TECHNICAL MEMORANDUM

TO:	JOHN HALL, HALL & ASSOCIATES	DATE:	MARCH 20, 2012
CC:	GREAT BAY MUNICIPAL COALITION	RE:	SQUAMSCOTT RIVER AUGUST-SEPTEMBER 2011 FIELD STUDIES
FROM:	THOMAS W. GALLAGHER CRISTHIAN MANCILLA	FILE:	HAAS – 174334

I. INTRODUCTION

As part of a Memorandum of Agreement between the Great Bay Municipal Coalition and New Hampshire Department of Environmental Services (NHDES), relative to reducing uncertainty in nutrient criteria for the Great Bay Estuary, the Coalition agreed to perform field studies and develop a coupled hydrodynamic water quality model of the Squamscott River for the purpose of developing a scientifically based relationship (model) between nitrogen, algae (chl-a) and dissolved oxygen (DO) in the Squamscott River. This agreement was reached after reviewing the underlying basis for the regression equation developed by NHDES to predict tidal river DO improvements and determining that the 3 μg/L change in chlorophyll-a projected to occur with lower TN concentrations could not physically produce a 3 mg/L change in minimum DO as originally assumed in the analyses. The parties agreed that a more detailed modeling effort would be used to assess the degree to which TN levels influenced algal growth and minimum DO concentrations. Ultimately it was intended that the more detailed effort could be used by NHDES to develop site-specific nitrogen criteria for the Squamscott River, as well as wasteload allocations (nutrient and BOD permit limits) for the Exeter wastewater treatment plant. Site-specific nitrogen criteria developed with the model would replace the draft nitrogen criteria developed by NHDES and presented in the June 2009 Numeric Nutrient Criteria for the Great Bay Estuary report. This Technical Memorandum presents a description and results of the Squamscott River field studies and a brief interpretation of the results. However, preceding a discussion of the field studies a brief review and critique of the original methodology used by NHDES to develop nitrogen and chl-a criteria for the tidal tributaries in the Great Bay Estuary is presented. The purpose of this critique is to support the conclusions that the prior effort did not produce scientifically defensible nitrogen and chl-a criteria for the tidal tributaries and mechanistic models that relate river nitrogen loads to chl-a and DO are required to determine the level of point and nonpoint source reductions to meet Squamscott River chl-a and DO criteria given the unique characteristics of that tidal river.

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II. REVIEW OF NHDES TIDAL TRIBUTARY NITROGEN AND CHL-A CRITERIA

NHDES utilized a type of simplified "stressor-response" regression in an attempt to correlate minimum DO conditions occurring in the tidal rivers, Great Bay and Portsmouth Harbor with the nitrogen levels occurring at these different locations. Several regressions were prepared to "prove" the relationship between total nitrogen and minimum DO. For example, NHDES developed 90th percentile chl-a and median total nitrogen (TN) criteria to meet the minimum DO standard of 5 mg/L from an analysis of continuous DO data recorded at stations in Great Bay Estuary (Figure 1) coupled with chl-a and TN data. Figures 2 and 3 present the minimum DO datasonde measurements recorded at six stations in Great Bay Estuary in addition to 90th percentile chl-a and median TN data. The minimum DO criterion is achieved in Great Bay and the Coastal Marine Laboratory stations and periodically violated in the upper tidal reaches of the Lamprey River, Salmon Falls River, Oyster River, and the Squamscott River with the most severe DO violations occurring in the Lamprey River. It should be noted that the Lamprey River DO occurs at far lower algal growth levels than occurs in the other tidal rivers. Detailed evaluation of the Lamprey River by Pennock (2005), determined that the low DO was caused by the hydrodynamics peculiar to this specific tidal river and was not due to elevated algal growth. A 2005 Report by Jones on the Squamscott River also determined that minimum DO did not occur with elevated algal growth. Nonetheless, NHDES proceeded with the regression analyses presuming that the minimum DO was solely a function of the algal growth present in these systems.

In their report NHDES first notes that at the two stations (GRBGB and GRBCML) where the minimum DO was acceptable the 90th percentile chl-a and median TN are 3.3 μg/L and 0.30 mg/L respectively for GRBCML, and 9.3 μg/L and 0.39 mg/L for GRBGB, respectively. From this information NHDES concludes that the maximum measured 90th percentile chl-a and median TN at stations not impaired for DO are 9.3 μg/L and 0.39 mg/L, respectively. NHDES then states that the Lamprey River low DO recorded with the datasonde is influenced by stratifications that occurs at neap tide and possibly SOD and may not be representative of typical conditions and therefore excludes this data from further consideration. NHDES then observes that the minimum 90th percentile chl-a at the remaining three DO impaired river stations is 12.1 μg/L at the Squamscott River and the minimum median TN is 0.52 mg/L at the Salmon Falls River station. The final criteria for 90th percentile chl-a and median TN is established as the midpoint between the Great Bay chl-a (9.3 μg/L) and TN (0.39 mg/L) values and the minimum chl-a (12 μg/l) and TN (0.52 mg/L) measured in the DO impaired tidal tributaries, yielding a median 90th percentile chl-a criterion of 10 μg/L (rounded down from 10.7 μg/L) and a median TN criterion of 0.45 mg/L. Nowhere in this analysis was the specific hydrodynamics, detention time, or any other physical factor effecting algal growth or the DO regime considered. In essence, NHDES assumed that all of the physical characteristics from the diverse areas (tidal rivers, open bay, harbor mouth) were identical, with the only variables being DO, nitrogen and chlorophyll-a. As discussed below, this assessment methodology violated fundamental principles of ecological data analysis and did not conform to any accepted methods of "stressor-response" analysis because the changing physical conditions and their impact on the DO regime were completely ignored. Assessment of the impact of co-varying and changing ecological conditions on the parameters of concern is a standard part of any thorough data analysis.

The minimum DO at the monitoring stations used in these regressions is measured at various locations throughout the Great Bay Estuary including the tidal rivers, Great Bay, and Portsmouth Harbor. The minimum DO at each of these stations is affected by site specific factors including BOD oxidation (biochemical oxygen demand), ammonia oxidation, SOD, tidal exchange, ocean DO, atmospheric reaeration, stratification and algal photosynthesis and respiration. These critical factors influence ambient DO concentrations and are, without any serious scientific debate, radically different in the various open water settings and across the individual tidal rivers themselves. Therefore, it is not scientifically defensible to assert that the only discriminating variable between sites is algal photosynthesis and respiration. Moreover, as determined through this study, the Squamscott River algal data cannot be plotted on the same chart with any other tidal river because there is a major algal source discharging to that river (Exeter treatment facility). The Exeter discharge may account for up to 100% of the algal levels measured in the river, though higher algal growth does occur periodically in the system under low flow conditions due to available nutrient levels. Thus the elevated algal level found in the Squamscott River is not solely attributable to the TN concentration occurring in that river but is also a function of an external load. This condition is unique to the Squamscott River and occurs nowhere else in the areas evaluated by NHDES in producing the DO-TN regression.

The regression analysis was heavily influenced by the Squamscott River data. The failure to account for the Exeter algal loading is a serious data evaluation error that renders the regression analysis completely unreliable for its intended purpose, even if the differing physical setting influences were not considered. As discussed in more detail within this report, the Squamscott spatial surveys will show that water quality measured at the mouth of the Squamscott River does not reasonably represent water quality throughout the river and therefore should not be used to predict nutrient-chl-a-DO conditions in the upstream areas. The Squamscott River also has extensive tidal marshes lining much of its banks, unlike the other areas included in the NHDES regression analysis. These areas contribute lower DO during the ebb tide and this DO condition may not be significantly affected by the nutrient level present in the river itself as low DO is a common condition in tidal marshes.

Given the unique factors influencing the DO regime of the Squamscott River, that do not occur in other areas used to develop the NHDES regression analysis, the only scientifically-defensible method to determine the effect of algae on minimum DO levels is to develop a DO model that properly represents each component of the DO balance, including algal photosynthesis and respiration. If algal photosynthesis is an important component of the total DO balance, a nutrient-algal model should be developed to quantitatively relate nitrogen concentrations to algal photosynthesis and respiration. However, as discussed below, given the magnitude of the algal loading from the Exeter facility, modeling the system would not be a useful exercise until that external input is addressed.

III. DESCRIPTION OF STUDY AREA

The study area for this water quality field study comprises the Squamscott River from the Great Dam in downtown Exeter to the Railroad Bridge in Stratham and Newfields (about 6.4 miles from the dam). The Squamscott River is part of a set of waterbodies included in the Great Bay Estuary System. Figure 4 presents an overview of the Great Bay Estuary System. Upstream of the dam the river is called Exeter and represents an approximate total drainage area of 107 mi^2. A USGS flow station is located a few miles upstream and captures a drainage area of 63.5 mi^2. An additional drainage area of approximately 20 mi^2 drains to the Squamscott River downstream of the dam location. The annual average flow at the dam is about 200 cfs (1997-2011) while the monthly flows, during the summer (June-September), have an average value of 88 cfs. Figure 5 presents the estimated annual and summer average flows (June-September) at the dam. Figure 6 presents the average cross sectional depth and area along the Squamscott River from the dam to the Railroad Bridge (RR) at the river entrance. These cross sectional depths and areas were computed from several bathymetry datasets, including one collected specifically for the development of a water quality model of the study area.

Two point sources directly discharge into the Squamscott River: Exeter WWTP and Newfields WWTP. The 2005-2006 average effluent flows are 2.25 MGD and 0.07 MGD, for both, respectively. The location of these facilities is depicted in Figure 4. The Exeter facility utilizes aerated lagoons that allow for significant algal growth to occur within the facility. The mechanical plant employed by Newfields does not have this characteristic.

IV. FIELD STUDIES

The purpose of these field studies was to collect data that could potentially be used to calibrate a mechanistic coupled hydrodynamic/water quality model of the Squamscott River. The primary purpose of the modeling study is to quantify the factors contributing to the DO balance in the Squamscott River, including CBOD oxidation, ammonia oxidation, SOD, algal photosynthesis and respiration and atmospheric reaeration. The calibrated model would then be used to assess the effect of nitrogen point and nonpoint source loads on the DO levels in the Squamscott River.

A. SAMPLING OBJECTIVES

1. Measurement of Point and NPS Loads

Although there are historical measurements of Exeter WWTP effluent water quality, water quality effluent measurements were made during the time period of river surveys because it is this effluent quality that is impacting the Squamscott River DO. No water quality effluent measurements were taken for the Newfields WWTP because its effluent flow is relatively small. The principal non point source (NPS) loads are represented by the flow and water quality flowing over the dam. Consequently, water quality measurements were taken at a location immediately upstream of the dam.

2. Squamscott River Water Quality

The sampling strategy for the Squamscott River was to collect data to develop an approximate AM and PM "snapshot" of Squamscott River water quality and to also install datasondes at three stations to continuously sample for certain water quality parameters. Because the tidal motion is at a minimum near slack tide conditions, it was proposed to perform spatial surveys near morning and afternoon slack tide conditions. "Near" slack tide conditions may be defined as from one to one and a half hours before slack tide to one to one and half hours after slack tide. Sampling at consecutive AM and PM slack tides provided a "snapshot" view of the Squamscott River at high and low tide. If these high and low tide spatial water quality profiles are shifted downstream and upstream, respectively, until the salinity concentrations overlay, a composite picture of a mid tide water quality spatial profile is produced. A goal of this exercise was to produce an estimate of the change in Squamscott River DO between AM and PM without the interference of tidal motion.

B. IMPLEMENTATION OF SAMPLING EVENTS

1. Continuous Monitoring

Three Eureka datasondes were deployed for continuous monitoring of temperature, salinity, turbidity, pH, chlorophyll-a (chl-a) and DO. The datasonde locations were: the Oxbow Cut, the US Route 101 Bridge, the Newfields town dock, and the Squamscott River Railroad Bridge. For calibration purposes, chlorophyll-a, phaeophytin and colored dissolved organic matter (CDOM) measurements were collected at the datasonde deployment locations. The UNH/SWMP YSI long term datasonde deployed at the Railroad Bridge was also employed for this study. Figure 7 presents the datasonde locations. One of the Eureka datasondes was deployed at the UNH YSI datasonde location for a few days to check for consistency between both datasonde measurements. Both datasondes produced similar results.

2. Spatial Water Quality Field Measurements

Two spatial water quality surveys were performed at 10 locations along the Squamscott River, including a station upstream of the dam and one station in the near Great Bay area. Figure 7 depicts the locations of these water quality stations. Both surveys attempted to focus on periods near maximum spring and neap tides and during steady low flow conditions to the extent possible. During each spatial survey, 2 sets of measurements were performed at each location: near slack high and near slack low tide conditions. The water quality constituents measured during these spatial surveys were: BOD5, ultimate BOD (uBOD), CDOM, NO2, NO3, NH4, total dissolved nitrogen (TDN), TN, total phosphorus (TP), PO4, dissolved organic carbon (DOC), total suspended solids (TSS), non-volatile suspended solids (NVSS), particulate organic carbon (POC), particulate organic nitrogen (PON), and chlorophyll-a. At each location included in the spatial surveys, multiple depth measurements were taken using YSI datasondes from Jackson Environmental Laboratory. These datasonde measurements included: temperature, salinity, turbidity, light attenuation, solar irradiance, DO, pH, and depth.

3. Effluent and Above Dam Water Quality Measurements

Multiple water quality measurements were performed on the Exeter effluent and above the dam at the head of the Squamscott River. These measurements included: BOD5, uBOD, CDOM, NO2, NO3, NH4, TDN, TN, TP, PO4, DOC, TSS, NVSS, POC, PON, and chlorophyll-a.

4. Photosynthesis and Respiration (P&R) Study

P&R tests were performed on three separate days. Algal photosynthesis and respiration rates could be estimated from these light and dark bottle studies and eventually provide a comparison between modeled and measured primary productivity.

C. RESULTS OF SPATIAL SURVEYS

For each of the spatial surveys, eight tidal stations in the Squamscott River, one in Great Bay, and one above Exeter Dam were sampled at both high water and low water slack conditions. The times of high and low water slack tides were based on published NOAA Tide Tables. For logistical reasons it is not possible to sample each stations at exactly slack tide conditions and as a compromise, each tidal station was sampled within approximately 1 ½ hours of predicted slack conditions. An example of data collected on the high and low water slack conditions is shown in the top panel of Figure 8 for the August 12th salinity measurements. The salinity data are plotted versus river milepoint with milepoint 0 at the Exeter Dam and Station 9 at the Railroad Bridge (milepoint 6.5). Station 10 in Great Bay is plotted at milepoint 8.7.

To produce a longitudinal profile of water quality at one tidal condition an approach was developed to translate high tide measurements downstream to a mean tide condition and translate low tide measurement upstream to the same mean tide condition. The distance to translate the high and low water slack tide water quality measurements was based on producing a longitudinal salinity profile that approximated one smooth salinity distribution that would be expected if one had sampled at mean tide conditions. The August 12th high and low tide salinity measurements translated to mean tide are shown in the bottom panel of Figure 8. The salinity profile is a representation of what would be expected if samples were collected at both morning and afternoon mean tide conditions. As a practical matter mean tide condition is difficult to sample because water velocities are generally fastest, therefore resulting in a short time frame to capture mean tide.

1. August 12, 2011 Survey

The August 12th survey was conducted during low flow conditions. On the day of the survey the estimated flow at Exeter Dam was 23 cfs. However, a few days prior to the survey, the estimated Exeter Dam flow was approximately 10 cfs. Spring tide conditions occurred during the August 12th survey with a tidal range of 2.1 m.

The results of the translated data for salinity, DO, % DO Saturation and chl-a are shown in Figure 9. The salinity at mean tide varies from 5 ppt just below the Exeter Dam to 30 ppt in Great Bay. At most locations, the water column was vertically uniform with some evidence of stratification at some stations. Most DO concentrations are near or above saturation with peak DO concentrations at 15 mg/L. The DO data also indicate that afternoon concentrations are 1 mg/L to 3 mg/L higher than morning measurements as a consequence of oxygen production by algal photosynthesis. Upstream chl-a concentrations are over 100 μg/L and decrease in the downstream direction due to dilution by Great Bay waters.

A major factor in the occurrence of elevated chl-a levels in the Upper Squamscott River is the extremely high concentration of chl-a in the Exeter WWTP effluent. Exeter treats its wastewater with an aerated lagoon system as opposed to a conventional activated sludge system. With ample nutrients and sunlight, algae grow in the last aerated lagoon prior to discharge and chl-a levels can reach 300 μg/L to 500 μg/L in the effluent. On August 12th, the Exeter WWTP effluent chl-a was 435 μg/L.

Figure 10 presents spatial profiles of chl-a, dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and the photosynthetically available radiation (PAR) light extinction coefficient. Dissolved inorganic nitrogen (ammonia plus nitrite and nitrate) is near zero downstream of milepoint 4 and is a limiting factor in the further growth of algae in this segment of the Squamscott River. Dissolved inorganic phosphorus averages near 0.025 mg/L and therefore does not limit algal growth. The high extinction coefficient of approximately 3.0/m in the Upper Squamscott River is also likely contributing to a reduction in the growth rate of algae. In addition to nitrogen and reduced light limiting algal growth in Squamscott River, the high flushing rate associated with the large tidal range (approximately 2 m) is also a factor controlling growth in the Squamscott River.

Figure 11 shows the total nitrogen concentration and its forms in the Squamscott River. Ammonia levels are near zero throughout the Squamscott River despite the fact that the Exeter WWTP effluent NH_4 on the day of the survey was approximately 5.5 mg/L. The Exeter effluent ammonia was likely used for algal growth and possibly transformed to nitrate by nitrifying bacteria. Nitrate levels are also low for most of the Squamscott River even though the Exeter WWTP effluent nitrate was 9.2 mg/L on the day of the survey. Nitrate was also likely used by algae for growth and also possibly lost to the atmosphere by denitrification in the sediment. The bottom panel in Figure 11 indicates that most of the organic nitrogen is in the particulate form and likely associated with algal cell nitrogen. A similar spatial profile of Squamscott River phosphorus is presented in Figure 12. The inorganic phosphorus concentrations are generally above algal growth limiting concentrations. Most of the organic phosphorus is likely associated with algal cells.

Figure 13 presents spatial profiles of total organic carbon, particulate carbon, and dissolved organic carbon in the Squamscott River. The total organic carbon of 8 mg/L to 10 mg/L in the Squamscott River is approximately evenly divided between dissolved and particulate phases. The average particulate carbon concentration is mostly due to the high river concentration of algal during this survey. For a carbon to chl-a ratio of 30/1, the algal contribution to river particulate organic carbon would be 3.75 mg/L for an average upstream Squamscott River chl-a concentration of 125 μg/L. The dissolved organic carbon is mostly associated with the CDOM flowing over the Exeter Dam.

Figure 14 presents spatial profiles of the light extinction coefficient and the factors that contribute to water column light extinction: CDOM, suspended solids and chl-a. During this survey, the high levels of chl-a are the principal factor reducing water column light. The algal contribution to light extinction can be approximated by applying the factor of 0.0188 (used by Morrison[1] in his study of Great Bay water transparency) to the chl-a concentration in μg/L. For an average upstream chl-a concentration of 125 μg/L the component of K_d associated with algal cells is 2.35/m (0.0188 x 125) which is approximately 80% of the total

[1] (Using Moored Arrays and Hyperspectral Aerial Imaging to Develop Nutrient Criteria for New Hampshire's Estuaries, 2008)

average K_d of 2.8/m in the Upper Squamscott River. The balance of the reduction in water column transparency is due to CDOM and nonalgal turbidity.

2. August 24, 2012 Survey

The same set of spatial profiles of Squamscott River water quality presented for the August 12th survey are contained in Figures 15 through 20. The river flow during and immediately prior to the August 24th survey was slightly higher than the August 12th survey, averaging 35 cfs. However, one week prior to the survey the river flow at Exeter Dam was approximately 90 cfs. In contrast to the August 12th spring tide condition, the August 24th survey was conducted during neap tide conditions with a tidal range of 1.4 m.

The most significant difference in Squamscott River water quality between the August 24th and August 12th surveys is the greatly reduced chl-a levels on August 24th (Figure 15). It is likely higher river flows preceding the August 24th survey flushed out the elevated chl-a levels that occurred during early August low flow conditions. Other water quality variables including DO and nutrients also reflect the effects of reduced chl-a levels. Dissolved oxygen levels are below saturation with a few measurements below the DO standard of 5.0 mg/L. The inorganic nitrogen and phosphorus levels shown on Figure 16 are also considerably higher than the August 12th concentrations as a consequence of reduced rate of algal uptake of nutrients. Total nitrogen levels (Figure 17) are similar to the August 12th concentrations and particulate organic nitrogen levels are lower due to the reduced algal biomass on August 24th. A similar pattern for phosphorus is shown in Figure 16 and Figure 18 with higher dissolved inorganic phosphorus (PO4) and lower organic phosphorus.

Water transparency as indicated by the light extinction coefficient (Figure 16) on the August 24th survey is similar to August 12th values. For the August 24th survey, CDOM is the principal contributor to light extinction in contrast to algal (chl-a) during the August 12th survey. The component of Kd associated with algal cells can be computed as described in the previous section and for this survey it accounts for approximately 20% of the total average Kd in the Upper Squamscott River. August 24th CDOM levels are approximately double the August 12th values in the Upper Squamscott River and chl-a concentrations are about 25% of the August 12th values. Higher CDOM levels during the August 24th survey may have been a contributing factor to reduced algal levels in addition to the greater flushing rate associated with the higher flows prior to the August 24th survey.

The spatial profile of Squamscott River organic carbon is shown in Figure 19. The August 24th river particulate organic nitrogen is approximately one third of the August 12th values due primarily to the lower algal levels. However, August 24th dissolved organic carbon concentrations are nearly double August 12th levels. The higher August 24th dissolved

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organic concentrations are likely associated with the higher CDOM concentrations related to the greater August 24th river flows.

D. DATASONDE RESULTS (AUGUST/SEPTEMBER 2011)

In addition to the two August spatial surveys, datasonde with probes to continuously record depth, salinity, temperature, chl-a and DO were installed at two locations in the Squamscott River: the Route 101 Bridge (Mile 1.9) and at Newfields (Mile 4.3) (Figures 21 through 24). Measurements were made between August 15th and September 30, 2011 with a one week interruption during Hurricane Irene. A datasonde was also placed at the Oxbow (Mile 2.2) (Figure 25 and 26) for a one week periods in August. The primary purpose of the datasonde data was to provide a more complete description of DO and chl-a levels in the Squamscott River. August – September 2011 water quality data is also presented for the datasonde at the Railroad Bridge (Mile 6.5) (Figures 27 and 28) that is maintained by the Centralized Data Management Office (CDMO) of the National Estuarine Research System. Also to assist in interpreting this data river flow, light intensity and air temperature is presented for this two month period (Figure 29).

Figure 21 shows the depth, salinity and temperature recorded at the Route 101 Bridge Station. The depth measurements are not intended to indicate the actual depth, but rather the tidal variation in stage. For example after Hurricane Irene, the depth sensor was not placed at the same depth it was at before the hurricane. For convenience, the hydrograph of the Exeter River flow at the USGS gage is presented as the red line on the depth plot. The salinity varies with river flow as expected ranging from a high of 15 ppt after a sustained low flow period to zero at high flow conditions. Figure 22 presents the chl-a and DO data at the Route 101 Bridge. An elevated chl-a concentration of 50 μg/L is measured on August 14th after a low flow period followed by a substantial decline in chl-a concentrations during the subsequent high flow period.

