phosphorus
1.0
0.9
0.8
0.6
0.5
0.4
0.3
0.1
0.0
PO4, mg/l
Upstream
14
13
11
9
6
5
4
3
2
1
Town Creek Main Channel Model Segments
Downstream
Oxford WWTP
Model Predicted Values
8/17/98 Observed Data


Organic Phosphorus
0.500
0.375
0.250
0.125
0.000
OP, mg/l
Upstream
14
13
11
9
6
5
4
3
2
1
Town Creek Main Channel Model Segments
Downstream
Oxford WWTP
Model Predicted Values
8/17/98 Observed Data

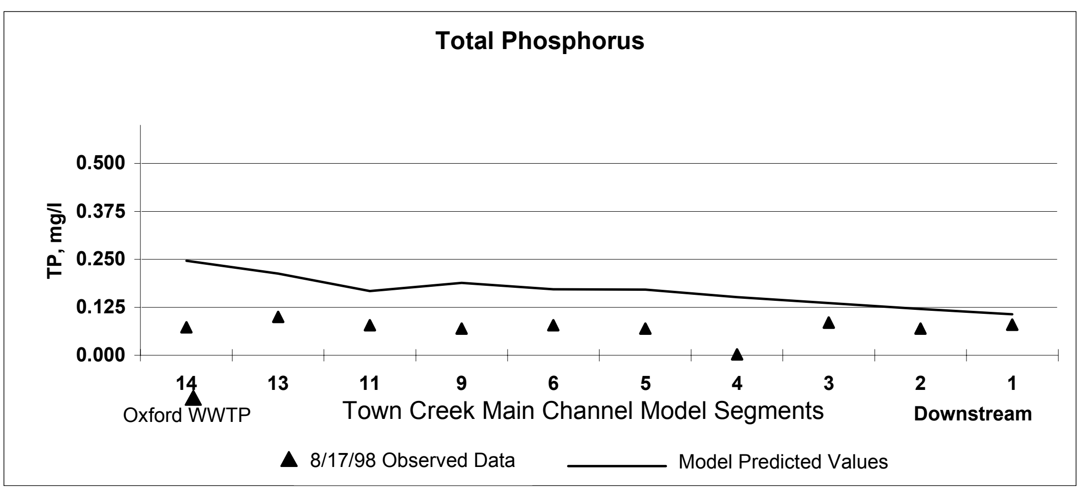

Total Phosphorus
0.500
0.375
0.250
0.125
0.000
TP, mg/l
14
13
11
9
6
5
4
3
2
1
Oxford WWTP
Town Creek Main Channel Model Segments
Downstream
8/17/98 Observed Data
Model Predicted Values

Figure A18: Model Verification (Low Flow)

Table A11: Nonpoint Source Concentrations for Baseline Scenario (Low Flow)

Segment Number	**NH4** *mg/l*	**NO_{23}** *mg/l*	**PO_4** *mg/l*	**CHL *a*** *μg/l*	**CBOD** *mg/l*	**DO** *mg/l*	**ON** *mg/l*	**OP** *mg/l*
1	0.033	0.006	0.056	12.3	1.35	6.5	0.570	0.003
2	0.022	0.007	0.056	13.9	1.10	6.3	0.605	0.004
3	0.020	0.007	0.066	11.9	2.25	6.2	0.803	0.004
4	0.020	0.007	0.066	11.9	2.25	6.2	0.803	0.004
5	0.021	0.010	0.066	12.3	2.25	5.7	0.649	0.004
6	0.028	0.006	0.070	11.9	1.46	6.7	0.649	0.004
7	0.028	0.006	0.070	11.9	1.46	6.7	0.649	0.004
8	0.028	0.006	0.070	11.9	1.46	6.7	0.649	0.004
9	0.031	0.008	0.065	13.6	1.76	6.0	0.596	0.002
10	0.031	0.008	0.065	13.6	1.76	6.0	0.596	0.002
11	0.028	0.006	0.070	11.9	1.46	6.7	0.649	0.004
12	0.028	0.006	0.070	11.9	1.16	6.7	0.649	0.004
13	0.024	0.012	0.098	19.6	2.30	5.1	0.776	0.002
14	0.039	0.003	0.098	14.5	2.10	4.2	0.738	0.002

Table A12: Nonpoint Source Concentrations for Future TMDL Scenario (Low Flow)

Segment Number	**NH4** *mg/l*	**NO_{23}** *mg/l*	**PO_4** *mg/l*	**CHL *a*** *μg/l*	**CBOD** *mg/l*	**DO** *mg/l*	**ON** *mg/l*	**OP** *mg/l*
1	0.021	0.004	0.036	8.00	0.89	6.5	0.37	0.002
2	0.014	0.005	0.036	9.04	0.71	6.3	0.39	0.003
3	0.013	0.005	0.043	7.74	1.47	6.2	0.52	0.003
4	0.013	0.005	0.043	7.74	1.47	6.2	0.52	0.003
5	0.014	0.007	0.043	8.00	1.47	5.7	0.42	0.003
6	0.018	0.004	0.046	7.74	0.95	6.7	0.42	0.003
7	0.018	0.004	0.046	7.74	0.95	6.7	0.42	0.003
8	0.018	0.004	0.046	7.74	0.96	6.7	0.42	0.003
9	0.020	0.005	0.042	8.84	1.14	6.0	0.39	0.001
10	0.020	0.005	0.042	8.84	1.14	6.0	0.39	0.001
11	0.018	0.004	0.046	7.74	0.95	6.7	0.42	0.003
12	0.018	0.004	0.046	7.74	0.95	6.7	0.42	0.003
13	0.016	0.008	0.064	12.74	1.49	5.1	0.50	0.001
14	0.025	0.002	0.064	9.43	1.37	4.2	0.48	0.001

