UNC Nutrient Management Study - In Situ Observational Study of Jordan Lake
Progress Report: Year 1 1/1/2017 – 6/30/2017

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Background and Objectives

B. Everett Jordan Lake is a reservoir west of Raleigh and south of Durham in Chatham County, NC, Figure 1. It is owned and operated by the US Army Corps of Engineers, which dammed and flooded the Haw River and New Hope River between 1973 and 1983. The reservoir receives water input from the Haw River, Upper New Hope and Lower New Hope watersheds, Table 1. Associated with these water inputs are nutrients, sediments and, in some cases, significant debris. The Haw River watershed is mixed agricultural, rural and urban land use while the Upper and Lower New Hope watersheds are principally urban. The primary outflow from the lake occurs over the Jordan Lake Dam and comprises the starting point of the Cape Fear River. The Haw River drains the Haw River watershed and discharges into the southern Haw River arm of Jordan Lake approximately 5 miles upstream of the Jordan Lake Dam. The Haw River provides 70 – 90 percent of the annual flow into the lake. The Upper and Lower New Hope watersheds drain into the New Hope Creek arm of Jordan Lake which extends approximately 17 miles upstream from the Dam. The Haw River arm and the New Hope Creek arm are naturally separated by a narrow channel referred to as the "s-bends" or "narrows". The New Hope Creek arm is further subdivided by two causeways with relatively narrow bridge openings, one where NC Highway 64 crosses the lake and the other where Farrington Road crosses the lake.

Table 1. Watersheds draining into Jordan Lake, (Tetra Tech, 2014)

	Haw River	**Upper New Hope**	**Lower New Hope**	**TOTAL**
Acres	859,185	147,485	71,861	1,078,531
Percent of Total	79.7	13.7	6.7	100

As part of the UNC Nutrient Management Study, we initiated a multi-part observational program in January, 2017 to help clarify the impacts of watershed input on key processes controlling water quality in Jordan Lake and to help inform management actions designed to improve water quality in the lake.

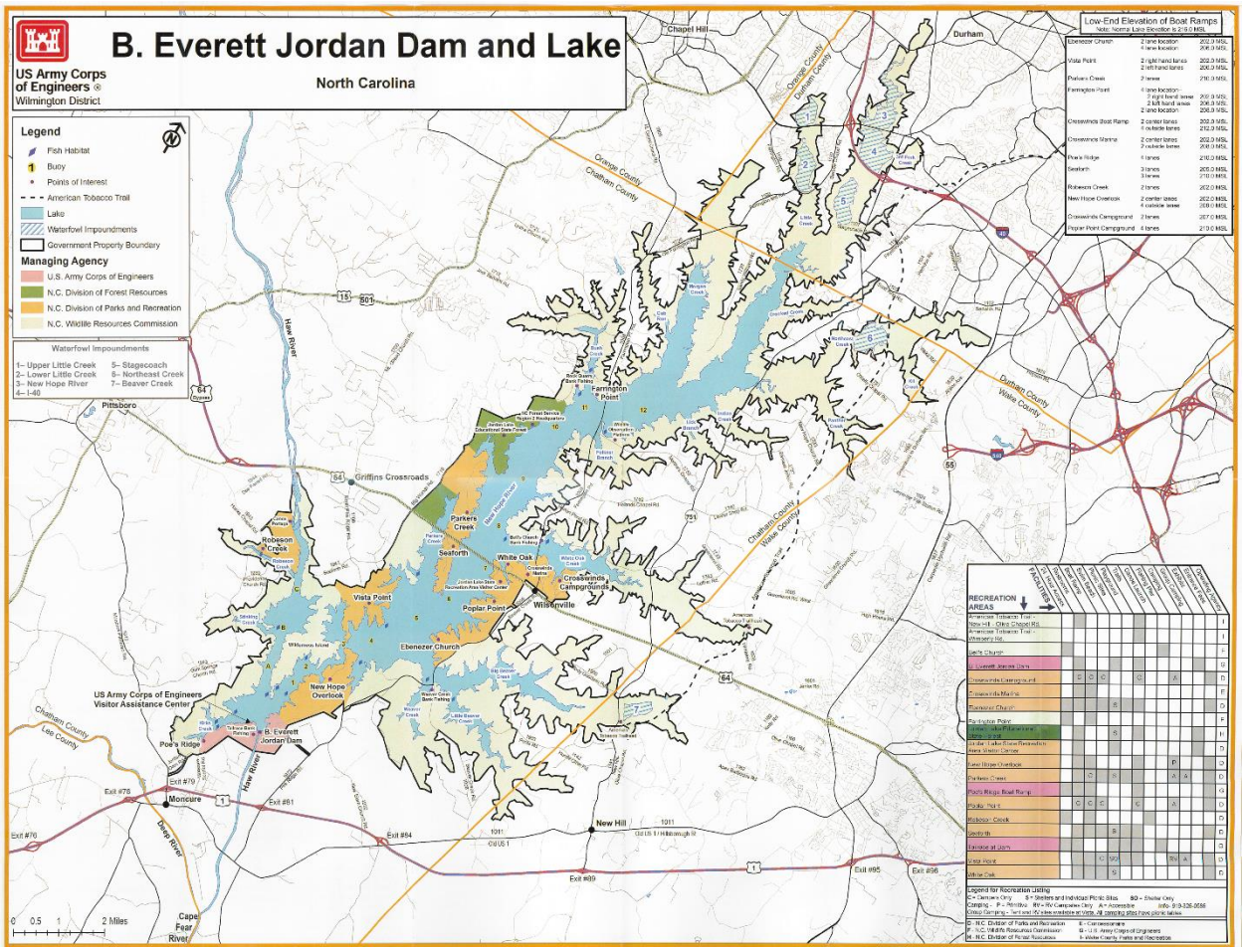

Figure 1. Map of B. Everett Jordan Dam and Lake
source https://commons.wikimedia.org/wiki/File:B._Everett_Jordan_Lake_Map.png