The DO in August shows a response to both changes in solar radiation and chl-a levels. DO levels are lower on August 15th and 16th than the next few days even though chl-a concentrations are higher on August 15th and 16th. This is explained by the low solar radiation (Figure 29) on August 15th and 16th reducing oxygen production by algal photosynthesis. Dissolved oxygen concentration gradually declines as chl-a decreases. On August 25th there is a steep decline in DO below the DO standard possibly reflecting lower chl-a levels and reduced solar radiation. Similar DO variability with solar radiation and chl-a occurs in September. There are also some increasing trends in DO starting September 8th due to an increase in DO saturation of approximately 1.0 mg/L as the water temperature declines from mean 25°C to less than 20°C.

The same data collected at the Newfields location (Figures 23 and 24) show the same behavior. At this station there is some stratification and because the sensor is at a fixed depth it records water quality at the surface during low tide and near bottom water quality at high tide. This is evident in the large range in salinity over a tidal cycle shown in Figure 23. Figure 24 shows the same pattern of decreasing DO with decreasing chl-a concentrations that is exacerbated with the limited sunlight on August 25th. A datasonde was installed in the upstream area of the Squamscott River at the Oxbow for a one week period in August (Figures 25 and 26). There is the same pattern of declining DO with decreasing chl-a.

The datasonde at the Railroad Bridge (Figures 27 and 28) provides some DO data that was recorded during early August when river flows were very low and during the time near the August 12th survey when chl-a levels were high. The salinity data on Figure 27 indicates that there is probably stratification during high flow conditions because the variations in salinity in late August appear to be greater than would be expected from tidal translation. The DO data in Figure 28 shows the effects of the elevated chl-a levels during the August 12th survey with DO levels over 160% saturation. Although there is no chl-a data it is likely the temporal patterns in DO are largely a result of oxygen production associated with high chl-a levels.

V. MASS BALANCE ANALYSIS

Although the purpose of these field studies was to develop data for the calibration of a time variable, three dimensional, coupled hydrodynamic/water quality model of the Squamscott River and adjacent waters of Great Bay, a preliminary mass balance analysis was performed to derive some preliminary insight into the nutrient-algal dynamics in the Squamscott River.

The mass balance was performed with the assumption of steady state and that all computed water quality constituents are treated as a conservative substance such as a dye. Even though this is not true for chl-a and inorganic forms of nitrogen and phosphorus, it is useful to compare computed river profiles of chl-a and nutrients with measured water quality. For example, if measured river inorganic nutrient profiles are considerably less than computed profiles, then it can be concluded that there has been a significant loss of inorganic nutrients from the water column due to such factors as algal uptake or possible diffusion of nutrients to the river sediment. On the other hand, measured chl-a concentrations well above the computed chl-a profile indicates substantial growth of algae in the river.

The concept behind the mass balance calculation is to use measured salinity concentrations to define the fraction of Squamscott River water at any location that is freshwater and Great Bay water. For example, with an average Great Bay salinity concentration of 25 ppt, a location in the river with a salinity concentration of 10 ppt would be 40% (10/25) Great Bay water and 60% freshwater. The water quality constituent concentration in the freshwater at this location is simply the flow weighted concentration of the water quality constituent in the freshwater flowing over Exeter Dam and the Exeter WWTP effluent. The Great Bay water quality constituent concentration is based on measurements. To continue this example, the water quality concentration at a river location would be computed as 40% of the blended freshwater (upstream plus Exeter effluent) and 60% of the measured Great Bay concentrations.

The results of the mass balance calculations for the August 12th survey for chl-a and nutrients are shown in Figure 30. The top panel shows the mass balance for chl-a. On the day of the survey, the Exeter WWTP effluent chl-a was 435 μg/L. Because there was some variability in river flow prior to the August 12th survey, the mass balance was computed for river flows of 15 cfs and 23 cfs as a sensitivity to this range in river flow. The mass balance calculations start at the location of the Exeter WWTP discharge and extend into Great Bay. As shown in Figure 30 the calculated chl-a concentration in the Upper Squamscott River is 40 μg/L to 50 μg/L and is mostly due to the Exeter effluent chl-a since the upstream and Great Bay chl-a concentration are 10 μg/L and 5 μg/L, respectively. The fact that the measured chl-a is well above the computed 40 μg/L to 50 μg/L concentration indicates that there is additional substantial algal growth in the Upper Squamscott River.

The TN mass balance suggests a minor net loss of nitrogen from the water column, possibly a consequence of settling of algal cells with some additional net flux of inorganic nitrogen to the sediment. The significant difference between the computed ammonia and nitrate profiles and the measured data is primarily due to uptake by algae. A similar pattern occurs for phosphorus as shown by the bottom two panels in Figure 30.

A similar set of mass balance calculations is shown for the August 24th survey in Figure 31. The chl-a profiles shown in the top panel suggest that Squamscott River chl-a levels on August 24th can mostly be explained by the Exeter WWTP discharge with no further growth in the river. Total nitrogen appears nearly conservative with the possibility of some diffusion of nitrogen from the sediment. There is a significant discrepancy between the computed and measured ammonia concentrations even though there is little or no nutrient uptake by algae. The loss of ammonia in the water column may be due to nitrification, but the nitrate produced through nitrification does not appear in the water column and may have diffused into the sediment and been converted to nitrogen gas through denitrification. Total phosphorus appears to behave conservatively or possibly a slight loss to the sediment.

Although the interpretation of these mass balance calculations is preliminary they clearly indicate some important factors about nitrogen-chl-a dynamics in the Squamscott River. The discharge of algal cells that grow in the aerated lagoon of the Exeter WWTP can have a significant effect on Squamscott River algal concentrations, in particular during sunny-low flow conditions. In addition inorganic nitrogen and phosphorus from the Exeter WWTP can support further growth of algae in the river. There is also a suggestion that nitrification may also occur in the Squamscott River and loss of nitrate from the water column through sediment denitrification may be a net loss of nitrogen in this river system.

IV. DISCUSSION OF RESULTS

Both the August spatial surveys and the datasonde results show that there is no simple relationship between algal levels (chl-a) and DO in the Squamscott River as was assumed by NHDES in developing chl-a criteria for tidal tributaries to the Great Bay Estuary. The effect of algae on river DO is dependent on flow, solar radiation, water clarity, and nutrient concentrations in addition to the algal levels. During the August 12, 2011 survey, both early morning and afternoon river DO concentration were supersaturated as a consequence of chl-a levels over 100 μg/L and sunny condition in contrast to the August 24, 2011 survey when some DO measurements were below the DO standard of 5.0 μg/L and chl-a levels were between 10 μg/L and 50 μg/L. These spatial survey results show that elevated chl-a levels can substantially raise river DO levels. The general pattern of high river DO with high chl-a concentrations is reflected in the August 15-26, 2011 datasonde results at Newfields (Figure 24) when river DO levels substantially decline as river chl-a decreases. However, on this same figure, the effect of solar radiation on river DO is demonstrated by the below saturation August 15-16, 2011 river DO even though chl-a levels are elevated.

The results of these field studies indicate that dissolved oxygen levels in the Squamscott River periodically fall below the instantaneous DO criterion of 5.0 mg/L. These excursions below the DO criterion are correlated with low chl-a levels and possibly low solar radiation. During the August 12th survey chl-a levels at mean tide conditions ranged from over 150 μg/L in the Upper Squamscott River to 50 μg/L at the mouth of the river. Corresponding morning dissolved oxygen levels were generally over 100% saturation with afternoon DO concentration approximately 1.0 mg/L to 3.0 mg/L higher. In contrast, morning DO levels during the August 24th survey, when river chl-a levels were much lower, were less than 100% saturation with some morning DO concentrations below 5.0 mg/L. Thus, for the conditions analyzed, the elevated algal levels tend to increase the river DO on average. However, such elevated algal levels probably contribute to increased SOD which will contribute to lower DO when algal levels are low, as discussed further below.

The Exeter WWTP discharge is a dominant factor affecting DO levels of the Squamscott River. Extremely high algal levels (300 μg/L to 500 μg/L chl-a) are discharged from their aerated lagoon wastewater treatment system and can substantially increase river chl-a. In addition, total nitrogen and inorganic nitrogen concentrations in the Exeter effluent are generally near 20 mg/L and 15 mg/L respectively and thereby provide nutrients for additional algal growth in the river.

When river algal levels decrease due to high flows or turbid conditions, oxygen production by algal photosynthesis is substantially reduced or nonexistent and river DO levels decline. Some of this decline in river DO is associated with the decay of algal cells that settled to the river bottom when river chl-a levels were elevated. These decaying algal cells contribute to the sediment oxygen demand caused by all forms of settled particulate organic carbon. Therefore, there is a residual oxygen demand produced by settled algal cells that occurs at times when there is no photosynthesically produced oxygen to offset this demand. When Exeter upgrades its WWTP to an activated sludge plant and reduces its effluent nitrogen, there should be an immediate and substantial reduction in river chl-a levels accompanied by a decrease in river SOD.

For example, the results of the preliminary mass balance for the August 12, 2011 survey indicate that the Exeter WWTP discharge with 435 μg/L of chl-a raised the Squamscott River chl-a concentration by 50 μg/L without any consideration of further algal growth in the river. Without this significant input of algae by the Exeter WWTP discharge, the Squamscott River chl-a concentrations would be a result of some additional growth of the average chl-a of 10 μg/L coming over the Exeter Dam and the average chl-a of 5 μg/L from Great Bay. Although the additional increase in Squamscott River chl-a concentration due to further algal growth above these relatively low upstream and downstream background chl-a conditions is dependent on flushing time and river water clarity. Squamscott River chl-a levels near 50 μg/L to 100 μg/L will not occur when the Exeter WWTP converts to an activated sludge treatment system.

A reduction in Exeter's effluent nitrogen will also limit the available inorganic nitrogen for further growth above background chl-a levels. For example, at a nominal TN permit limit of 8 mg/L it is estimated that the long term effluent inorganic nitrogen concentration would be approximately 3.0 mg/L versus the current 15 mg/L to 20 mg/L measured in August 2011. As a guide, the following dilution and algal cell nitrogen composition calculation is intended to put into perspective the potential benefit of an improved Exeter WWTP effluent. For an Exeter WWTP effluent dilution ratio of 10/1 the increase in Squamscott River inorganic nitrogen would be approximately 0.30 mg/L. If a typical algal cell nitrogen to chl-a ratio of 10/1 is assumed, an available river inorganic nitrogen concentration of 0.30 mg/L would support a water column chl-a concentration of approximately 30 μg/L. The substantial reduction in the concentration of algal cells that settle to the river bottom and contribute to river SOD as a consequence of a reduction in the Exeter WWTP effluent nitrogen will increase Squamscott River minimum DO levels and possibly attain the DO standard.

A mechanistic water quality model coupled with additional field data (SOD, atmospheric reaeration) would provide a quantitative approach for developing a credible Exeter effluent TN limit. In the absence of a modeling analysis, the insight gained from available field studies, mass balance calculations, and best professional judgment indicate that with an upgrade of the Exeter WWTP to an activated sludge system with a monthly TN limit of 8 mg/L there will be a substantial reduction in Squamscott River chl-a levels and an increase in river DO. A decision on the benefit of further Exeter effluent TN reduction should be made with a calibrated water quality model, preferably calibrated with river field data collected after the Exeter WWTP upgrade because the current discharge of significant algal biomass is such an unusual condition and not very representative of an effluent from an activated sludge system with some level of nitrogen removal.

References

Jones, S.H. 2005. Survey of dissolved oxygen in the Lamprey and Squamscott rivers. Summary report. Office of Research and Development, Atlantic Ecology Division, U.S. Environmental Protection Agency, Narragansett, RI.

NHDES, 2009. Numeric Nutrient Criteria for the Great Bay Estuary. Final report. R-WD-09-12. New Hampshire Department of Environmental Services, Concord, NH.

Pennock, J. 2005. 2004 Lamprey River dissolved oxygen study. Final report. R-WD-06-24. NH Estuaries Project, Portsmouth, NH.

FIGURES

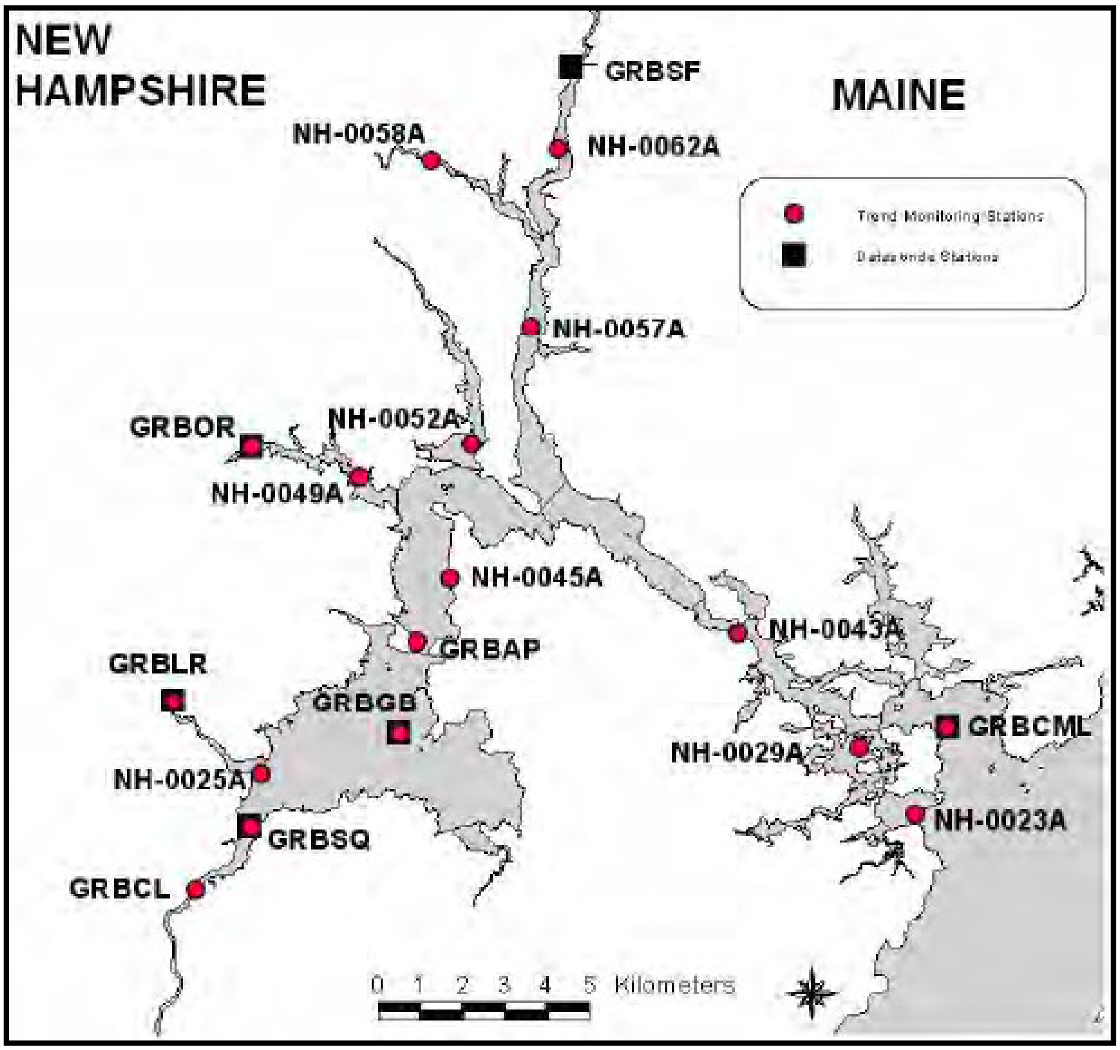


Figure 1. Trend Monitoring Stations for Water Quality in the Great Bay Estuary (New Hampshire DES, 2009)

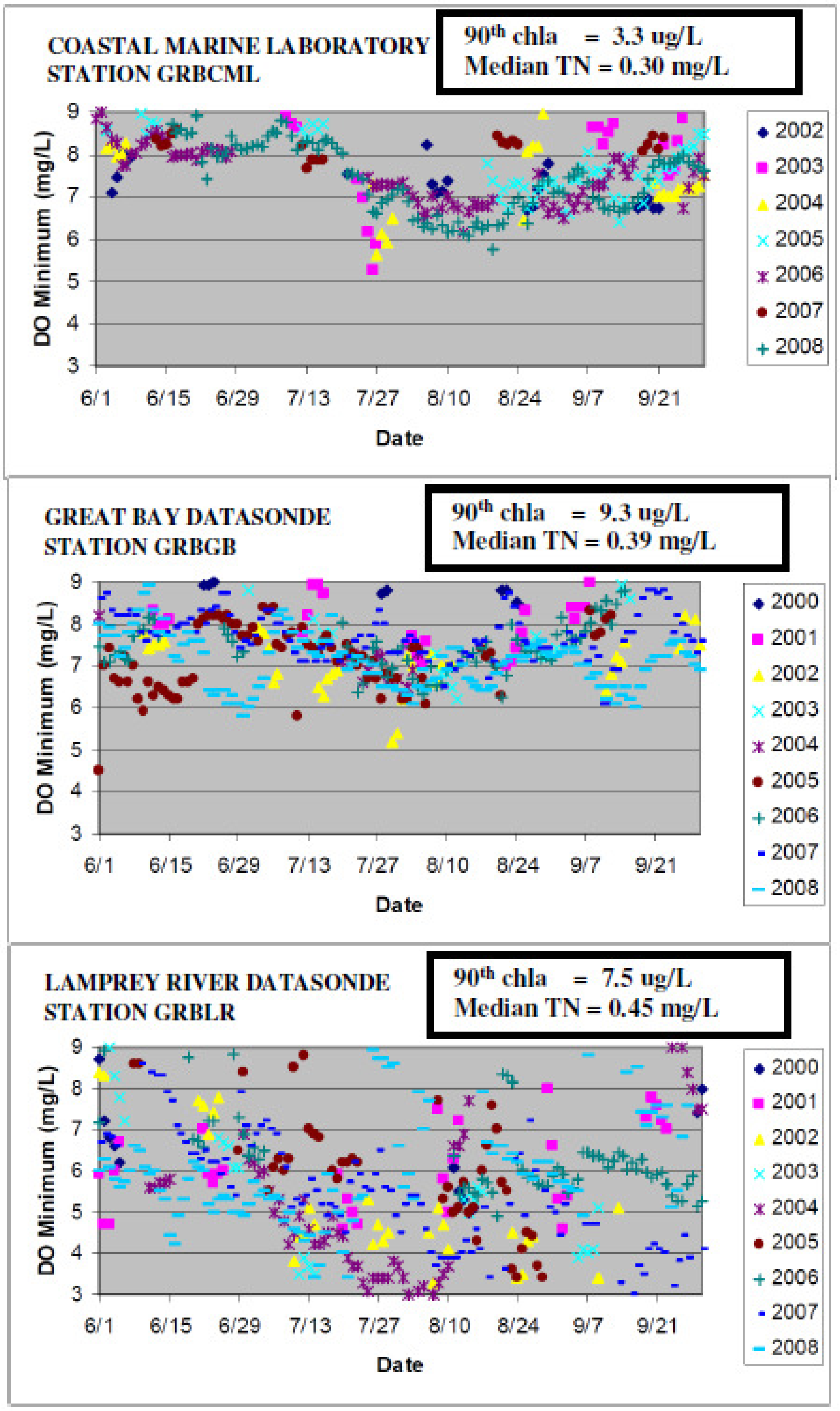


Figure 2. Daily Minimum DO (mg/L), June-September, 2000-2008. Stations GRBCML, GRBGB, GRBLR (New Hampshire DES, 2009)