Low Flow Baseline Conditions Scenario

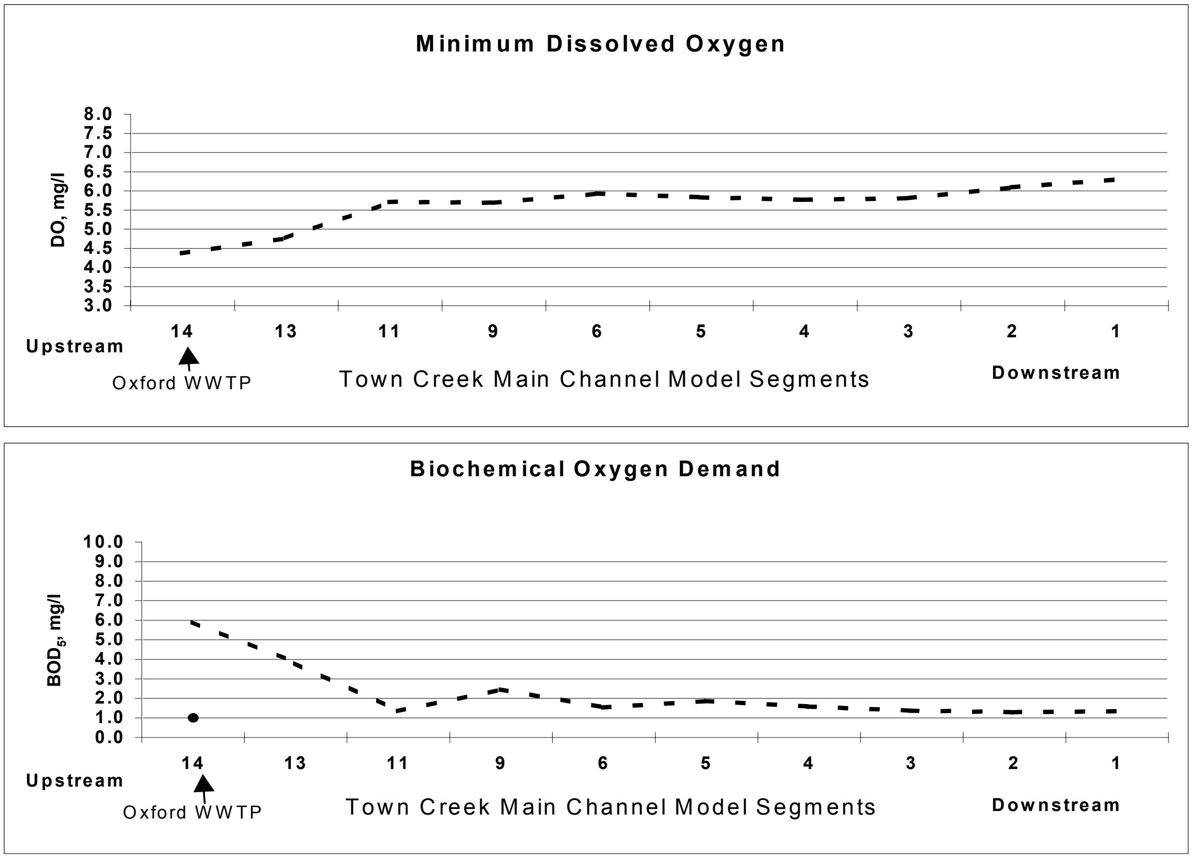


Figure A19: Baseline Conditions Scenario Results (Low Flow)

Table A13: Baseline Nonpoint Source and Point Source Concentrations and Loadings

Parameters	Concentration (mg/l)				Loadings (lb/mon)				
	Model Segments								
	8	9	12	14	8	9	12	14	Total
Nonpoint Source Flow (mgd)	**.010**	**.0058**	**.016**	**.0061**					**0.038**
BOD	0.97	1.17	0.97	1.4	3.6	2.55	5.82	3.2	15.2
Total Nitrogen	0.683	0.635	0.683	0.78	1.7	0.92	2.73	1.19	6.54
Total Phosphorus	0.074	0.067	0.074	0.10	0.19	0.10	0.29	0.15	0.73
Point Source									
Flow = 0.208 mgd									
BOD	30.0				1,561				
Total Nitrogen	18.0				937				
Total Phosphorus	2.0				104				

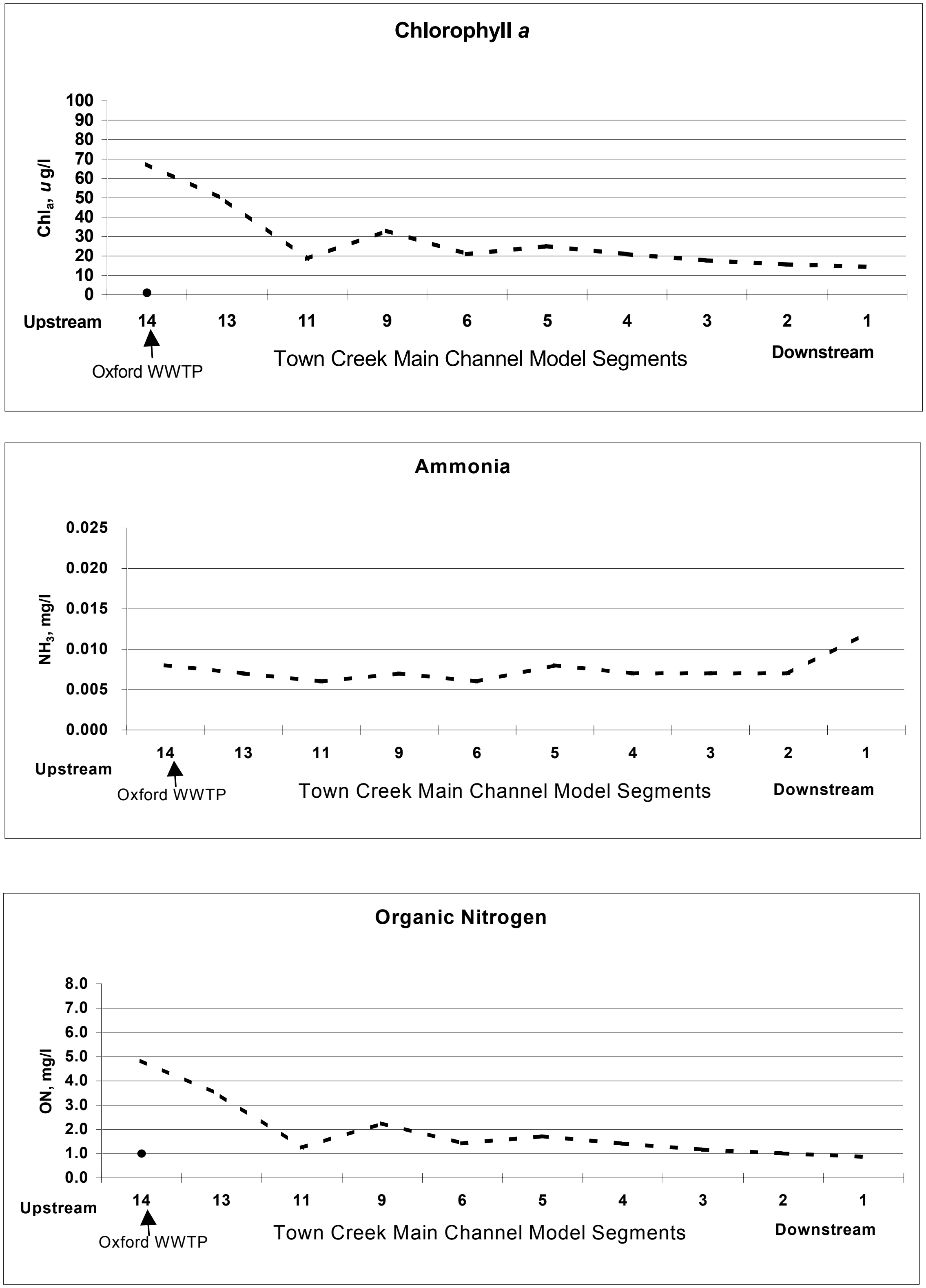


Figure A20: Baseline Conditions Scenario Results (Low Flow)

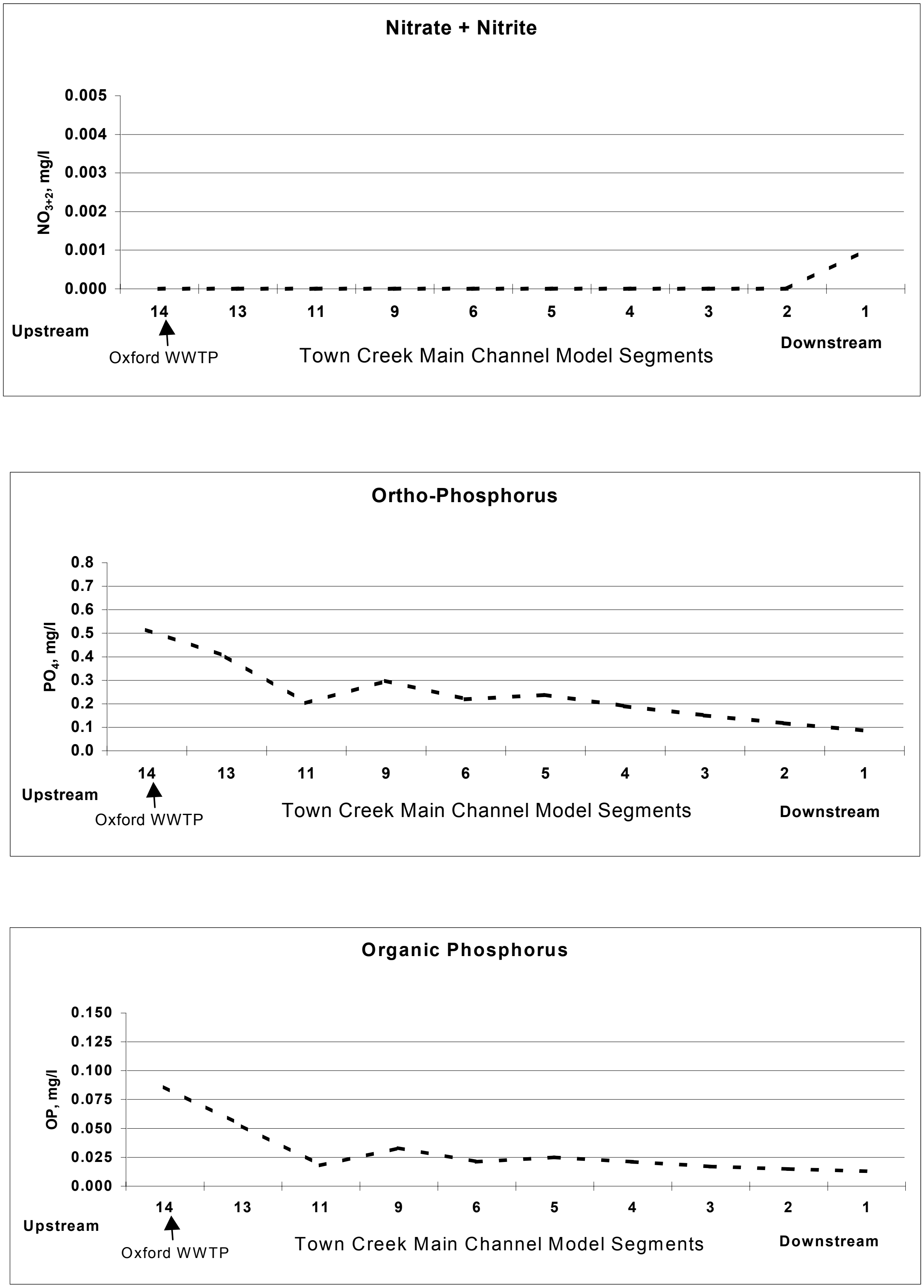


Figure A21: Baseline Conditions Scenario Results (Low Flow)