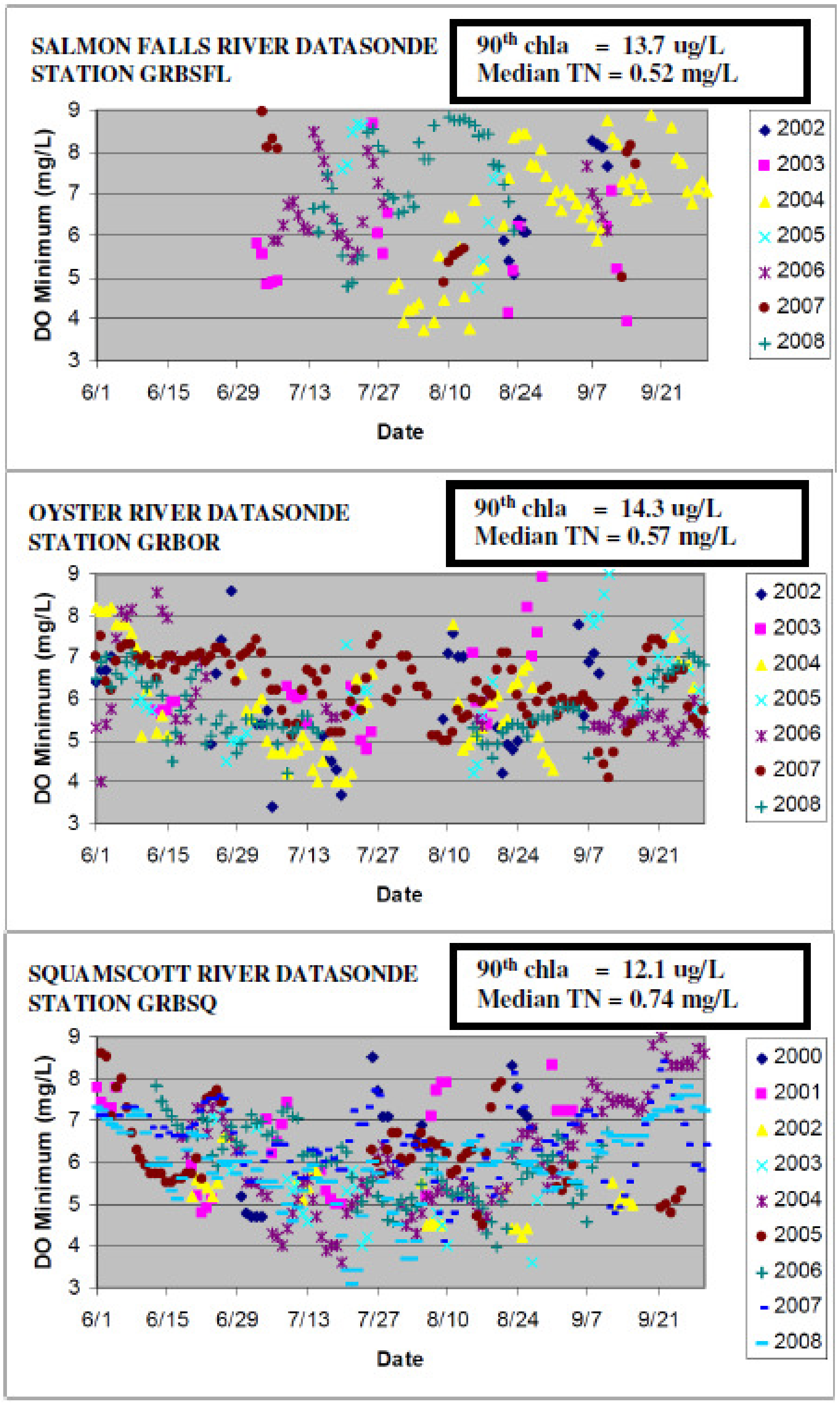
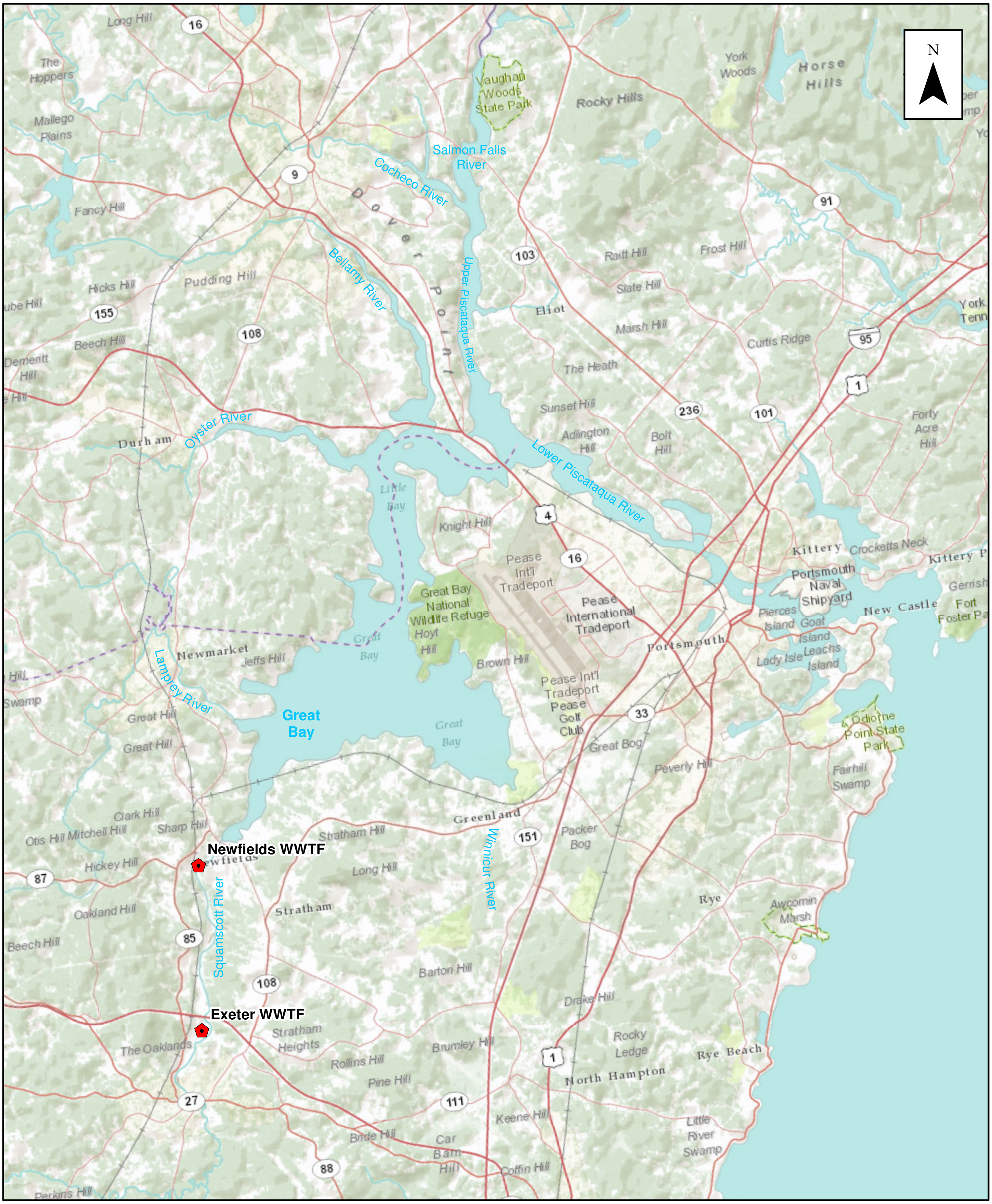


Figure 3. Daily Minimum DO (mg/L), June-September, 2000-2008. Stations GRBSFL, GRBOR, GRBSQ (New Hampshire DES, 2009)



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, AND, USGS, NRCAN, Kadaster NL, and the GIS User Community

0 1 2 4 Miles

HDR | HydroQual

Figure 4. Overview Map

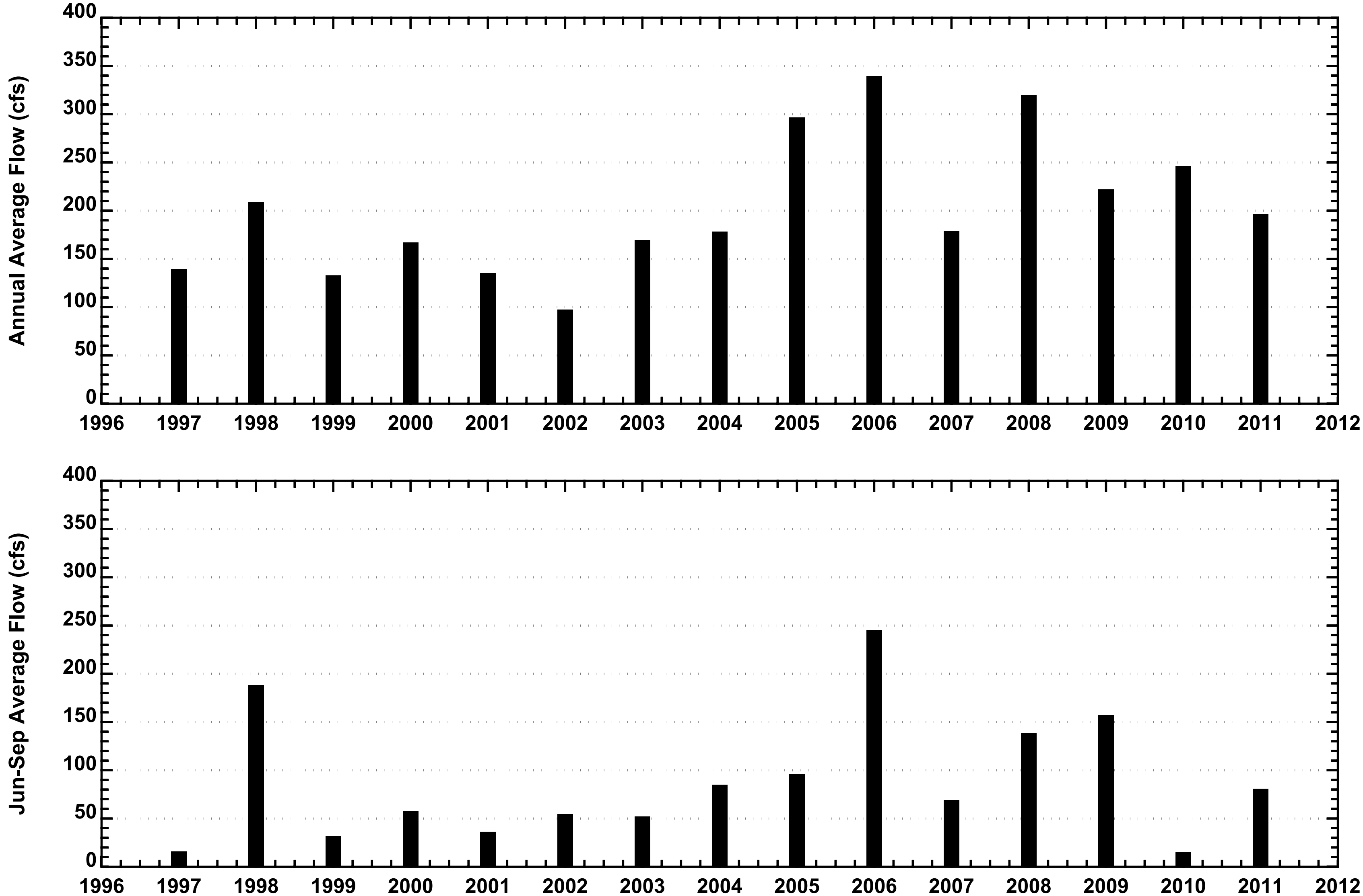


Figure 5. Exeter River Estimated Flow at the Dam (1997-2011)

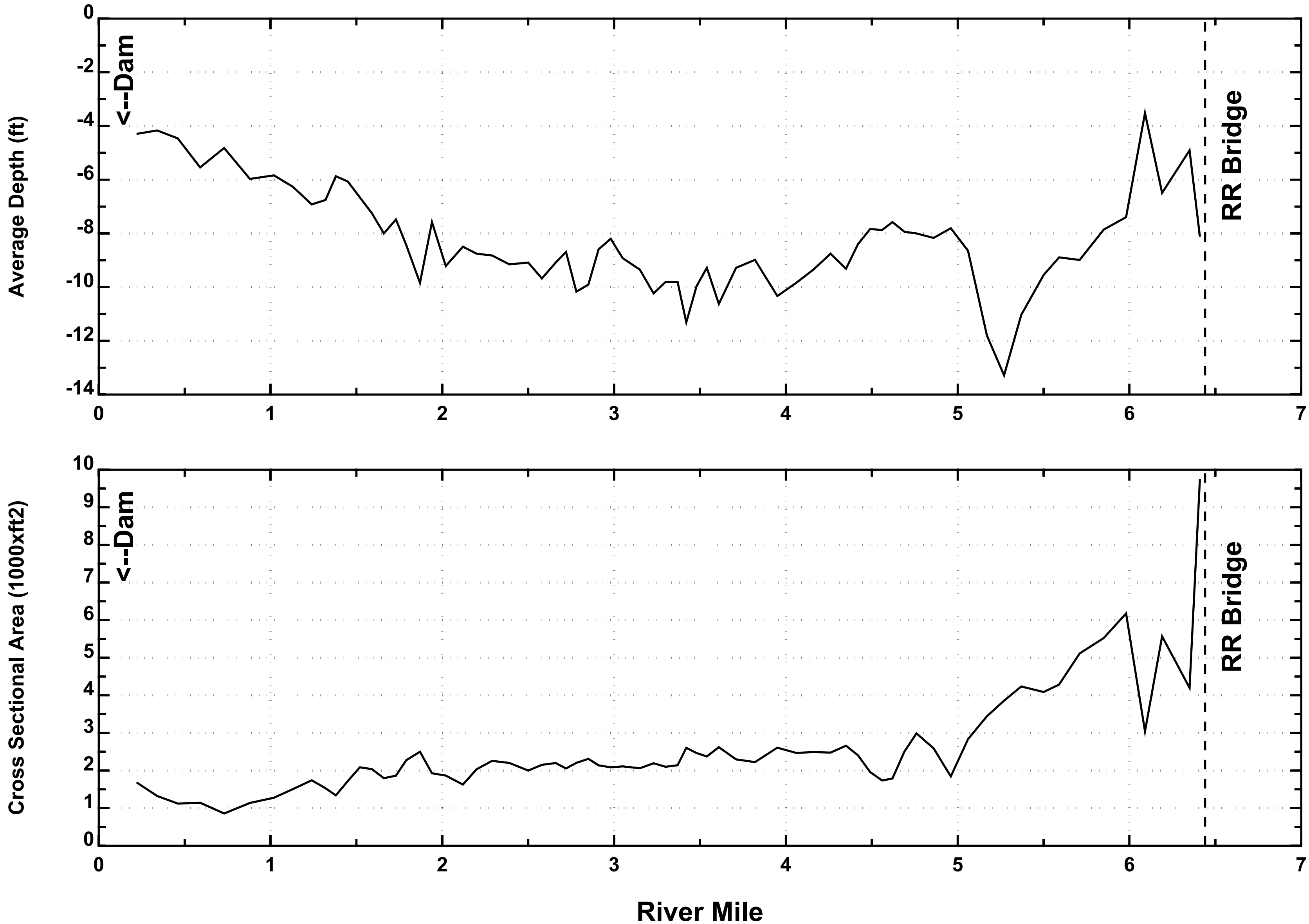
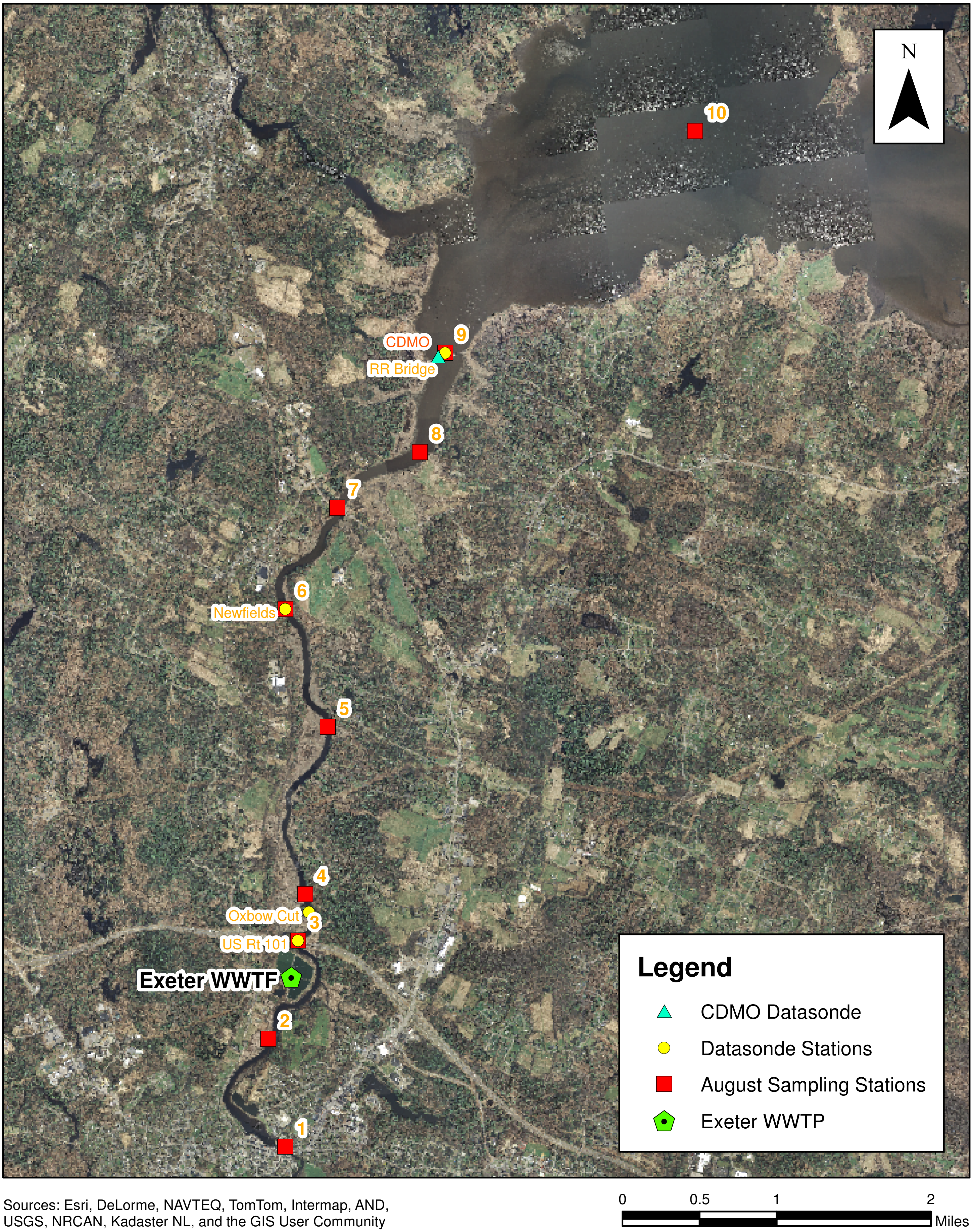


Figure 6. Squamscott River Average Cross Sectional Depth and Area



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, AND, USGS, NRCAN, Kadaster NL, and the GIS User Community

HDR | HydroQual

Figure 7. Water Quality Station Locations

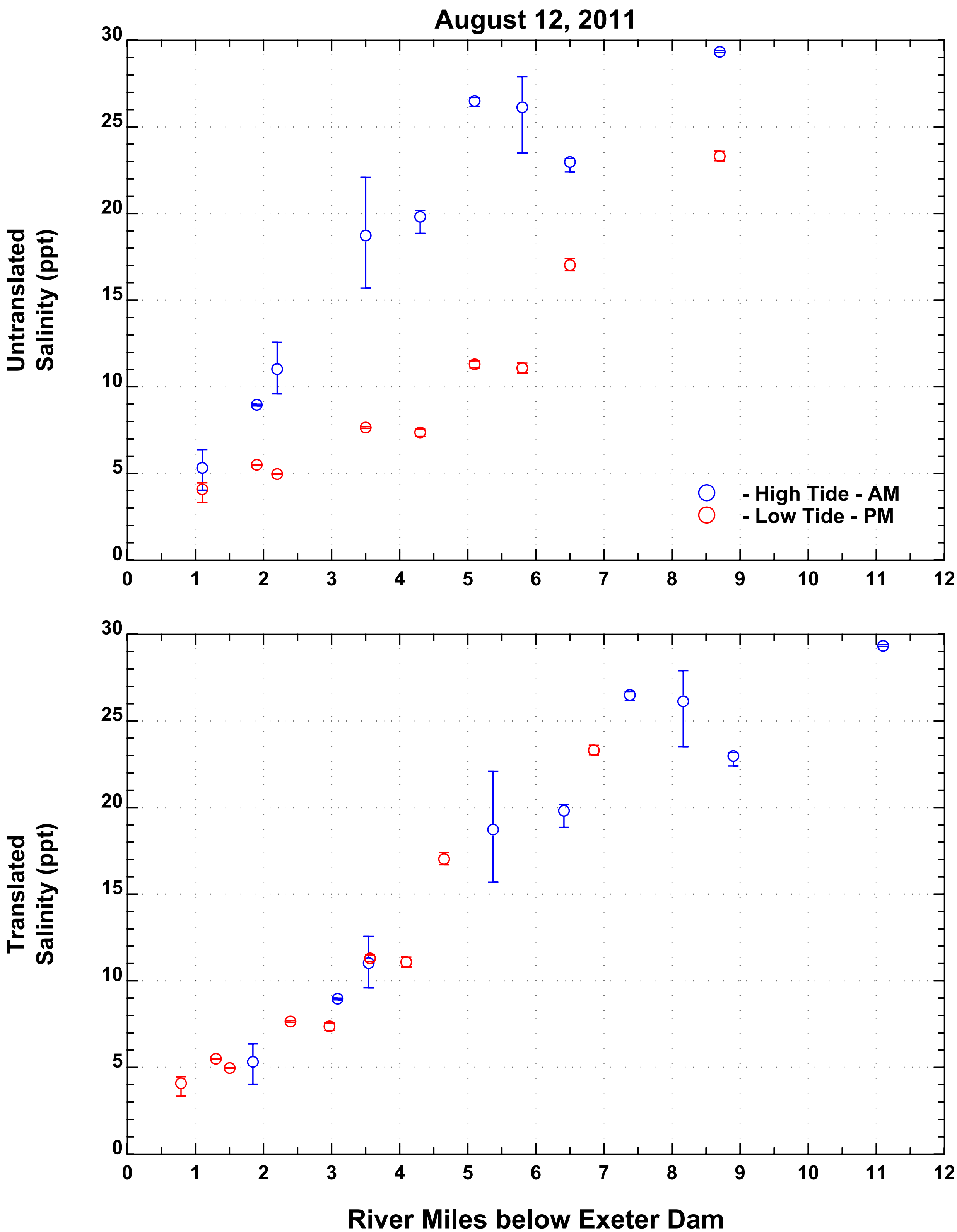


Figure 8. August 12, 2011 Squamscott River Salinity Profiles (Untranslated and Translated to Mean Tide)

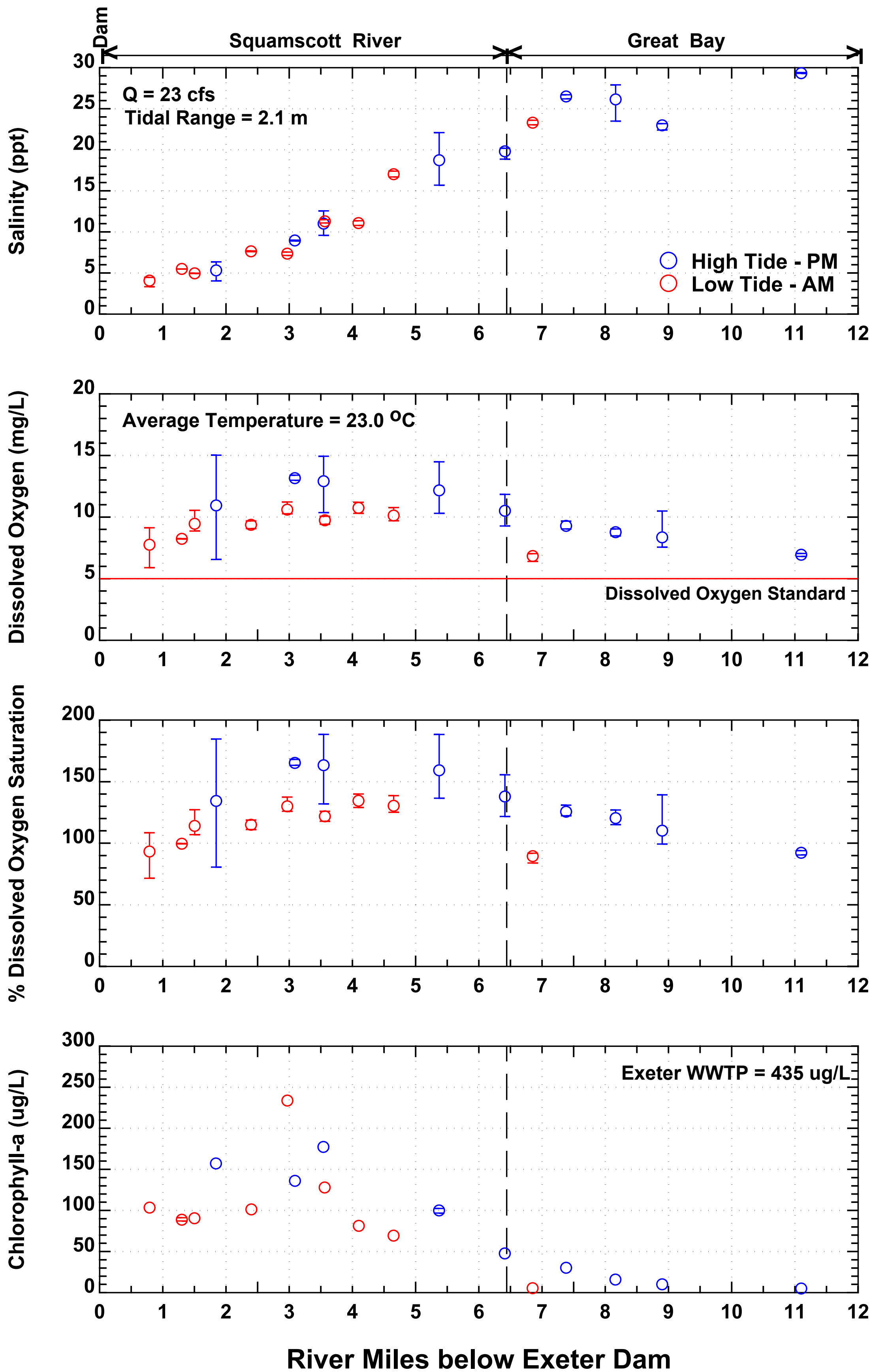


Figure 9. August 12, 2011 Spatial Profiles translated to Mean Tide Conditions Salinity, Dissolved Oxygen, % Dissolved Oxygen Saturation, Chlorophyll-a