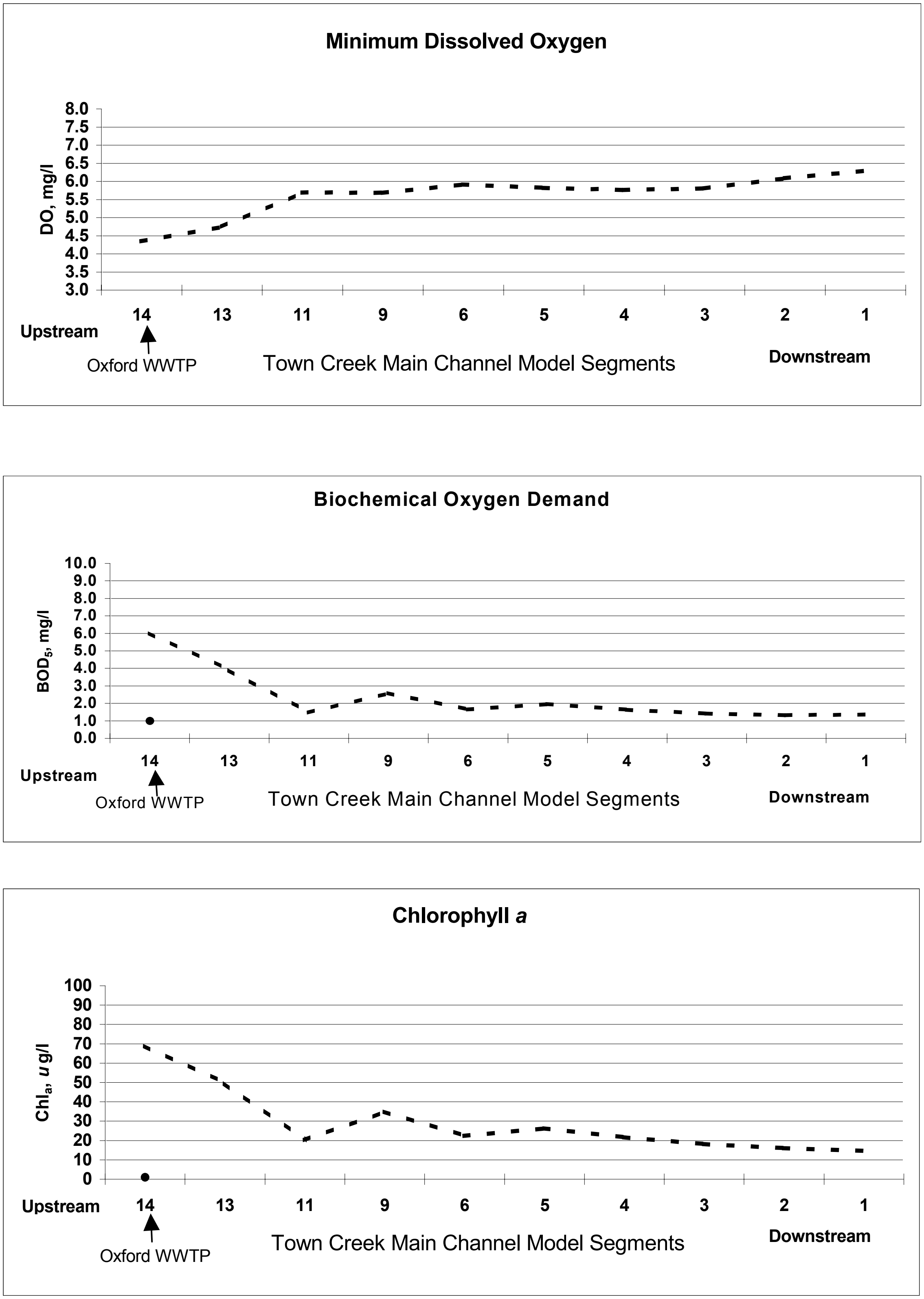
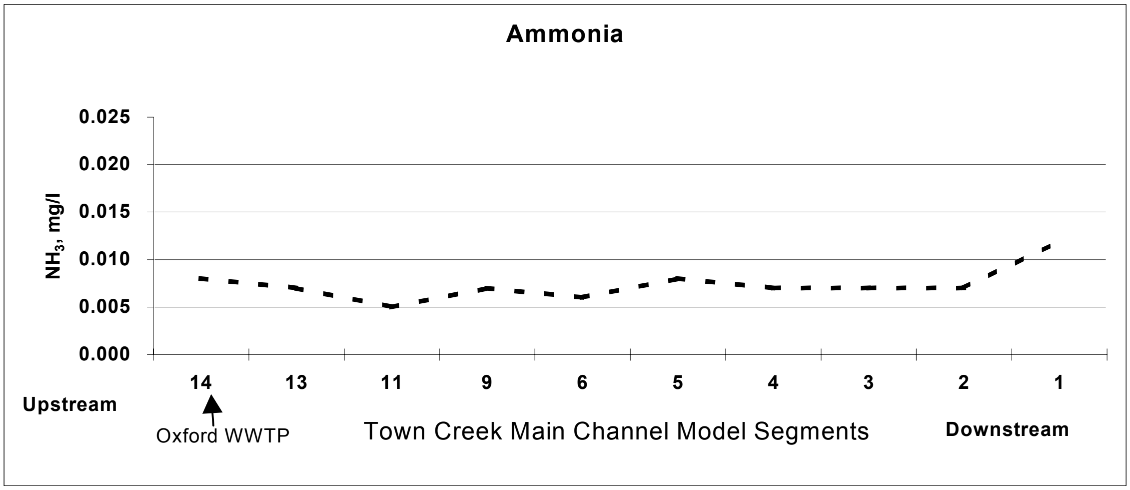
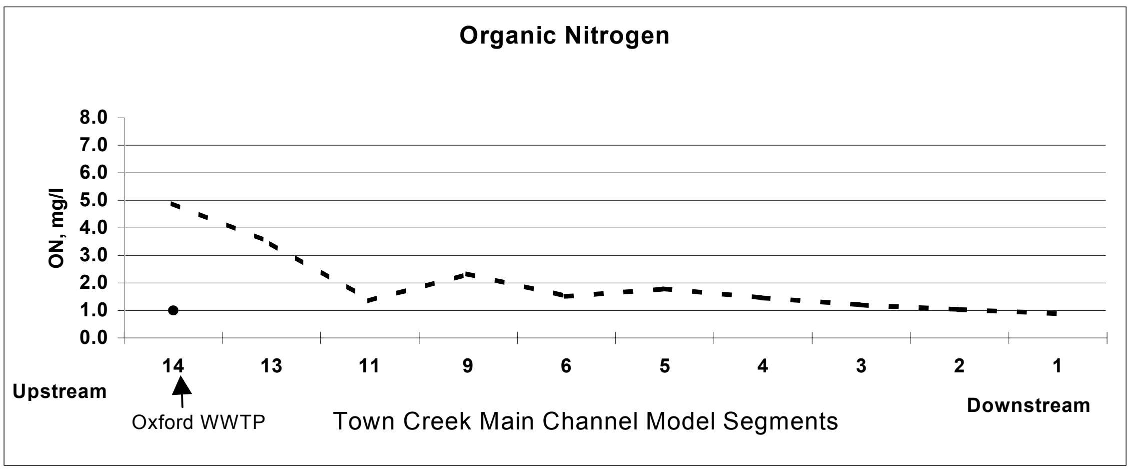


Figure A22: Baseline Conditions Scenario Results (Average Annual Flow)





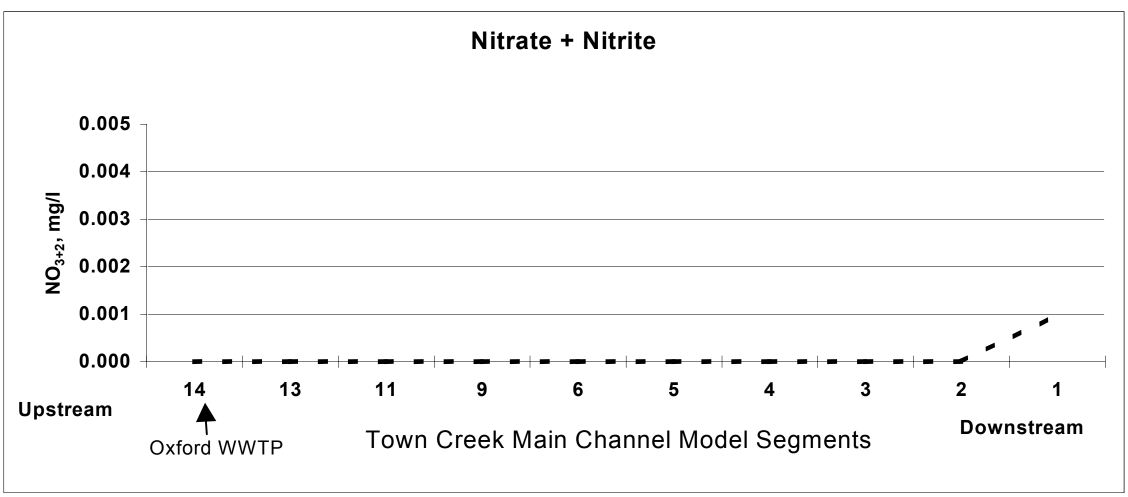
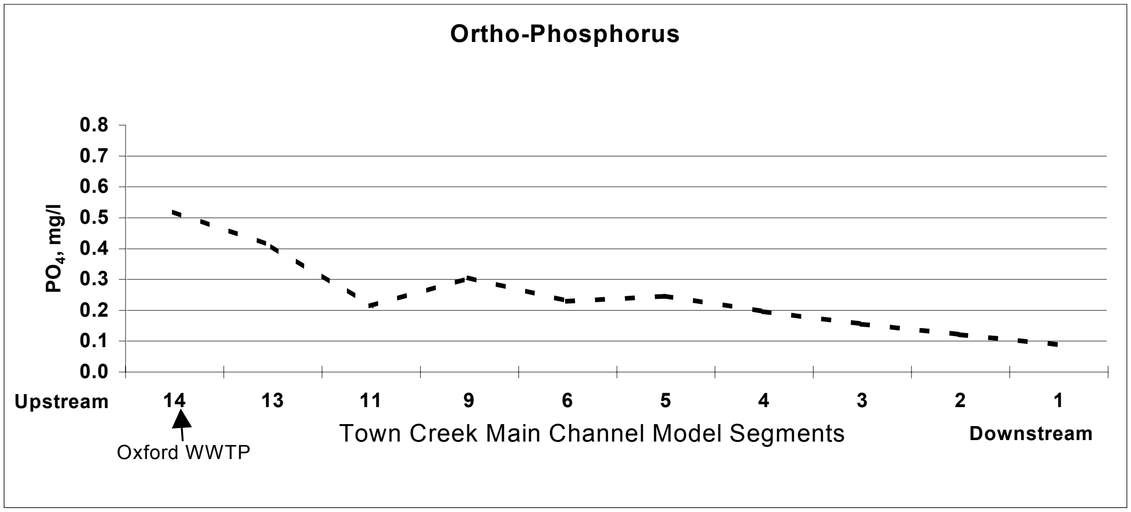