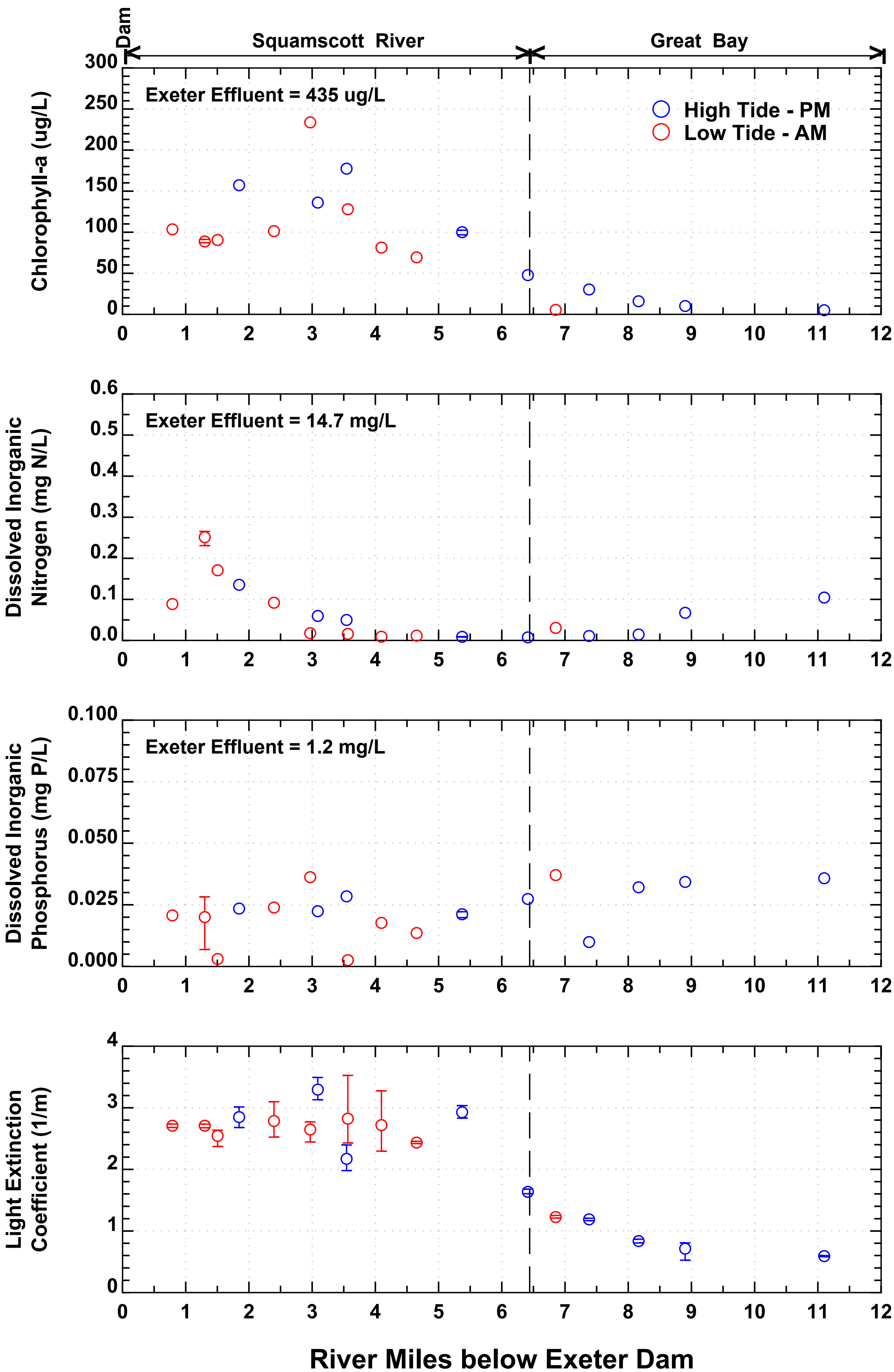


Figure 10. August 12, 2011 Spatial Profiles translated to Mean Tide Conditions Chlorophyll-a, Dissolved Inorganic Nitrogen Dissolved Inorganic Phophorus, Light Extinction Coefficient

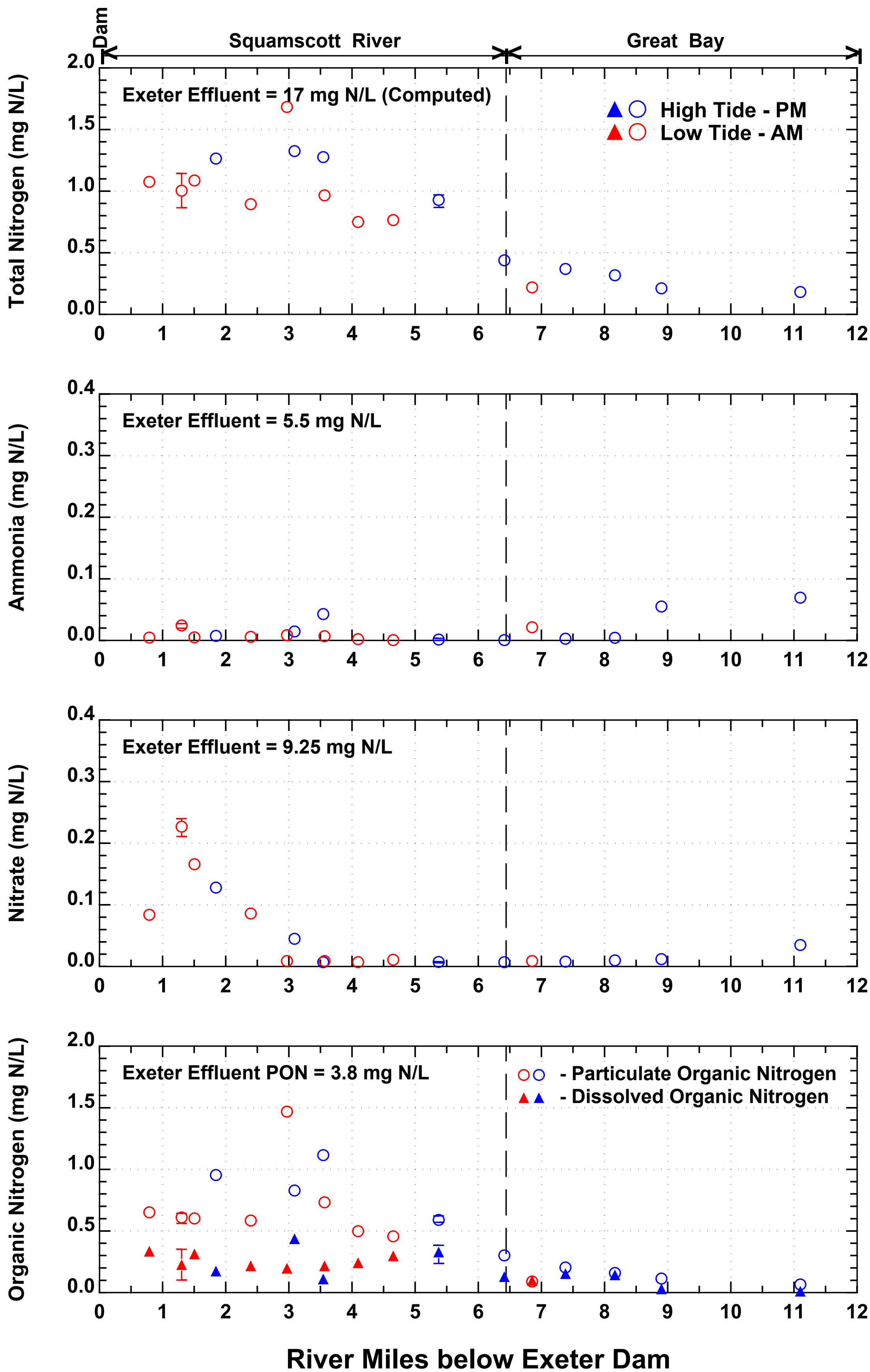


Figure 11. August 12, 2011 Spatial Profiles translated to Mean Tide Conditions Total Nitrogen, Ammonia, Nitrate and Organic Nitrogen

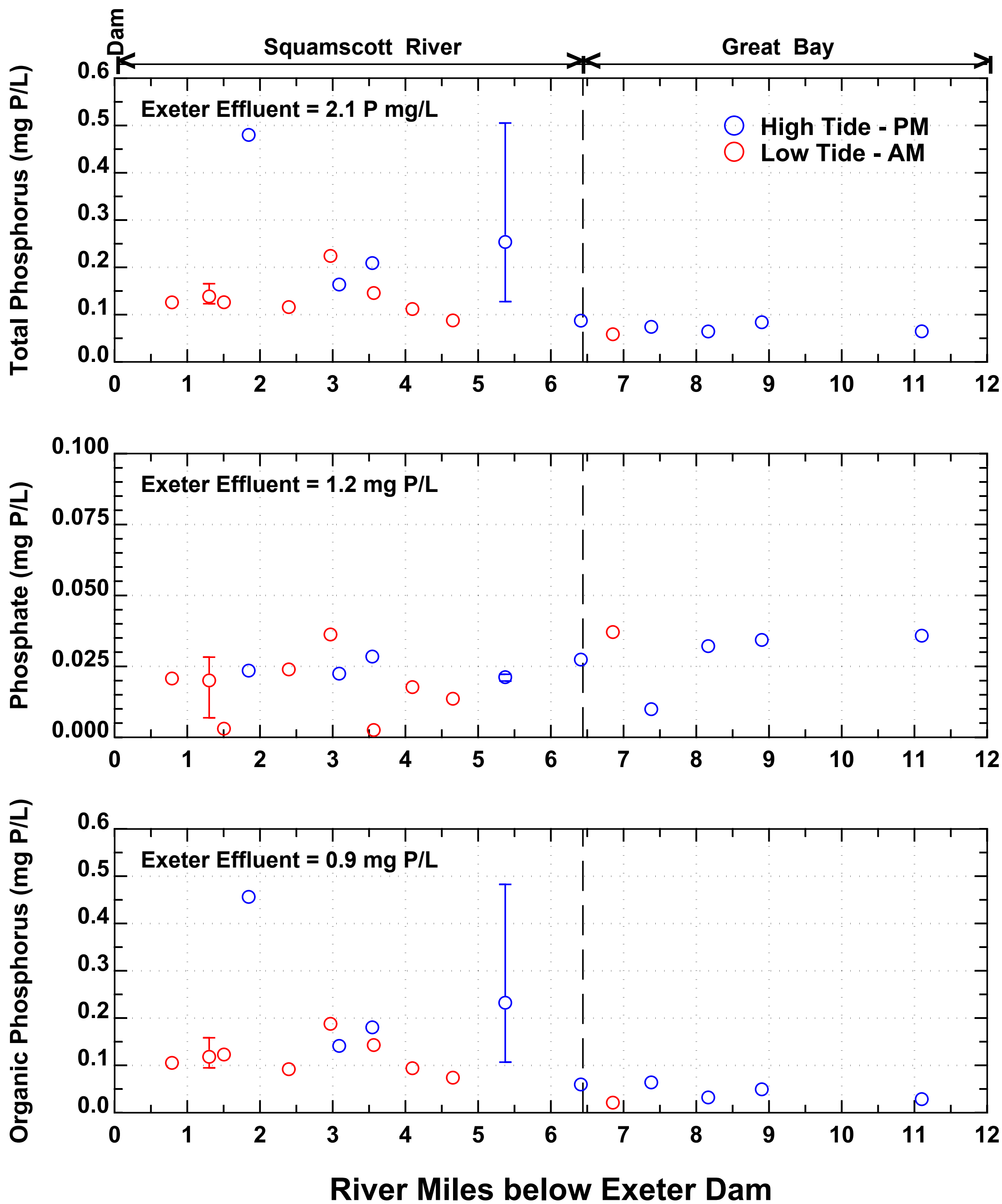


Figure 12. August 12, 2011 Spatial Profiles translated to Mean Tide Conditions Total Phosphorus, Phosphate and Organic Phosphorus

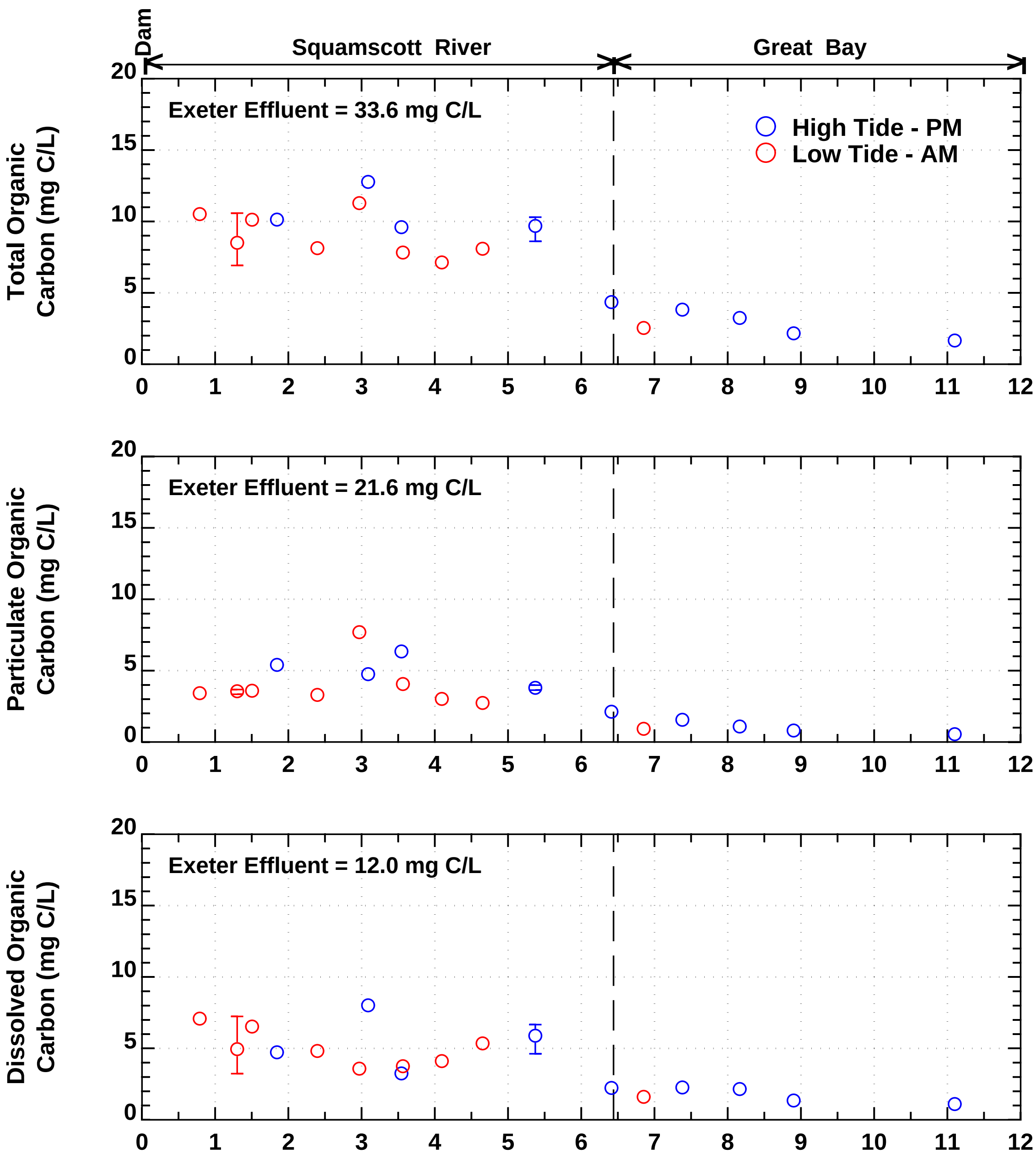


Figure 13. August 12, 2011 Spatial Profiles translated to Mean Tide Conditions Particulate and Dissolved Organic Carbon

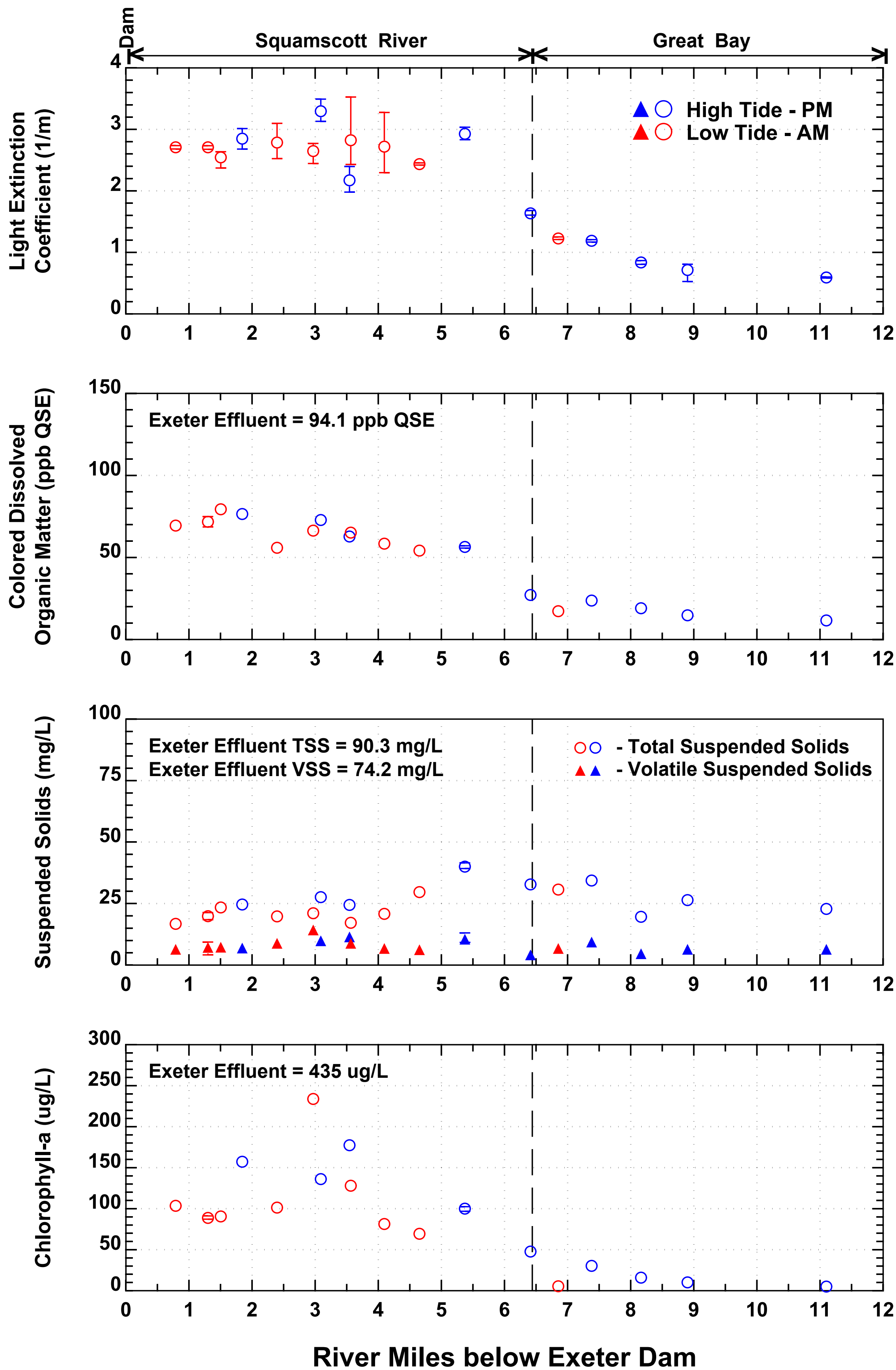


Figure 14. August 12, 2011 Spatial Profiles translated to Mean Tide Conditions Light Extinction Coefficient, Colored Dissolved Organic Matter Suspended Solids and Chlorophyll-a

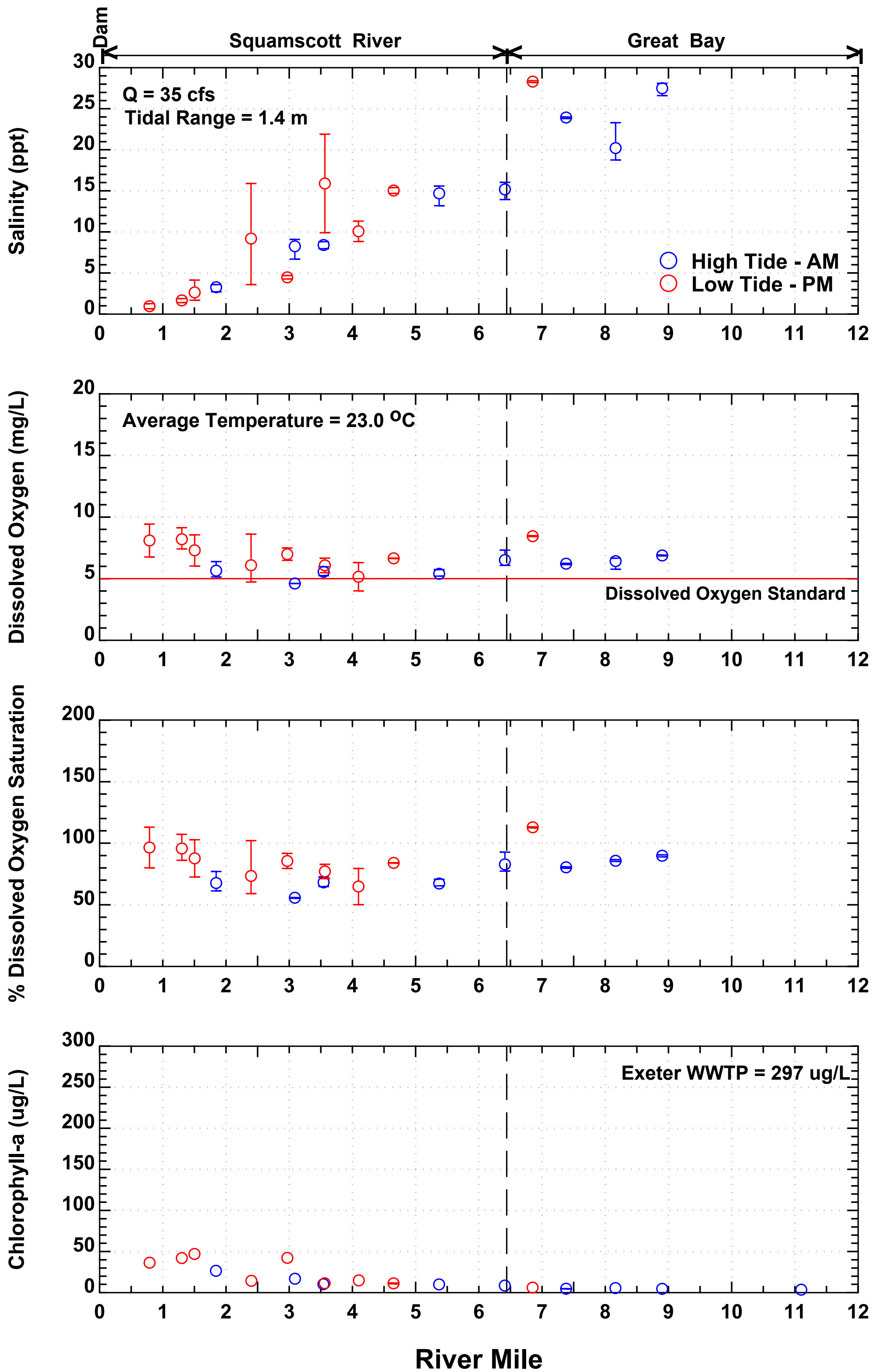


Figure 15. August 24, 2011 Spatial Profiles translated to Mean Tide Conditions Salinity, Dissolved Oxygen, % Dissolved Oxygen Saturation, Chlorophyll-a