Figure A23: Baseline Conditions Scenario Results (Average Annual Flow)



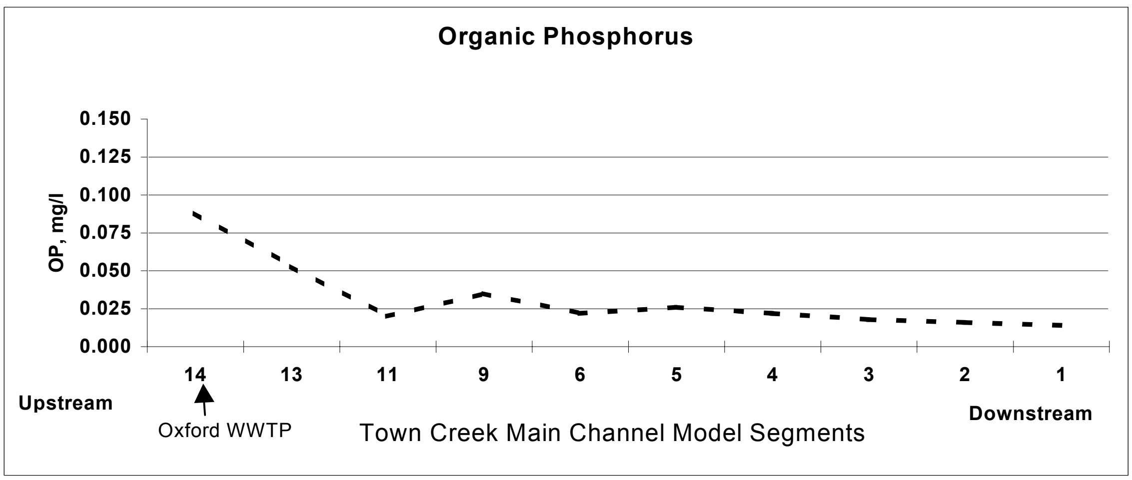


Figure A24: Baseline Conditions Scenario Results (Average Annual Flow)

Future Low Flow TMDL Scenario Results

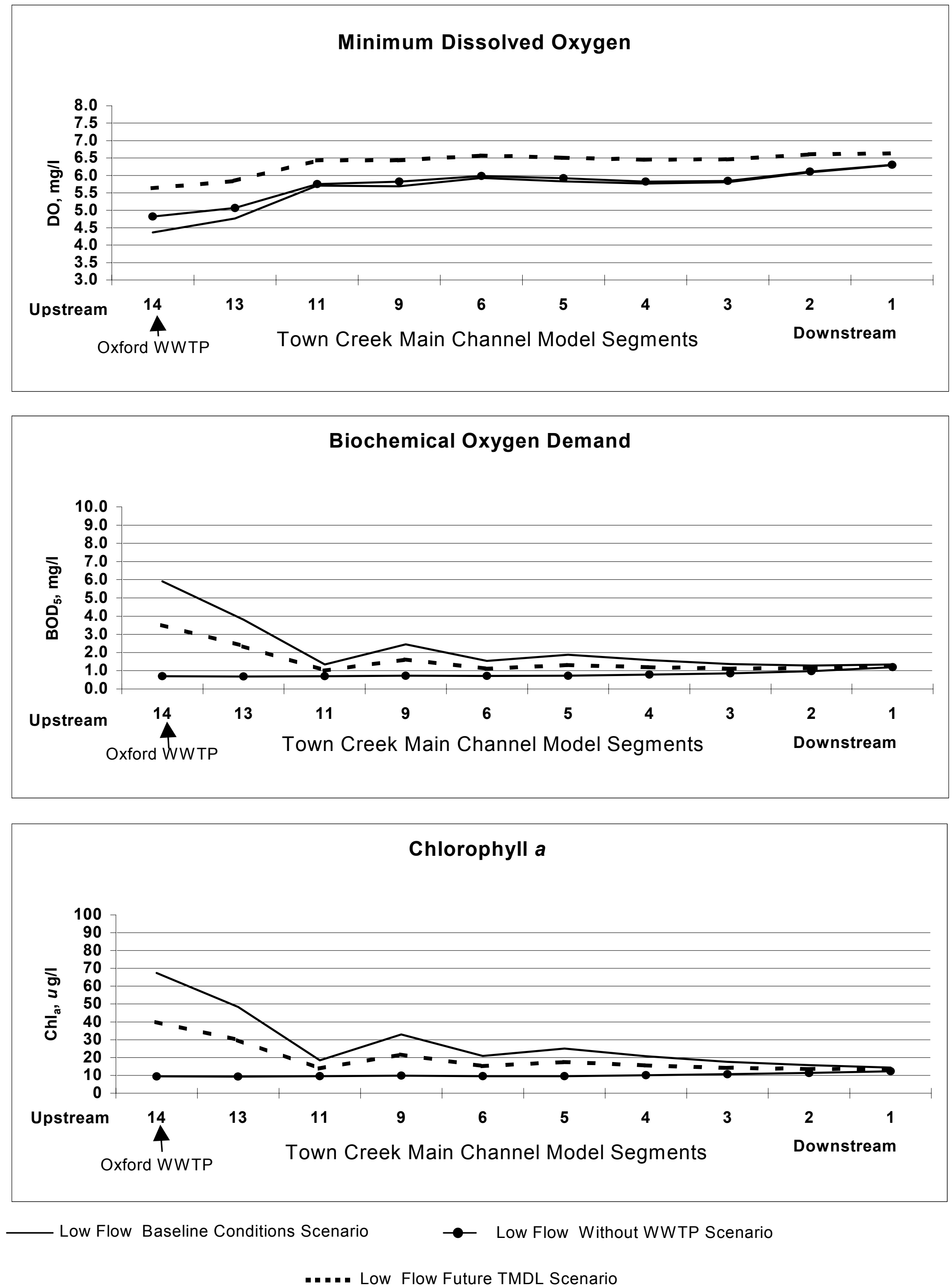


Figure A25: Future Low Flow TMDL Scenario Results

Future Average Annual Flow TMDL Scenario Results

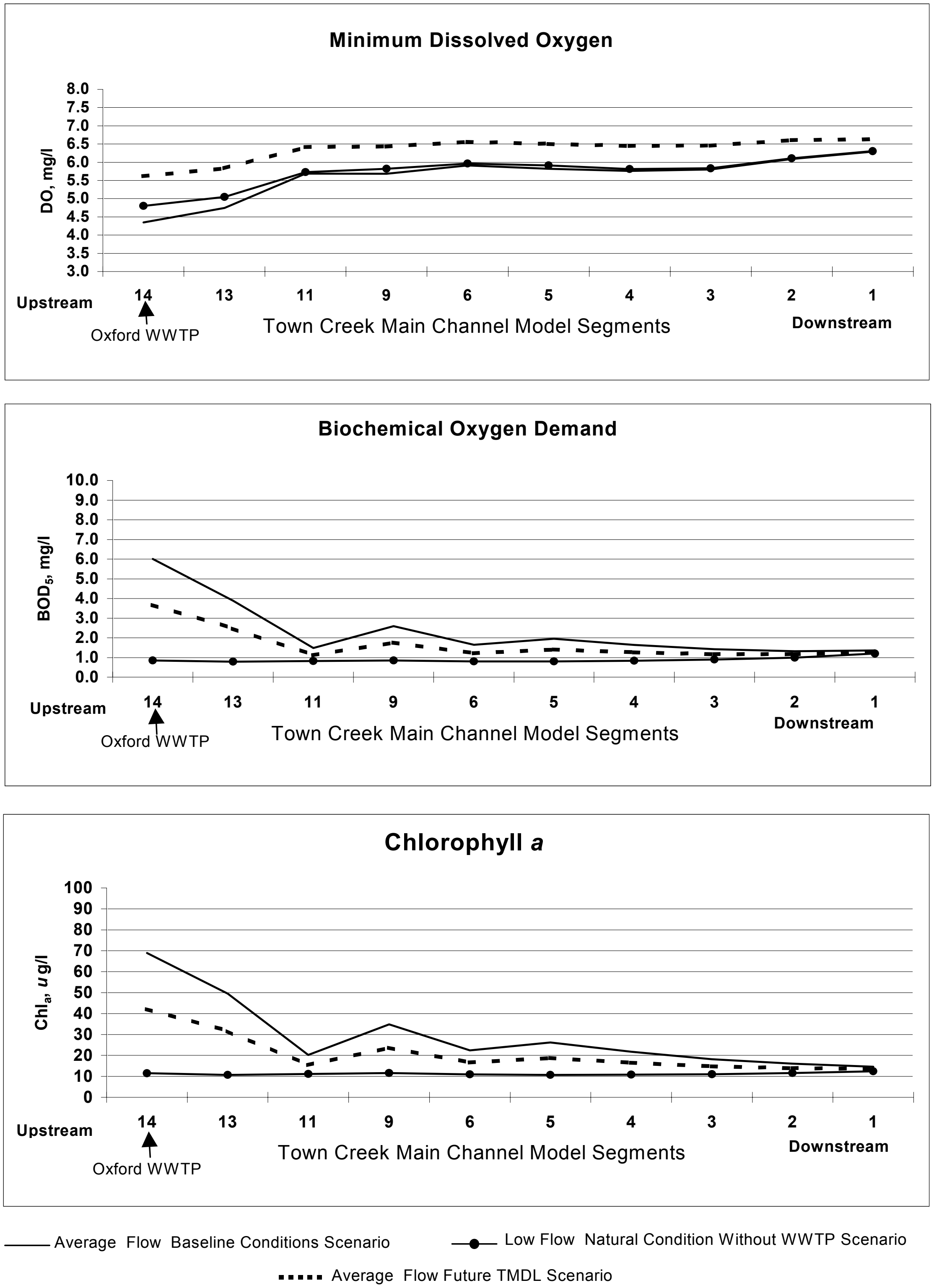
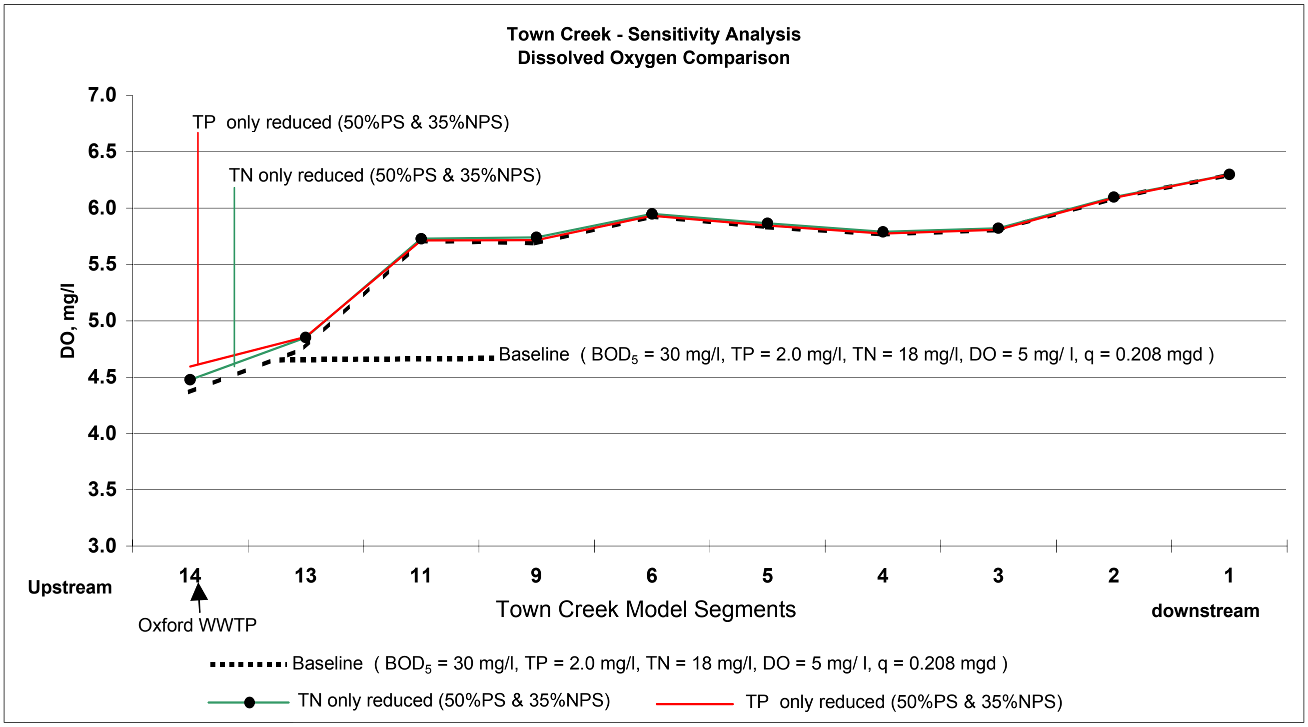