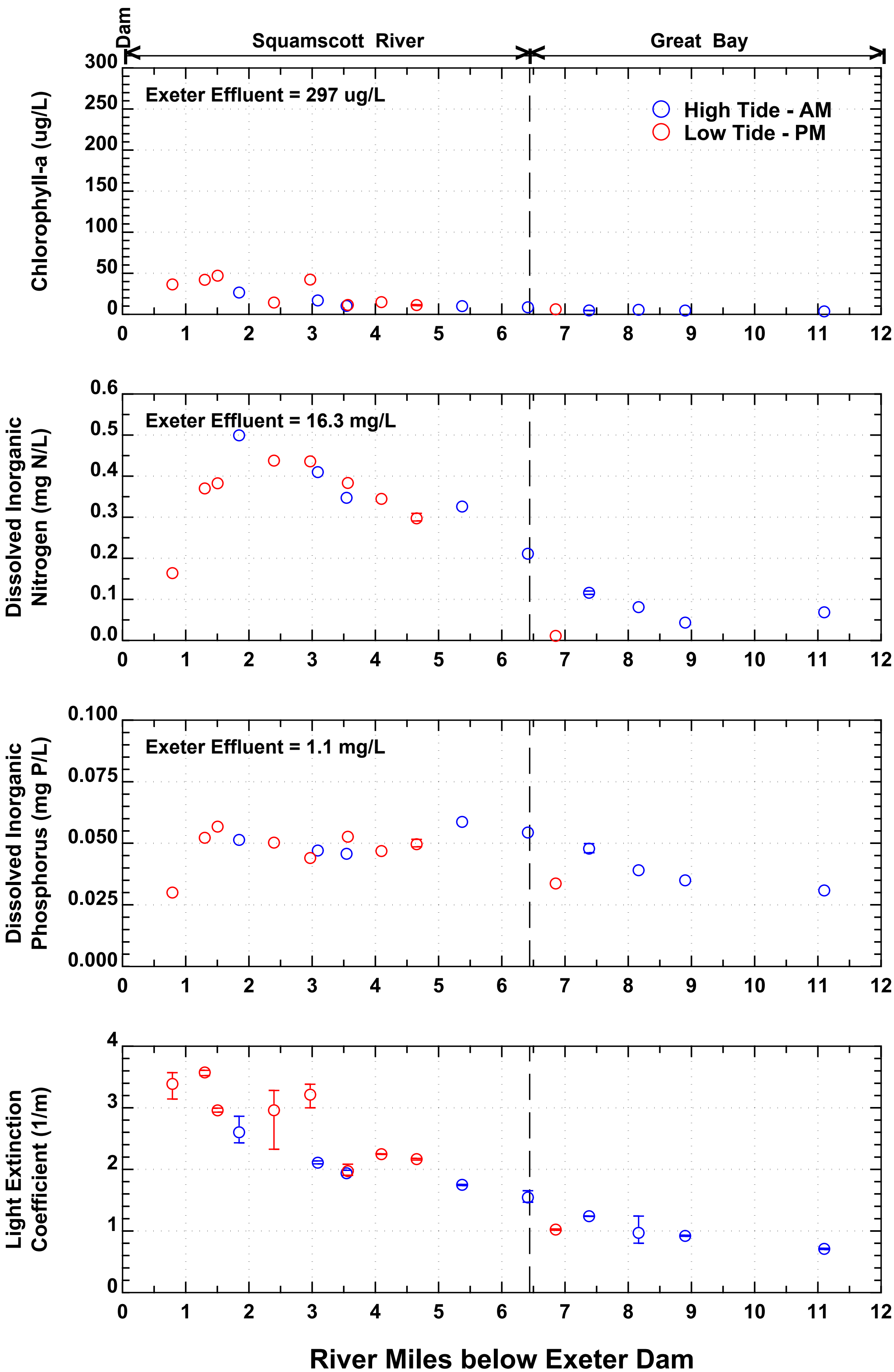


**Figure 16. August 24, 2011 Spatial Profiles translated to Mean Tide Conditions
Chlorophyll-a, Dissolved Inorganic Nitrogen
Dissolved Inorganic Phophorus, Light Extinction Coefficient**

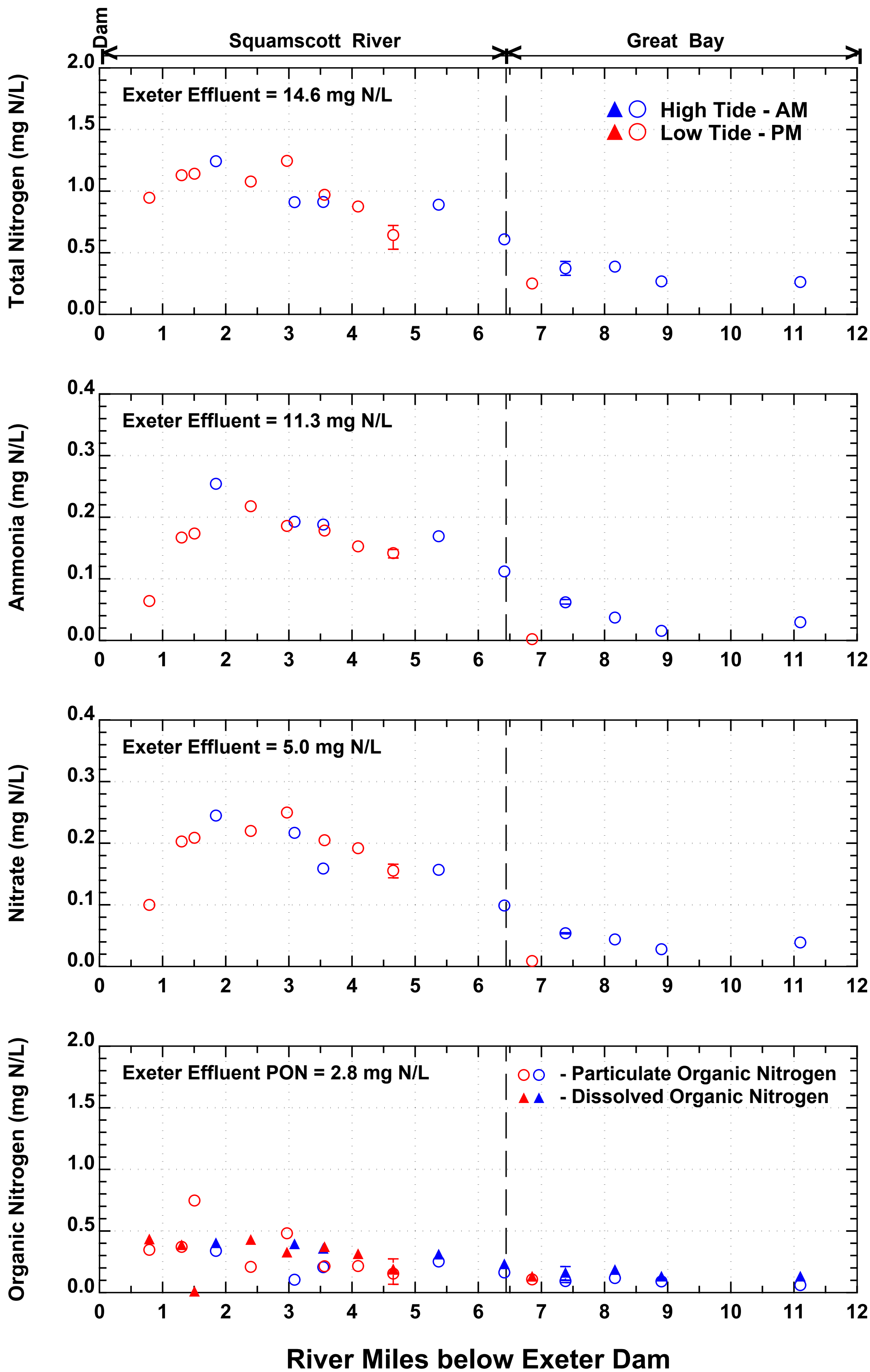


Figure 17. August 24, 2011 Spatial Profiles translated to Mean Tide Conditions Total Nitrogen, Ammonia, Nitrate and Organic Nitrogen

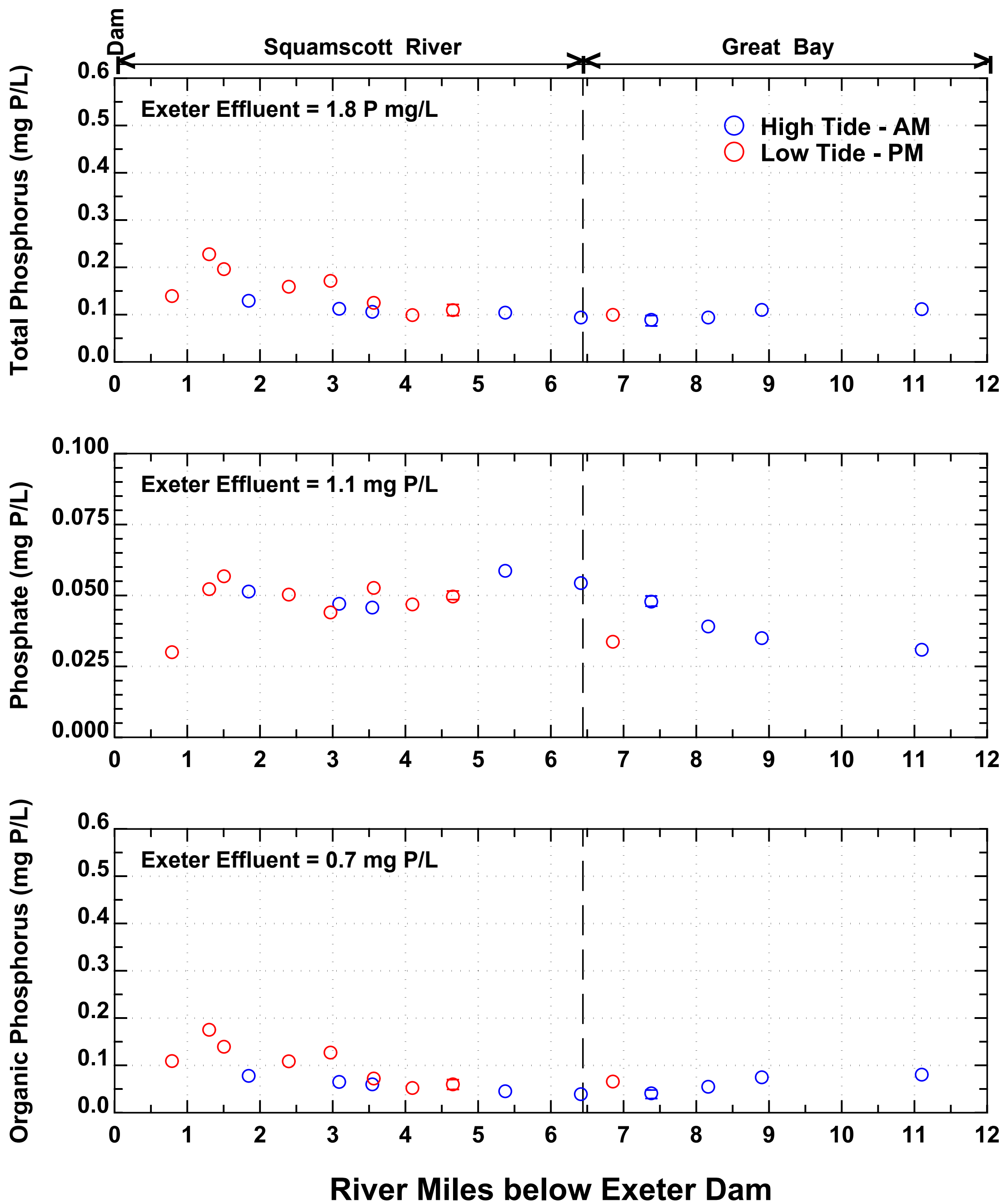


Figure 18. August 24, 2011 Spatial Profiles translated to Mean Tide Conditions Total Phosphorus, Phosphate and Organic Phosphorus

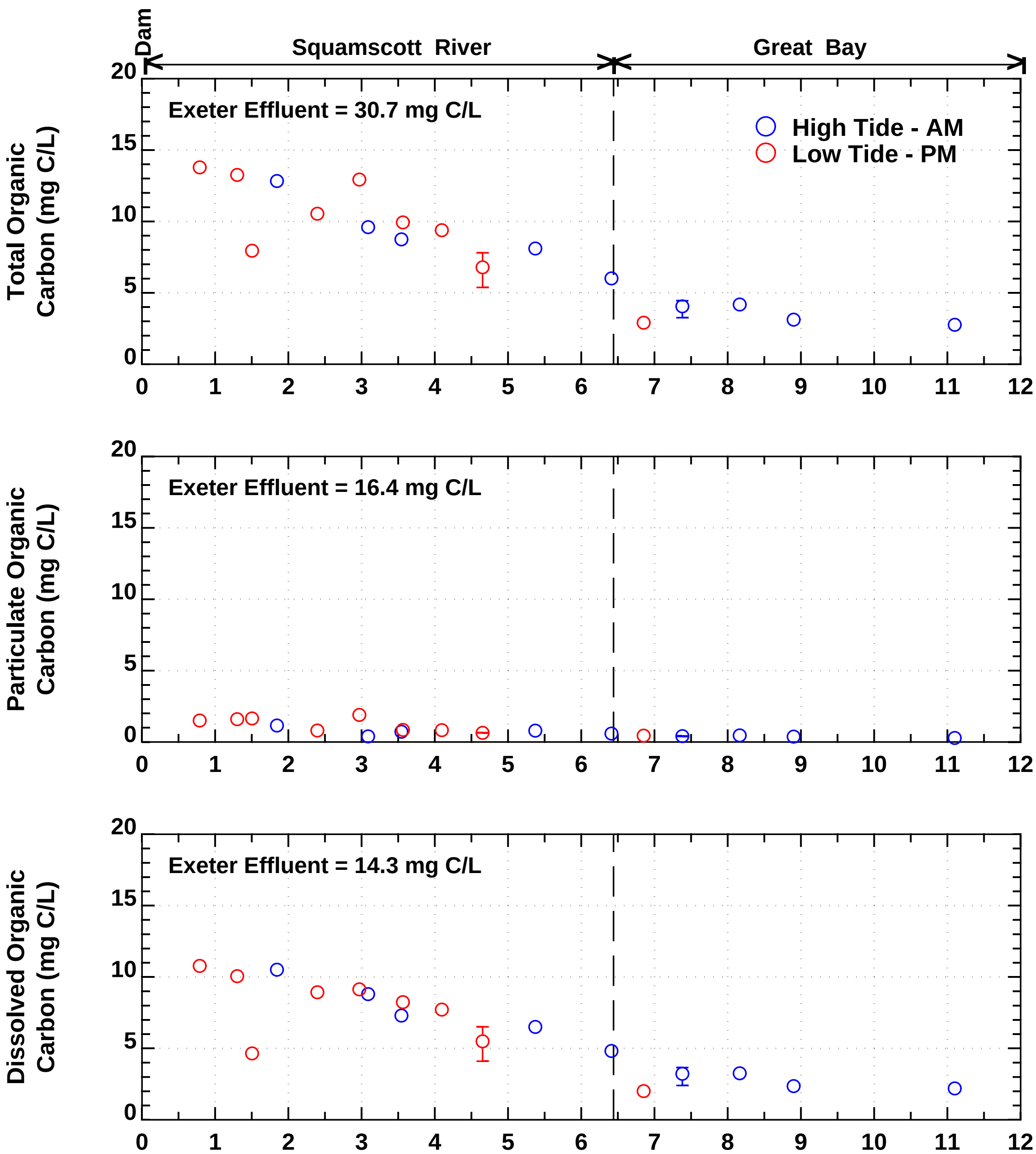


Figure 19. August 24, 2011 Spatial Profiles translated to Mean Tide Conditions Particulate and Dissolved Organic Carbon

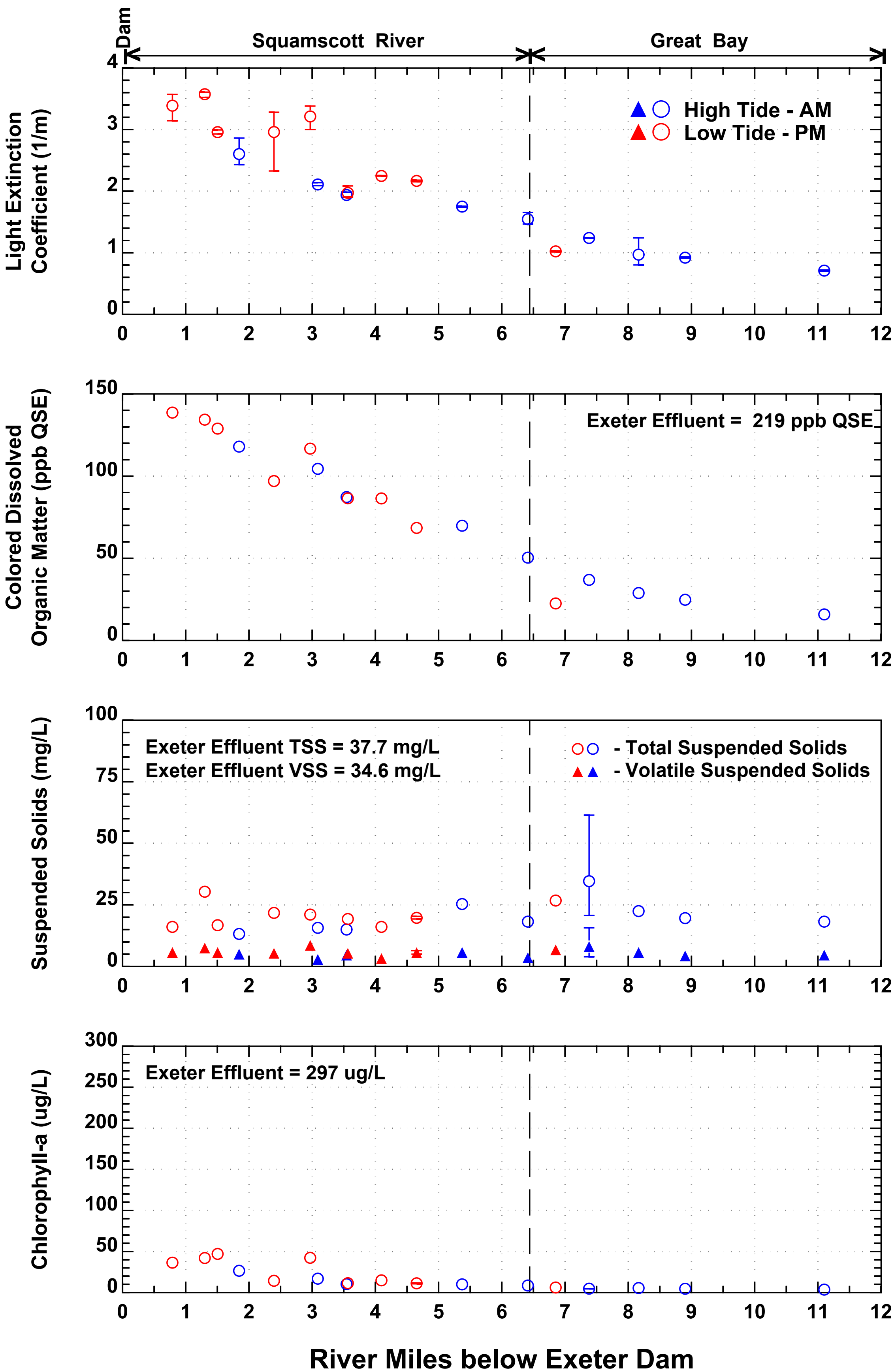


Figure 20. August 24, 2011 Spatial Profiles translated to Mean Tide Conditions Light Extinction Coefficient, Colored Dissolved Organic Matter Suspended Solids and Chlorophyll-a

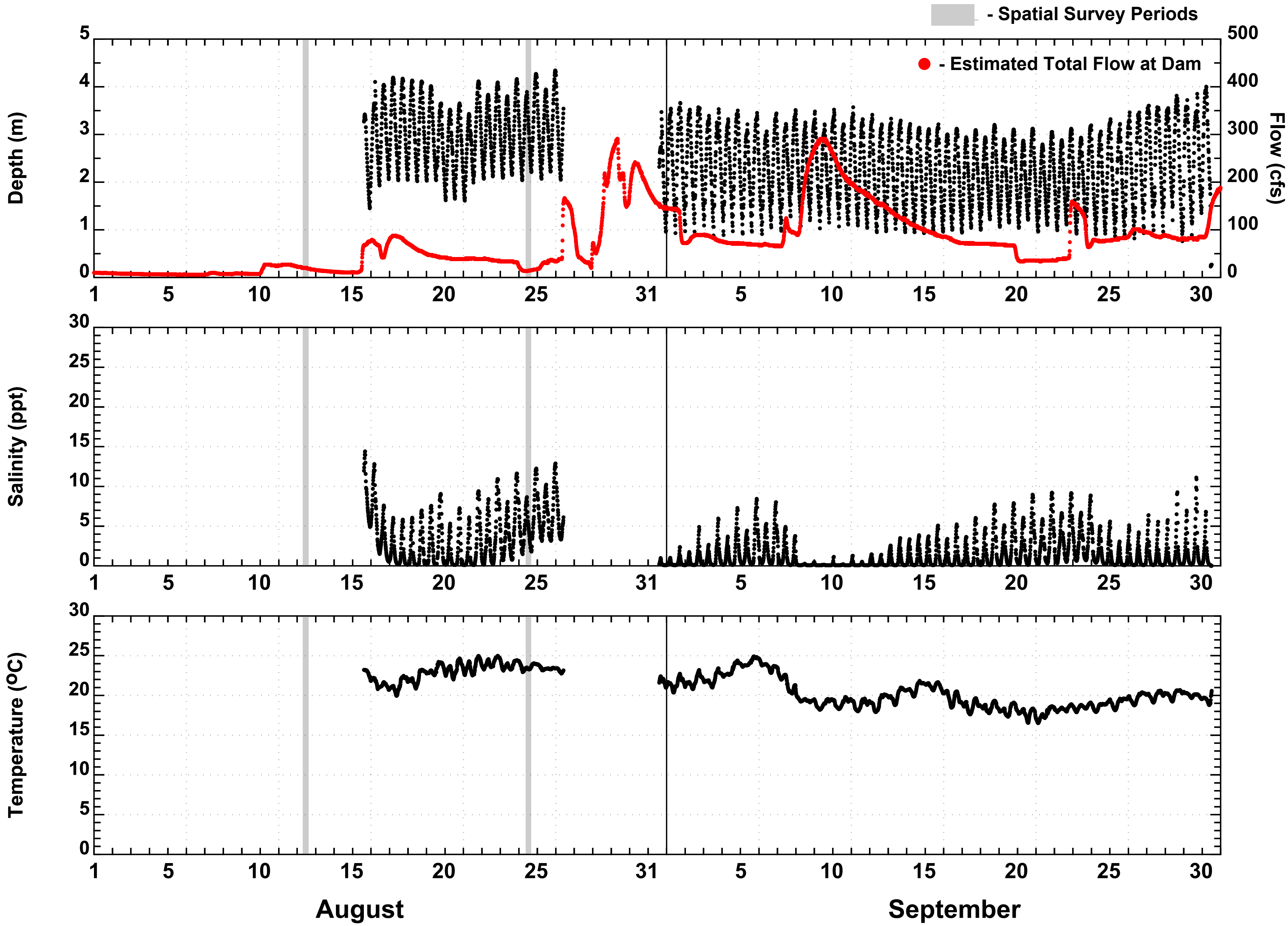


Figure 21. Squamscott River Aug-Sep 2011 Datasonde Measurements - Location: 101 Bridge (Depth, Salinity, Temperature)

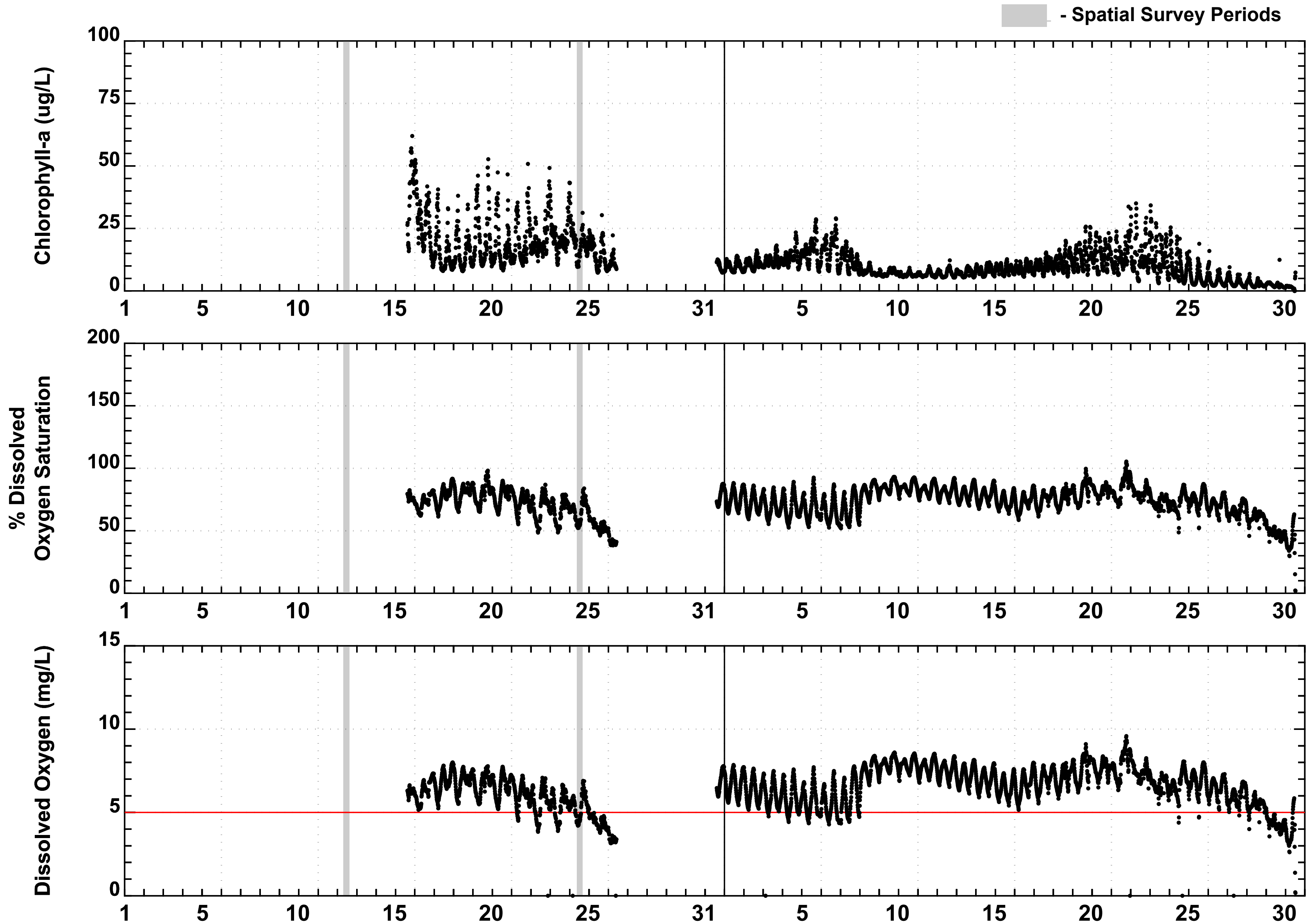


Figure 22. Squamscott River Aug-Sep 2011 Datasonde Measurements - Location: 101 Bridge (Chlorophyll-a, % Dissolved Oxygen Saturation, Dissolved Oxygen)

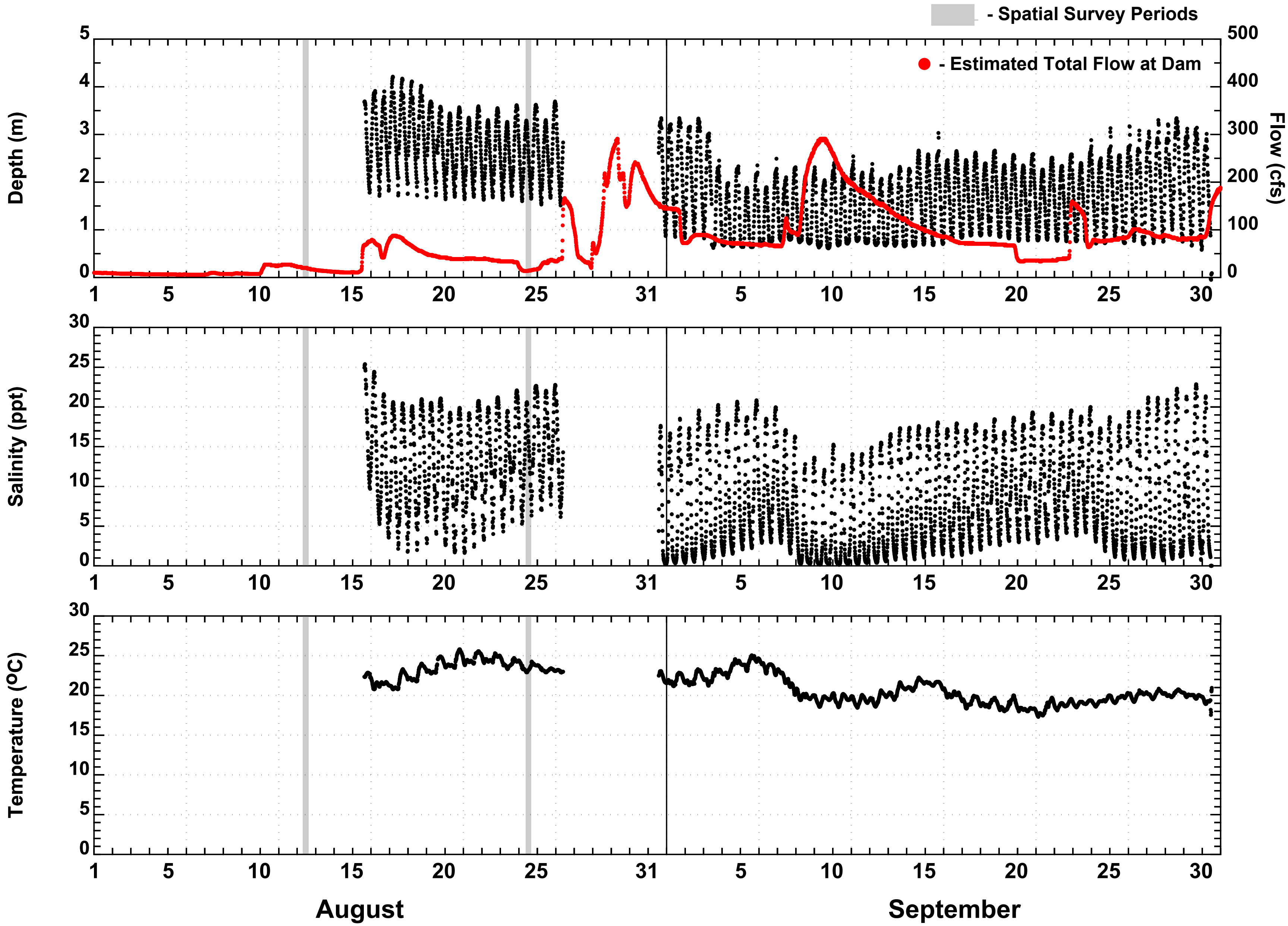


Figure 23. Squamscott River Aug-Sep 2011 Datasonde Measurements - Location: Newfields (Depth, Salinity, Temperature)

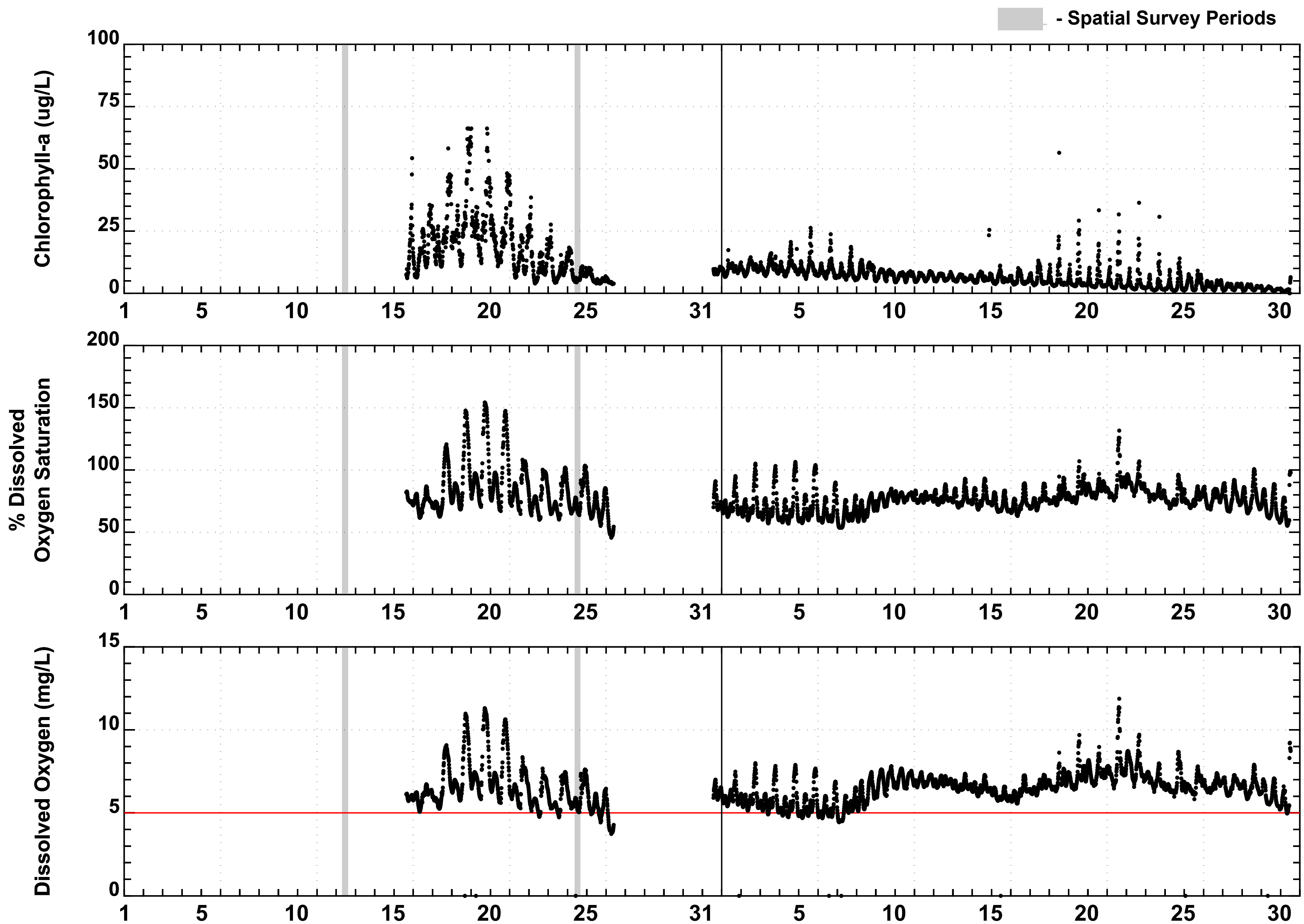


Figure 24. Squamscott River Aug-Sep 2011 Datasonde Measurements - Location: Newfields (Chlorophyll-a, % Dissolved Oxygen Saturation, Dissolved Oxygen)

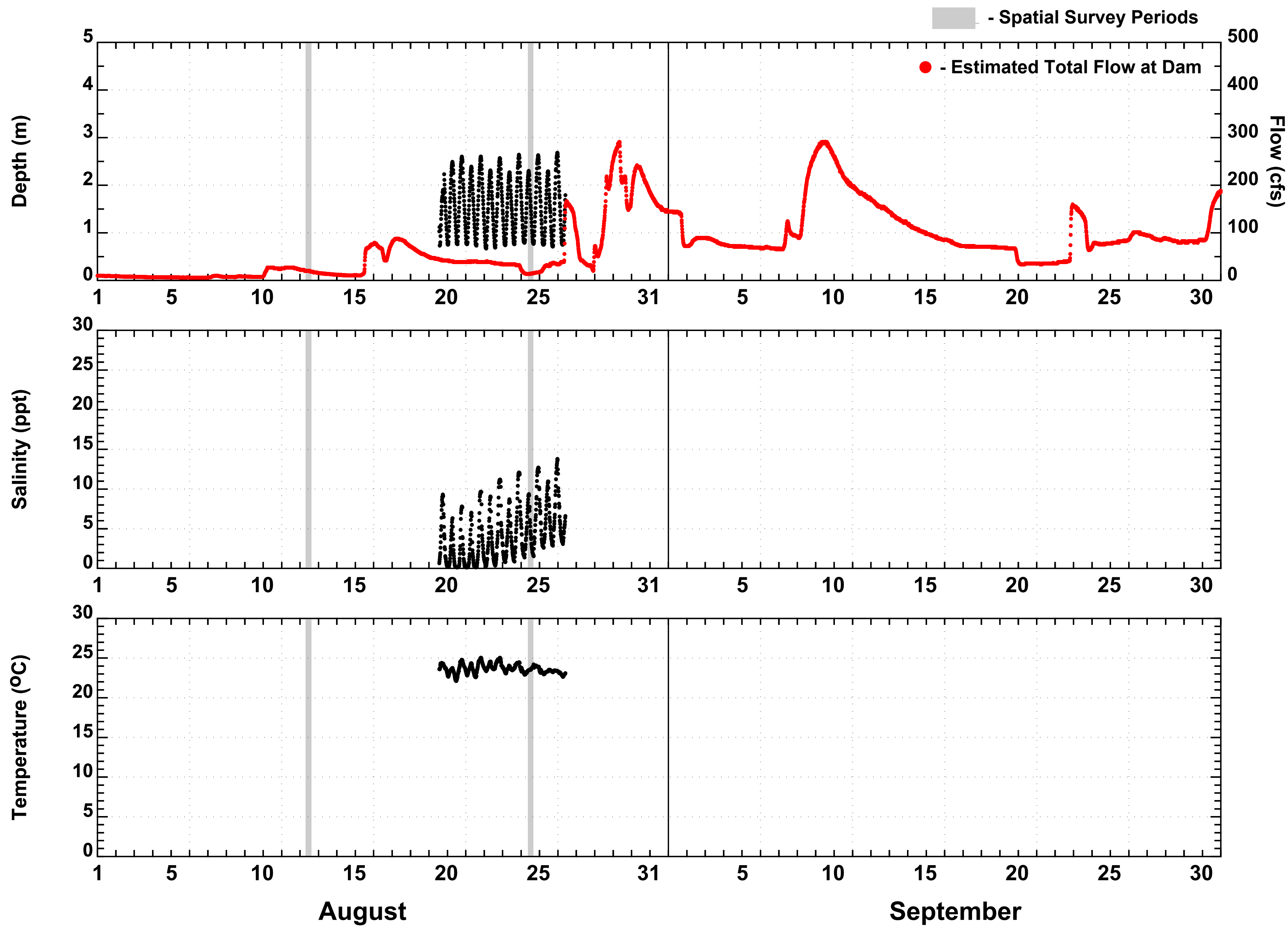


Figure 25. Squamscott River Aug-Sep 2011 Datasonde Measurements - Location: Oxbow (Depth, Salinity, Temperature)

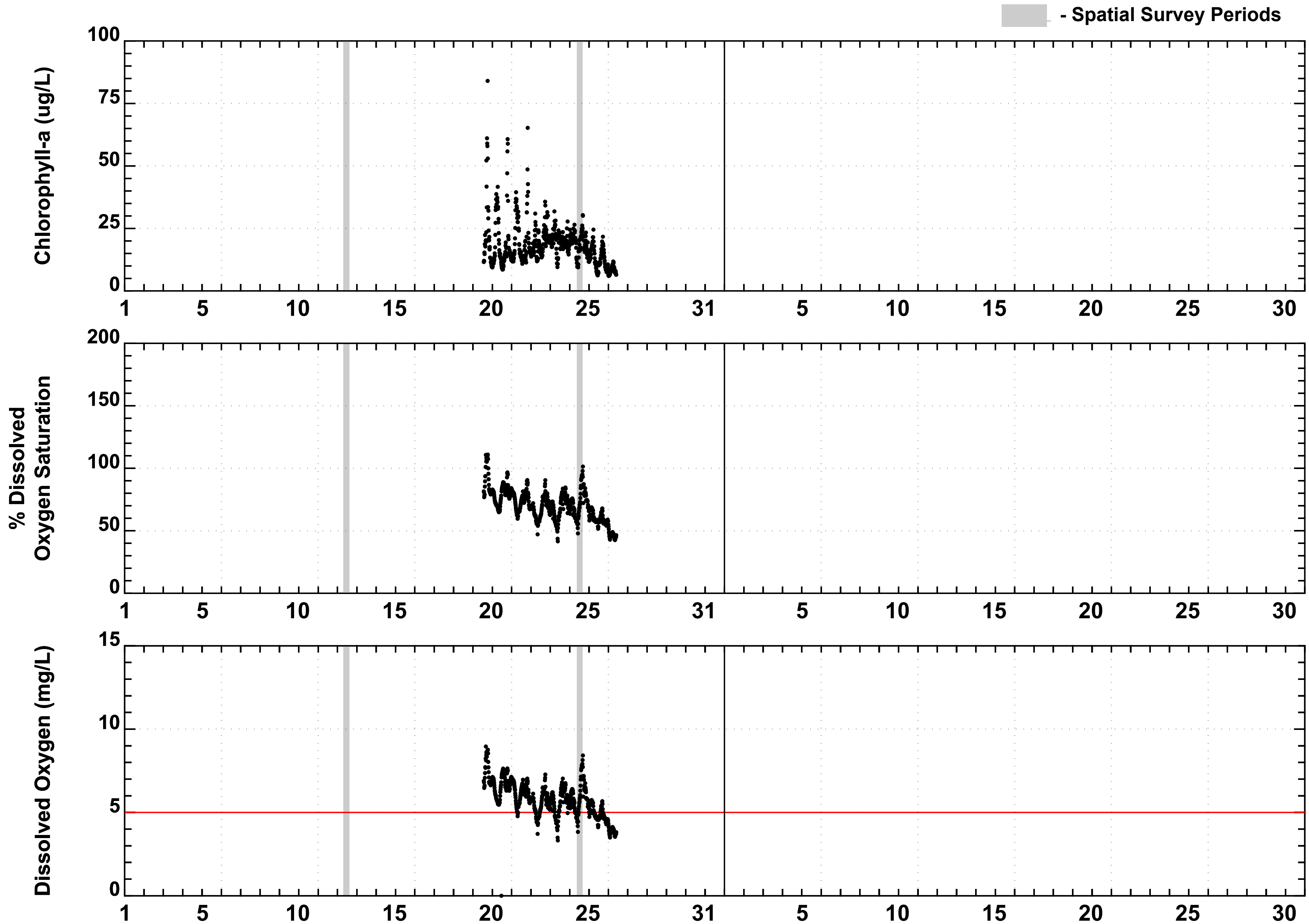


Figure 26. Squamscott River Aug-Sep 2011 Datasonde Measurements - Location: Oxbow (Chlorophyll-a, % Dissolved Oxygen Saturation, Dissolved Oxygen)