Figure A26: Future Average Annual Flow TMDL Scenario Results

Total Nitrogen and Total Phosphorus Sensitivity Analysis Results



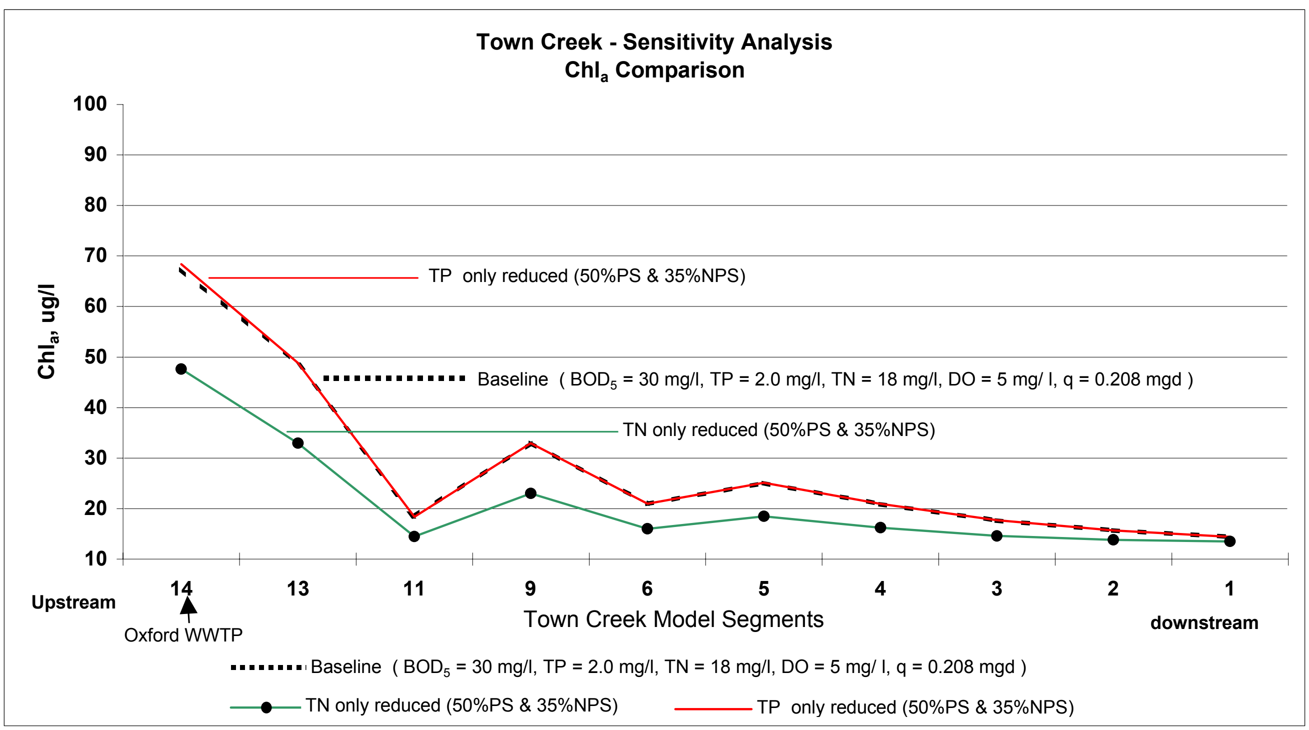


Figure A27: Sensitivity Analysis Results

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