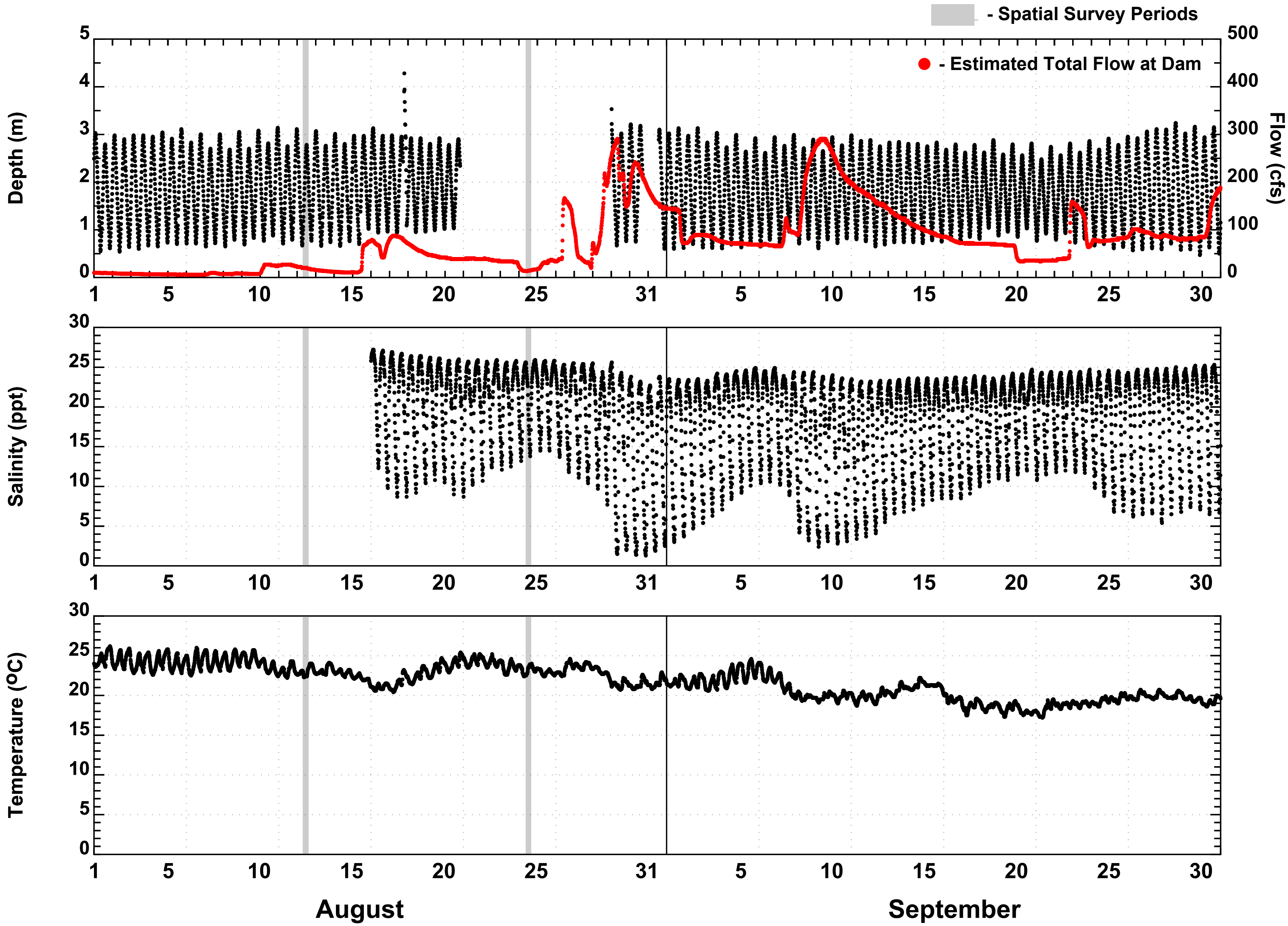


Figure 27. Squamscott River Aug-Sep 2011 Datasonde Measurements (CDMO) - Location: RR Bridge (Depth, Salinity, Temperature)

DATE: 2/03/2012 TIME: 12:55:25

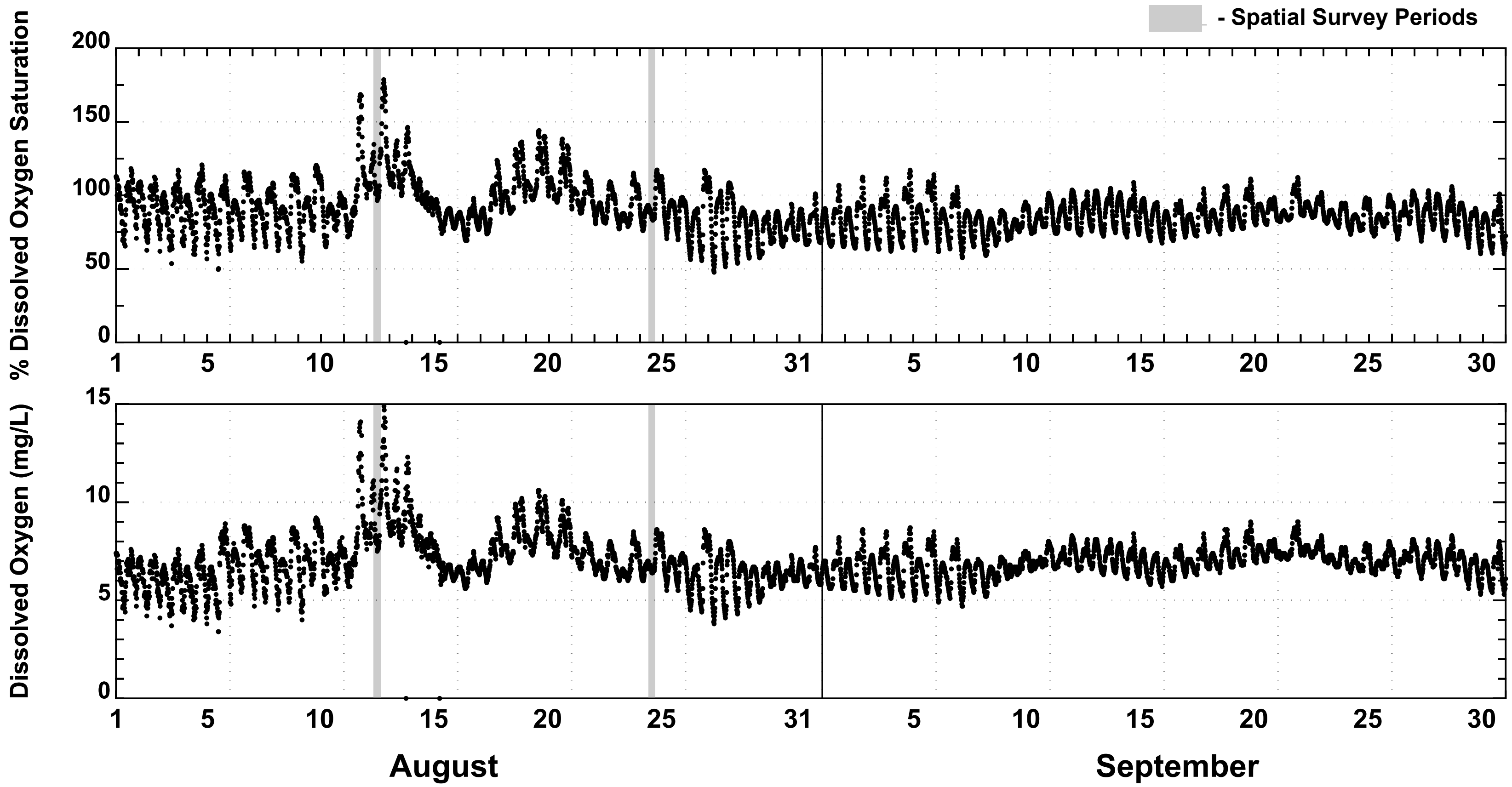


Figure 28. Squamscott River Aug-Sep 2011 Datasonde Measurements (CDMO) - Location: RR Bridge
(% Dissolved Oxygen Saturation, Dissovled Oxygen)

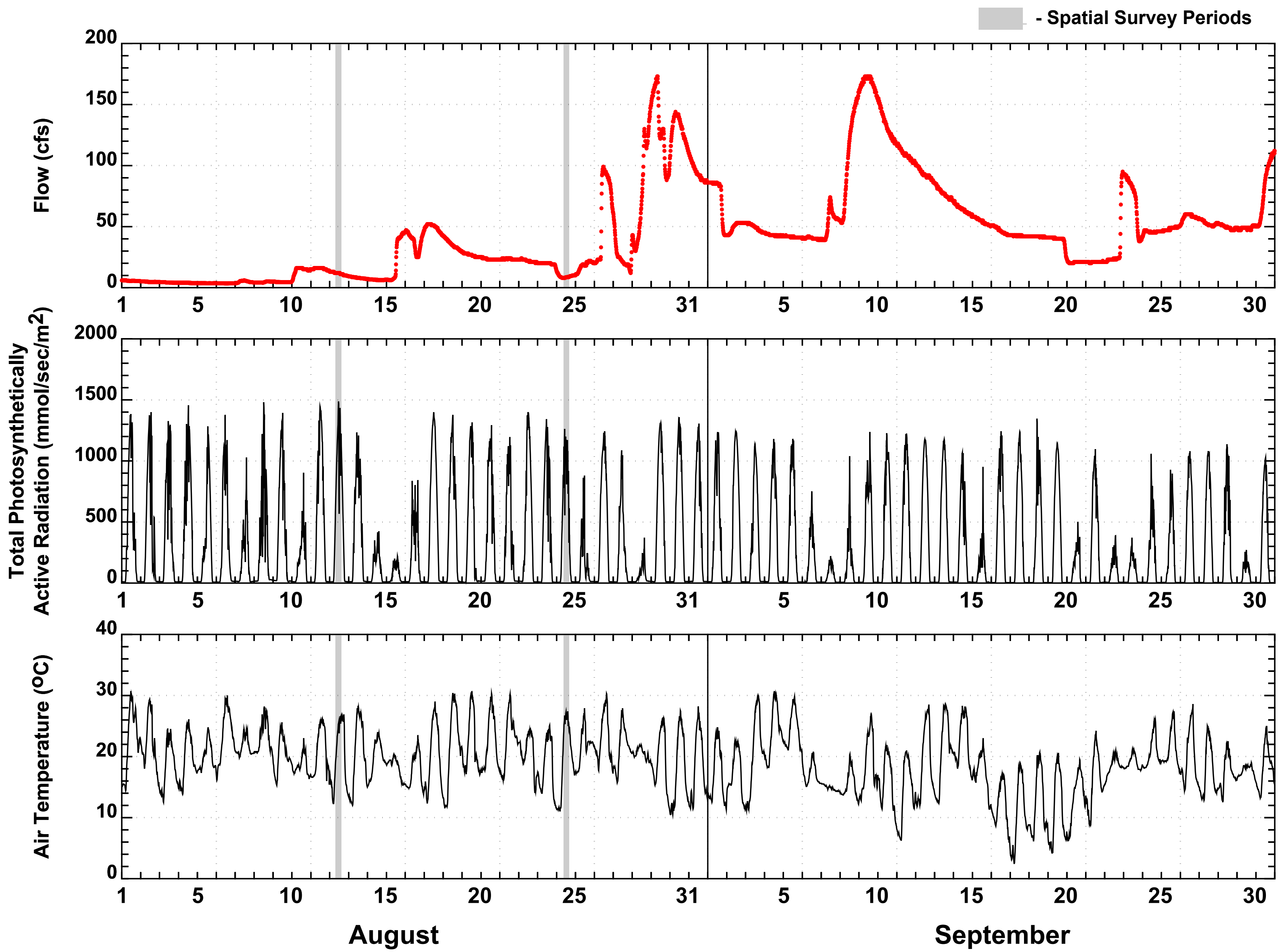


Figure 29. Aug-Sep 2011, Squamscott River Flow and Greenland Station, Met Data

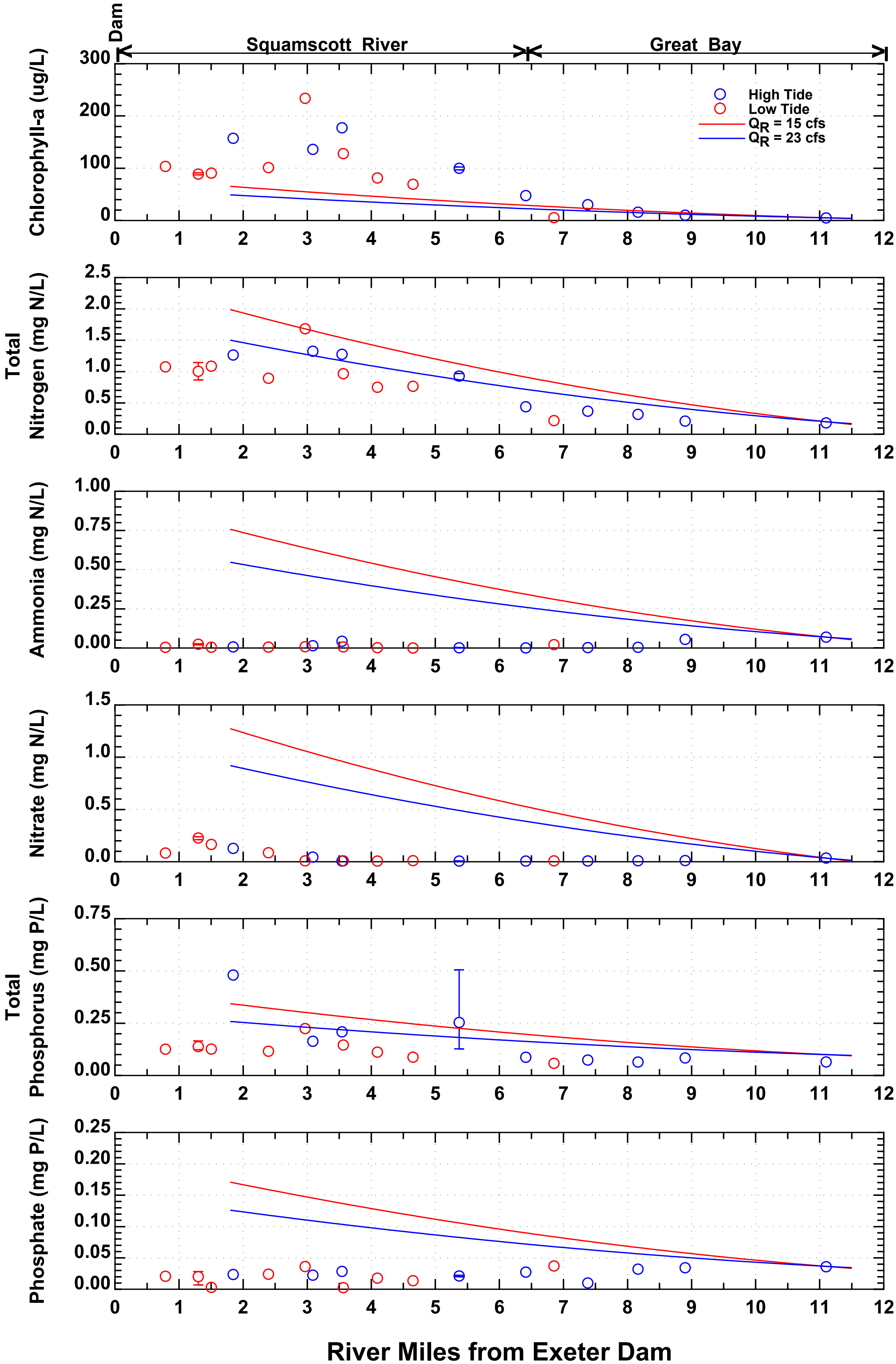


Figure 30. August 12, 2011 Spatial Profiles and Mass Balances Chlorophyll, Nitrogen, Phosphorus

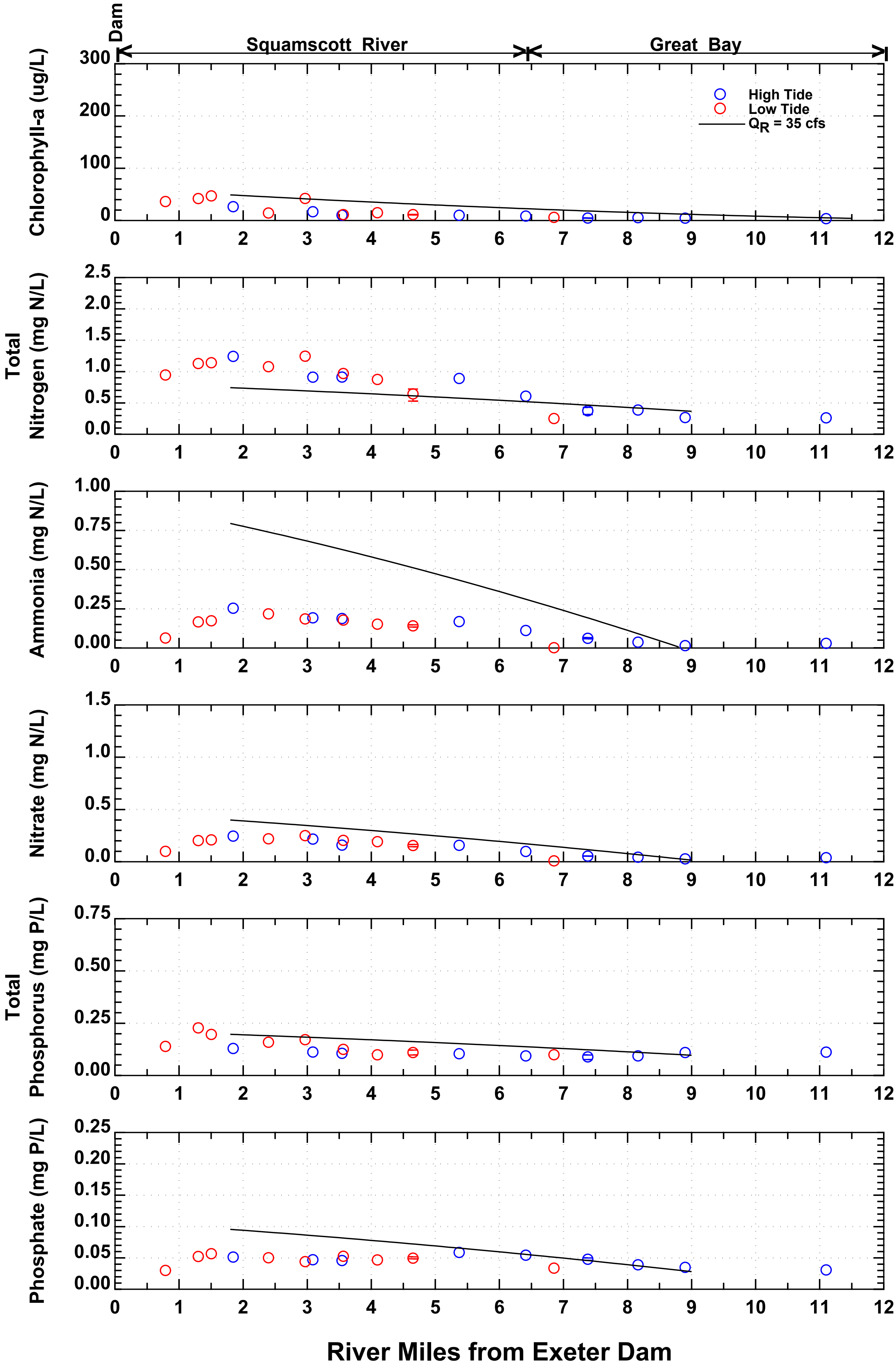


Figure 31. August 24, 2011 Spatial Profiles and Mass Balances Chlorophyll, Nitrogen, Phosphorus

APPENDIX A

DATA TABLES

Table 1. Station ID and River Mile Point below Dam

Station ID	Location	River Mile Point below Dam
1	Exeter Dam	0
2	Downtown Exeter	1.1
3	US Rt 1	1.9
4	Oxbow Cut	2.2
5	South of Newfields Town	3.5
6	Newfields Town Landing	4.3
7	US Rt 108	5.1
8	Between US Rt 108 and Railroad Bridge	5.8
9	Railroad Bridge	6.5
10	Great Bay	8.7

Table 2. Exeter Effluent Concentrations

Parameter	August 12, 2011	August 24, 2011
NH_4 (mg N/L)	5.5	11.3
NO_3 (mg N/L)	9.3	5.0
TDN (mg N/L)	8.5	14.2
PON (mg N/L)	3.8	2.8
TN (mg N/L)	-	14.6
TN Calculated (mg N/L)	12.3	17.0
PO_4 (mg P/L)	1.2	1.1
TDP (mg P/L)	1.6	1.5
TPP (mg P/L)	0.5	0.4
TP (mg P/L)	-	1.8
TP Calculated (mg P/L)	2.1	1.8
Chla (ug/L)	434.5	296.7
Pheophytin (ug/L)	141.7	133.9
TSS (mg/L)	90.3	37.7
VSS (mg/L)	74.2	34.6
CDOM (QSE)	94.5	218.9
DOC (mg C/L)	12.0	14.3
POC (mg C/L)	21.6	16.4
Ultimate Carbonaceous BOD (mg/L)	-	-

Table 3. August 12, 2011 Squamscott River Field Data

Station	Time	Tide	Water Depth (m)	Sample Depth (m)	Water Temp. (°C)	Salinity (ppt)	DO (mg/L)	pH	Secchi Depth (m)	Kd (1/m)
1 Exeter Dam	10:35	L	2	0.5	22.2	0.1	3.9	6.9	1.2	1.4
				1.2	22.1	0.1	3.9	6.8	-	
	15:19	H	2	0.5	22.8	0.1	4.6	7.4	1.2	1.8
				1.0	22.5	0.1	4.2	7.0	-	
				2.0	22.4	0.1	3.8	6.9	-	
2 Downtown Exeter	9:10	L	3.1	0.5	22.9	3.3	9.1	7.5	0.6	2.7
				1.6	23.6	4.5	8.2	7.3	-	
				2.6	23.8	4.5	5.9	7.3	-	
	14:56	H	3.5	0.5	24.6	4.0	15.0	8.9	0.4	2.8
				1.7	23.9	5.6	11.3	8.1	-	
				3.5	23.8	6.4	6.6	8.2	-	
3 US Rt 1	9:08	L	2.8	0.5	23.2	5.5	8.3	-	-	2.7
				1.5	23.2	5.5	8.2	-	-	
				3.1	23.2	5.5	8.2	-	-	
	15:00	H	5.2	0.5	24.2	8.9	13.4	-	-	3.3
				1.7	24.3	9.0	13.1	-	-	
				4.5	24.3	9.0	13.0	-	-	
4 Oxbow Cut	8:54	L	3	0.5	23.2	4.9	10.6	7.5	0.5	2.5
				1.5	23.2	5.0	8.9	7.5	-	
				2.5	23.2	5.0	9.0	7.5	-	
	14:32	H	5	0.5	24.3	9.6	14.9	8.6	0.6	2.2
				2.5	24.0	10.9	13.4	8.4	-	
				5.0	24.0	12.6	4.2	8.3	-	
5 South of Newfields Town	8:50	L	2.5	1.0	23.3	7.7	9.1	-	-	2.8
				2.0	23.3	7.6	9.7	-	-	
	14:32	H	6.4	0.5	24.3	15.7	14.5	-	-	2.9
				3.0	23.7	18.4	11.7	-	-	
				5.0	23.5	22.1	10.3	-	-	
6 Newfield Town Landing	8:33	L	2.2	0.5	23.4	7.1	11.2	8.1	0.5	2.6
				1.1	23.4	7.4	10.3	7.9	-	
				1.7	23.4	7.6	10.3	7.8	-	
	14:25	H	3.9	0.5	23.9	18.9	11.8	8.1	1.0	1.6
				2.9	23.5	20.1	10.6	8.1	-	
				3.4	23.4	20.2	10.4	8.1	-	
				3.9	23.4	20.2	9.3	8.1	-	
7 US Rt 108	8:30	L	2.1	0.5	23.4	11.1	10.1	-	-	2.8
				1.5	23.3	11.5	9.4	-	-	
	14:13	H	3.9	0.5	23.6	26.2	9.7	-	-	1.2
				2.0	23.4	26.6	9.1	-	-	
				3.5	23.4	26.7	9.0	-	-	
8 Between US Rt 108 and RR Bridge	8:08	L	1.9	0.5	23.4	10.8	11.2	8.1	0.5	2.7
				1.4	23.4	11.4	10.3	7.9	-	
	13:58	H	4	0.5	27.7	23.5	9.0	-	-	0.8
				2.0	23.3	27.0	8.8	-	-	
				3.5	23.3	27.9	8.5	-	-	
9 RR Bridge	8:06	L	3.2	0.5	23.3	16.7	10.8	-	-	2.4
				1.5	23.3	17.0	9.9	-	-	
				2.5	23.2	17.4	9.7	-	-	
	13:37	H	3.4	0.5	23.5	22.4	10.5	8.0	1.6	0.8
				1.7	22.7	23.2	7.7	7.9	-	
				2.9	22.6	23.2	7.7	7.9	-	
				3.4	22.6	23.2	7.6	7.9	-	
10 Great Bay	7:23	L	5.9	0.5	22.4	23.1	6.9	7.8	1.1	1.2
				-	22.3	23.6	6.4	7.8	-	
				2.8	22.3	23.3	7.0	7.9	-	
				5.2	22.2	23.3	7.0	7.9	-	
	13:28	H	8	1.0	21.5	29.4	7.1	-	-	0.6
				3.0	21.2	29.3	7.0	-	-	
				5.0	21.3	29.3	6.8	-	-	

Table 4. August 24, 2011 Squamscott River Field Data

Station	Time	Tide	Water Depth (m)	Sample Depth (m)	Water Temp. (°C)	Salinity (ppt)	DO (mg/L)	pH	Secchi Depth (m)	Kd (1/m)
1 Exeter Dam	10:20	H	1.9	0.5	22.1	0.1	3.8	7.2	1.1	3.5
			-	-	22.4	0.1	3.7	-	-	
			-	1.0	22.0	0.1	3.4	6.9	-	
			-	1.4	21.9	0.1	3.4	6.8	-	
	14:25	L	2.1	0.5	23.7	0.1	4.5	6.8	0.9	2.5
			-	1.6	22.2	0.1	3.8	6.9	-	
2 Downtown Exeter	10:05	H	3.3	0.5	23.9	2.7	6.4	7.3	0.8	2.6
			-	1.6	23.0	3.5	5.4	7.1	-	
			-	2.8	23.0	3.6	5.1	7.1	-	
	16:30	L	1.6	0.5	24.2	0.7	9.4	7.6	0.5	3.4
			-	1.1	23.3	1.3	6.8	7.2	-	
3 US Rt 1	10:16	H	5.4	0.5	22.4	9.1	4.6	-	-	2.1
			-	2.5	22.3	9.0	4.6	-	-	
			-	4.0	22.4	6.7	4.6	-	-	
	16:30	L	3.8	0.5	22.8	1.4	9.1	-	-	3.6
			-	2.0	22.4	1.7	8.1	-	-	
			-	3.0	22.2	1.9	7.4	-	-	
4 Oxbow Cut	9:53	H	2.6	0.5	22.7	8.0	6.0	7.4	0.8	1.9
			-	1.3	23.3	8.5	5.5	7.3	-	
			-	2.1	23.3	8.8	5.3	7.2	-	
	15:12	L	2.5	0.5	24.0	1.7	8.6	7.4	0.5	3.0
			-	1.0	23.8	2.1	7.3	7.3	-	
			-	2.0	23.4	4.1	6.0	7.1	-	
5 South of Newfields Town	9:56	H	5.4	2.0	21.9	13.2	5.7	-	-	1.7
			-	3.0	22.2	15.3	5.2	-	-	
			-	4.5	22.2	15.6	5.2	-	-	
	16:16	L	4.4	0.5	22.7	3.6	8.6	-	-	3.0
			-	2.0	22.0	8.1	4.9	-	-	
			-	3.5	21.9	15.9	4.7	-	-	
6 Newfield Town Landing	9:26	H	2.8	0.5	23.2	13.9	7.3	7.6	0.8	1.5
			-	1.4	23.0	15.6	6.1	7.6	-	
			-	2.3	22.9	16.0	6.2	7.6	-	
	15:59	L	1.6	0.5	24.3	4.3	6.5	7.5	0.6	3.2
			-	1.1	24.1	4.7	7.5	7.4	-	
7 US Rt 108	9:36	H	4.1	1.0	21.4	23.8	6.3	-	-	1.2
			-	2.0	21.4	24.0	6.2	-	-	
			-	4.0	21.4	24.0	6.2	-	-	
	16:04	L	2.6	0.5	23.4	9.9	6.7	-	-	2.0
			-	2.0	22.2	21.9	5.5	-	-	
8 Between US Rt 108 and RR Bridge	9:17	H	2.2	0.5	22.4	18.8	6.7	7.8	1.1	1.0
			-	-	22.4	23.3	6.6	-	-	
			-	1.1	5.0	19.2	5.8	7.8	-	
			-	2.0	22.4	19.6	6.6	7.8	-	
	15:45	L	1.6	0.5	24.1	8.8	4.0	7.3	0.8	2.2
			-	1.1	23.9	11.3	6.3	7.4	-	
9 RR Bridge	9:22	H	5.0	1.0	20.7	26.6	6.9	-	-	0.9
			-	2.5	20.8	27.8	6.9	-	-	
			-	4.0	20.8	28.1	6.9	-	-	
	15:05	L	2.4	0.5	22.8	14.7	6.7	-	-	2.2
			-	1.5	22.6	15.4	6.6	-	-	
10 Great Bay	9:03	H	7.8	1.0	19.0	30.7	7.4	-	-	0.7
			-	3.0	19.1	30.6	7.4	-	-	
			-	5.0	19.1	30.4	7.3	-	-	
	15:35	L	5.7	0.5	22.1	28.2	8.4	-	-	1.0
			-	2.0	22.1	28.3	8.5	-	-	
			-	4.0	21.9	28.4	8.5	-	-	

Table 5. August 12, 2011 Squamscott River Nitrogen Data

Station	Time	Tide	Water Depth (m)	Replicate	NH4 (mg N/L)	NO3 (mg N/L)	TDN (mg N/L)	PON (mg N/L)	TN (mg N/L)	TN Calculated[1] (mg N/L)
1 Exeter Dam	10:35	L	2		0.021	0.046	0.350	0.088	-	0.439
	15:19	H	2		0.011	0.045	0.350	0.114	-	0.464
2 Downtown Exeter Old SQM 15	9:10	L	3.1		0.005	0.084	0.424	0.651	-	1.075
	14:56	H	3.5		0.007	0.128	0.310	0.954	-	1.264
3 US Rt 1	9:08	L	2.8	A	0.027	0.230	0.359	0.643	-	1.002
				B	0.026	0.240	0.242	0.623	-	0.865
				C	0.020	0.211	0.582	0.562	-	1.144
	14:46	H	5.2		0.015	0.045	0.497	0.828	-	1.326
4 Oxbow Cut	8:54	L	3		0.005	0.166	0.485	0.602	-	1.087
	14:32	H	5		0.043	0.007	0.160	1.116	-	1.276
5 South of Newfields Town	8:50	L	2.5		0.006	0.086	0.309	0.585	-	0.894
	14:32	H	6.4	A	0.003	0.006	0.378	0.571	-	0.949
				B	0.000	0.008	0.392	0.577	-	0.969
				C	0.001	0.008	0.245	0.622	-	0.868
6 Newfield Town Landing	8:33	L	2.2		0.009	0.009	0.215	1.468	-	1.683
	14:25	H	3.9		0.001	0.007	0.137	0.302	-	0.439
7 US Rt 108	8:30	L	2.1		0.007	0.009	0.233	0.733	-	0.966
	14:13	H	3.9		0.003	0.008	0.165	0.204	-	0.369
8 Between US Rt 108 and RR Bridge	8:08	L	1.9		0.002	0.007	0.251	0.499	-	0.750
	13:58	H	4		0.004	0.010	0.158	0.159	-	0.317
9 RR Bridge	8:06	L	3.2		0.000	0.011	0.309	0.456	-	0.765
	13:37	H	3.4		0.055	0.012	0.097	0.114	-	0.211
10 Great Bay	7:23	L	5.9		0.021	0.009	0.129	0.090	-	0.219
	13:28	H	8		0.070	0.035	0.116	0.066	-	0.182
Exeter WWTP				-	5.493	9.250	8.458	3.821	-	12.279

1 TN = TDN + PON

Table 6. August 24, 2011 Squamscott River Nitrogen Data

Station	Time	Tide	Water Depth (m)	Replicate	NH4 (mg N/L)	NO3 (mg N/L)	TDN (mg N/L)	PON (mg N/L)	TN (mg N/L)	TN Calculated[1] (mg N/L)
1 Exeter Dam	10:20	H	1.9		0.019	0.059	0.497	0.106	0.776	0.603
	14:25	L	2.1		0.018	0.062	0.516	0.217	2.240	0.733
2 Downtown Exeter Old SQM 15	10:05	H	3.3		0.254	0.245	0.904	0.339	0.910	1.243
	10:05	L	1.6		0.064	0.100	0.599	0.347	0.934	0.946
3 US Rt 1	10:16	H	5.4		0.193	0.217	0.806	0.105	0.857	0.911
	16:30	L	3.8		0.167	0.203	0.758	0.371	1.051	1.130
4 Oxbow Cut	9:53	H	2.6		0.188	0.159	0.706	0.206	1.027	0.912
	15:12	L	2.5		0.174	0.209	0.394	0.748	1.114	1.141
5 South of Newfields Town	9:56	H	5.4		0.169	0.157	0.638	0.252	0.892	0.891
	16:16	L	4.4		0.218	0.220	0.869	0.209	1.211	1.078
6 Newfield Town Landing	9:26	H	2.8		0.112	0.099	0.445	0.164	0.777	0.609
	15:59	L	1.6		0.186	0.250	0.764	0.481	1.287	1.245
7 US Rt 108	9:36	H	4.1	A	0.066	0.054	0.219	0.097	0.664	0.316
			-	B	0.061	0.055	0.327	0.102	-	0.430
			-	C	0.059	0.053	0.295	0.081	-	0.377
	16:04	L	2.6		0.178	0.205	0.756	0.214	0.896	0.970
8 Between US Rt 108 and RR Bridge	9:17	H	2.2		0.037	0.044	0.269	0.118	0.467	0.387
	15:45	L	1.6		0.153	0.192	0.660	0.215	0.947	0.875
9 RR Bridge	9:22	H	5.0		0.016	0.028	0.177	0.091	0.354	0.268
	15:05	L	2.4	A	0.134	0.157	0.565	0.156	-	0.721
			-	B	0.148	0.144	0.529	0.153	0.758	0.682
				C	0.144	0.166	0.377	0.152	-	0.528
10 Great Bay	9:03	H	7.8		0.030	0.039	0.202	0.061	0.256	0.263
	15:35	L	5.7		0.002	0.009	0.144	0.107	0.424	0.251
Exeter WWTP					11.320	5.047	14.164	2.815	14.639	16.979

1 TN = TDN + PON

Table 7. August 12, 2011 Squamscott River Phosphorus Data

Station	Time	Tide	Water Depth (m)	Replicate	PO4 (mg P/L)	TDP (mg P/L)	TPP (mg P/L)	TP (mg P/L)	TP Calculated[1] (mg P/L)
1 Exeter Dam	10:35	L	2		0.009	0.031	0.017	-	0.05
	15:19	H	2		0.011	0.051	0.019	-	0.07
2 Downtown Exeter Old SQM 15	9:10	L	3.1		0.021	0.042	0.084	-	0.13
	14:56	H	3.5		0.024	0.378	0.102	-	0.48
3 US Rt 1	9:08	L	2.8	A	0.007	0.082	0.083	-	0.17
				B	0.028	0.053	0.070	-	0.12
				C	0.025	0.050	0.077	-	0.13
	14:46	H	5.2		0.022	0.073	0.090	-	0.16
4 Oxbow Cut	8:54	L	3		0.003	0.047	0.079	-	0.13
	14:32	H	5		0.028	0.102	0.107	-	0.21
5 South of Newfields Town	8:50	L	2.5		0.024	0.047	0.069	-	0.12
	14:32	H	6.4	A	0.022	0.060	0.068	-	0.13
				B	0.022	0.437	0.068	-	0.51
				C	0.020	0.058	0.069	-	0.13
6 Newfield Town Landing	8:33	L	2.2		0.036	0.106	0.118	-	0.22
	14:25	H	3.9		0.027	0.050	0.037	-	0.09
7 US Rt 108	8:30	L	2.1		0.003	0.072	0.073	-	0.15
	14:13	H	3.9		0.010	0.044	0.030	-	0.07
8 Between US Rt 108 and RR Bridge	8:08	L	1.9		0.018	0.054	0.058	-	0.11
	13:58	H	4		0.032	0.043	0.021	-	0.06
9 RR Bridge	8:06	L	3.2		0.014	0.037	0.050	-	0.09
	13:37	H	3.4		0.034	0.068	0.016	-	0.08
10 Great Bay	7:23	L	5.9		0.037	0.042	0.017	-	0.06
	13:28	H	8		0.036	0.056	0.009	-	0.06
Exeter WWTP				-	1.176	1.647	0.472	-	2.12

TP = TDP + TPP

Table 8. August 24, 2011 Squamscott River Phosphorus Data

Station	Time	Tide	Water Depth (m)	Replicate	PO4 (mg P/L)	TDP (mg P/L)	TPP (mg P/L)	TP (mg P/L)	TP Calculated[1] (mg P/L)
1 Exeter Dam	10:20	H	1.9		0.021	0.042	0.019	0.061	0.061
	14:25	L	2.1		0.019	0.077	0.048	0.088	0.125
2 Downtown Exeter Old SQM 15	10:05	H	3.3		0.051	0.071	0.058	0.107	0.129
	10:05	L	1.6		0.030	0.080	0.060	0.081	0.139
3 US Rt 1	10:16	H	5.4		0.047	0.060	0.052	0.110	0.112
	16:30	L	3.8		0.052	0.151	0.077	0.159	0.228
4 Oxbow Cut	9:53	H	2.6		0.046	0.096	0.010	0.104	0.106
	15:12	L	2.5		0.057	0.135	0.061	0.137	0.196
5 South of Newfields Town	9:56	H	5.4		0.059	0.066	0.038	0.071	0.104
	16:16	L	4.4		0.050	0.108	0.052	0.109	0.159
6 Newfield Town Landing	9:26	H	2.8		0.054	0.063	0.031	0.072	0.094
	15:59	L	1.6		0.044	0.078	0.093	0.138	0.171
7 US Rt 108	9:36	H	4.1	A	0.047	0.070	0.022	0.080	0.093
			-	B	0.050	0.077	0.021	-	0.098
			-	C	0.046	0.057	0.020	-	0.076
	16:04	L	2.6		0.053	0.085	0.040	0.095	0.125
8 Between US Rt 108 and RR Bridge	9:17	H	2.2		0.039	0.074	0.020	0.079	0.094
	15:45	L	1.6		0.047	0.059	0.040	0.110	0.099
9 RR Bridge	9:22	H	5.0		0.035	0.095	0.015	0.097	0.110
	15:05	L	2.4	A	0.049	0.081	0.029	-	0.110
			-	B	0.049	0.065	0.033	0.069	0.098
				C	0.052	0.088	0.033	-	0.122
10 Great Bay	9:03	H	7.8		0.031	0.102	0.010	0.103	0.112
	15:35	L	5.7		0.034	0.080	0.019	0.087	0.100
Exeter WWTP					1.100	1.467	0.358	1.787	1.825

TP = TDP + TPP

Table 9. August 12, 2011 Squamscott River Chla, Suspended Solids and CDOM

Station	Time	Tide	Water Depth (m)	Replicate	Chla (ug/L)	Pheophytin (ug/L)	TSS (mg/L)	VSS (mg/L)	CDOM ag440 (1/m)	CDOM (QSE)
1 Exeter Dam	10:35	L	2		9.4	2.3	3.6	0.7	3.7	99.9
	15:19	H	2		9.5	1.2	6.4	2.5	3.2	87.5
2 Downtown Exeter Old SQM 15	9:10	L	3.1		103.5	0.0	16.8	6.4	2.6	69.5
	14:56	H	3.5		157.3	0.0	24.6	6.9	2.8	76.5
3 US Rt 1	9:08	L	2.8	A	87.3	0.0	18.5	8.1	2.5	68.6
				B	87.9	4.8	19.8	4.2	2.8	75.0
				C	91.2	0.3	21.4	9.4	-	-
	14:46	H	5.2		136.1	7.9	27.6	9.9	2.7	72.8
4 Oxbow Cut	8:54	L	3		90.6	7.4	23.4	7.3	2.9	79.4
	14:32	H	5		177.4	4.5	24.5	11.5	2.3	62.8
5 South of Newfields Town	8:50	L	2.5		101.3	0.6	19.8	8.9	2.1	55.9
	14:32	H	6.4	A	102.5	0.0	39.2	9.2	2.1	55.8
				B	100.7	1.7	39.2	9.2	2.1	57.1
				C	96.9	6.0	41.5	13.1	-	-
6 Newfield Town Landing	8:33	L	2.2		233.8	1.7	21.1	14.3	2.5	66.3
	14:25	H	3.9		47.7	0.0	32.8	4.2	1.0	27.1
7 US Rt 108	8:30	L	2.1		128.0	0.0	17.2	8.9	2.4	65.1
	14:13	H	3.9		30.3	0.1	34.4	9.4	0.9	23.7
8 Between US Rt 108 and RR Bridge	8:08	L	1.9		81.3	3.7	20.8	6.8	2.2	58.4
	13:58	H	4		15.9	1.1	19.6	4.6	0.7	19.0
9 RR Bridge	8:06	L	3.2		69.4	2.8	29.7	6.3	2.0	54.2
	13:37	H	3.4		10.2	0.3	26.4	6.4	0.5	14.7
10 Great Bay	7:23	L	5.9		5.5	1.8	30.7	6.8	0.6	17.3
	13:28	H	8		5.0	1.0	22.9	6.4	0.4	11.6
Exeter WWTP				-	434.5	141.7	90.3	74.2	3.5	94.1

Table 10. August 24, 2011 Squamscott River Chla, Suspended Solids and CDOM

Station	Time	Tide	Water Depth (m)	Replicate	Chla (ug/L)	Pheophytin (ug/L)	TSS (mg/L)	VSS (mg/L)	CDOM ag440 (1/m)	CDOM (QSE)
1 Exeter Dam	10:20	H	1.9		6.5	1.9	5.7	3.2	5.1	136.6
	14:25	L	2.1		8.4	5.5	19.3	7.1	5.6	150.4
2 Downtown Exeter Old SQM 15	10:05	H	3.3		26.6	10.8	13.2	5.0	4.4	118.0
	10:05	L	1.6		36.4	3.0	16.1	5.7	5.1	138.7
3 US Rt 1	10:16	H	5.4		17.0	6.1	15.7	2.9	3.9	104.4
	16:30	L	3.8		42.0	4.2	30.4	7.5	5.0	134.4
4 Oxbow Cut	9:53	H	2.6		10.3	4.8	15.0	4.6	3.2	87.3
	15:12	L	2.5		47.2	2.4	16.8	5.7	4.8	129.0
5 South of Newfields Town	9:56	H	5.4		10.1	5.1	25.4	5.7	2.6	69.8
	16:16	L	4.4		14.4	6.0	21.8	5.4	3.6	97.0
6 Newfield Town Landing	9:26	H	2.8		8.6	4.0	18.2	3.6	1.9	50.4
	15:59	L	1.6		42.3	28.4	21.1	8.6	4.3	116.8
7 US Rt 108	9:36	H	4.1	A	4.8	1.6	61.4	15.7	1.4	36.8
			-	B	4.9	1.9	21.8	4.6	-	-
			-	C	4.6	2.4	20.7	3.9	-	-
	16:04	L	2.6		11.5	6.0	19.3	5.4	3.2	86.5
8 Between US Rt 108 and RR Bridge	9:17	H	2.2		5.5	1.5	22.5	5.7	1.1	28.9
	15:45	L	1.6		14.9	5.8	16.1	3.2	3.2	86.4
9 RR Bridge	9:22	H	5.0		4.7	1.7	19.6	4.3	0.9	24.7
	15:05	L	2.4	A	11.9	4.7	19.6	5.4	2.5	68.5
			-	B	10.7	5.2	19.3	5.0	-	-
				C	11.5	3.6	20.4	6.4	-	-
10 Great Bay	9:03	H	7.8		3.6	1.1	18.2	4.6	0.6	15.9
	15:35	L	5.7		6.1	1.4	26.8	6.8	0.8	22.5
Exeter WWTP					296.7	133.9	37.7	34.6	8.1	218.9

Table 11. August 12, 2011 Squamscott River Carbon

Station	Time	Tide	Water Depth (m)	Replicate	DOC (mg C/L)	POC (mg C/L)
1 Exeter Dam	10:35	L	2		7.58	0.88
	15:19	H	2		7.28	0.96
2 Downtown Exeter Old SQM 15	9:10	L	3.1		7.09	3.42
	14:56	H	3.5		4.72	5.40
3 US Rt 1	9:08	L	2.8	A	4.38	3.64
				B	3.24	3.68
				C	7.24	3.34
	14:46	H	5.2		8.02	4.75
4 Oxbow Cut	8:54	L	3		6.53	3.59
	14:32	H	5		3.25	6.35
5 South of Newfields Town	8:50	L	2.5		4.82	3.30
	14:32	H	6.4	A	6.67	3.63
				B	6.38	3.77
				C	4.63	3.98
6 Newfield Town Landing	8:33	L	2.2		3.59	7.70
	14:25	H	3.9		2.23	2.12
7 US Rt 108	8:30	L	2.1		3.76	4.06
	14:13	H	3.9		2.27	1.56
8 Between US Rt 108 and RR Bridge	8:08	L	1.9		4.12	3.02
	13:58	H	4		2.15	1.09
9 RR Bridge	8:06	L	3.2		5.36	2.73
	13:37	H	3.4		1.36	0.81
10 Great Bay	7:23	L	5.9		1.61	0.93
	13:28	H	8		1.10	0.55
Exeter WWTP				-	12.04	21.60

Table 12. August 24, 2011 Squamscott River Carbon

Station	Time	Tide	Water Depth (m)	Replicate	DOC (mg C/L)	POC (mg C/L)
1 Exeter Dam	10:20	H	1.9		11.4	0.9
	14:25	L	2.1		10.4	2.4
2 Downtown Exeter Old SQM 15	10:05	H	3.3		10.5	2.3
	10:05	L	1.6		10.8	3.0
3 US Rt 1	10:16	H	5.4		8.8	0.8
	16:30	L	3.8		10.1	3.2
4 Oxbow Cut	9:53	H	2.6		7.3	1.4
	15:12	L	2.5		4.7	3.3
5 South of Newfields Town	9:56	H	5.4		6.5	1.6
	16:16	L	4.4		8.9	1.6
6 Newfield Town Landing	9:26	H	2.8		4.8	1.2
	15:59	L	1.6		9.1	3.8
7 US Rt 108	9:36	H	4.1	A	2.4	0.9
			-	B	3.6	0.8
			-	C	3.7	0.8
	16:04	L	2.6		8.2	1.7
8 Between US Rt 108 and RR Bridge	9:17	H	2.2		3.3	0.9
	15:45	L	1.6		7.7	1.7
9 RR Bridge	9:22	H	5.0		2.4	0.8
	15:05	L	2.4	A	6.5	1.3
			-	B	5.9	1.3
				C	4.1	1.3
10 Great Bay	9:03	H	7.8		2.2	0.6
	15:35	L	5.7		2.0	0.9
Exeter WWTP					14.3	16.4