Specific objectives of this work are:

1.) to identify water circulation and exchanges in the lake, in particular, the extent to which the large volume of water entering via the Haw River influence the New Hope Creek arm of the lake;

2.) to better quantify the response of important water quality parameters in the lake to a range of forcing conditions (variations in flow, temperature, light and wind) via high frequency (e.g., hourly) in situ observations to complement the less frequent (e.g., monthly) sampling done by the NC Division of Environmental Quality; and

3.) to better quantify phytoplankton dynamics, including nutrient limitation and productivity, in Jordan Lake that are causing the lake to be out of compliance with state water quality standards.

Data Collection Plan and Methodology

Water Circulation and Exchange

Acoustic Doppler current profilers (ADCPs) have been deployed to measure water velocities through the water column at four locations along the lake, the lower Haw River, the s-bend, the highway 64 causeway and the Farrington Rd causeway, (red circles in Figure 2a, 2b). Each ADCP is mounted on a bottom stand with the instrument pointed upward (Figure 3) sampling the water column above. They are programmed to store 3-minute averaged water velocities every 10 minutes, with a vertical resolution of 0.5 m. These instruments were deployed on April 20, 2017 and data collection is planned to last for approximately one year. The instruments will be serviced after 6-months (October 2017, April 2018) at which time they will be cleaned, the batteries changed and data (stored internally) offloaded for analysis.

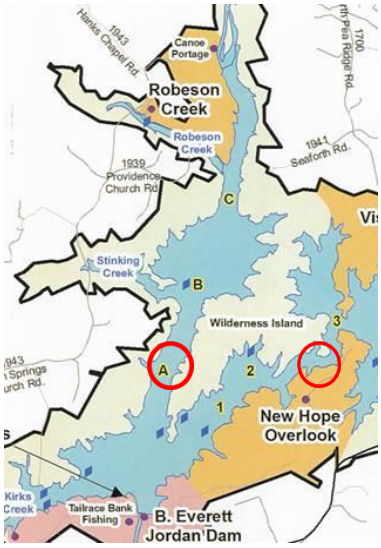

Figure 2a. Locations for ADCPs and thermistor strings in the lower portion of Jordan Lake

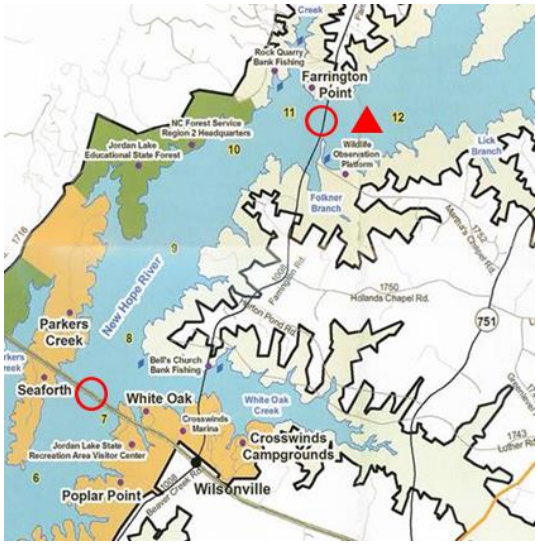

Figure 2b. Locations of ADCPs and thermistor string (circles) and the nutrient limitation bioassays (NC DEQ DWR station CFR086F) in the New Hope Creek arm of Jordan Lake.

Figure 3. Acoustic Doppler Current Profiler (ADCP) in a typical mounting

In Situ Water Quality Parameters

Near each ADCP we have deployed a mooring to measure temperature, irradiance, conductivity and water depth to aid in understanding water exchange, thermal stratification and light extinction. Each mooring consists of two parts, one suspended below a surface float and the other attached to the bottom using a taught line and submerged float, (Figure 4). This arrangement allows the full water column to be sampled while allowing for a possible change in lake level of as much as 30 ft. Each mooring contains approximately 20 HOBO temperature sensors (Figure 4) spanning the water column at 0.5 m intervals. A conductivity sensor is included with the HOBO located 2.2 m below the surface. The upper few HOBOs also include light sensors. Pressure sensors are included at the bottom and on top of the surface buoy to enable the determination of total water depth. Data is collected every 6 – 12 minutes. Due to fouling of the light and conductivity sensors, the part of the mooring attached to the surface float is recovered and cleaned monthly. At that time, vertical profiles of photosynthetically active radiation (PAR), (Li-Cor model LI-193 spherical sensor) and water quality indicators (Endeco-YSI multi-parameter probes models 6600 or EX02) are made from the attending boat to assist with calibration of the moored sensors and further enhance the data set. Water samples are also collected at surface, mid-depth and near bottom for laboratory analysis (see algal dynamics).

Water quality and meteorological data are also being measured in a semi-continuous manner using an Autonomous Vertical Profiler (AVP), Figure 5. This floating platform has a computer controlled winch system that allows it to remotely raise and lower a multi-parameter probe and collect vertical profiles of key water quality properties including water temperature, conductivity, in vivo fluorescence, dissolved oxygen concentration, turbidity and pH. In this case the AVP was programmed to perform a profile every 30 min and data are collected with a vertical resolution of approximately 4 cm. The profiler also measures

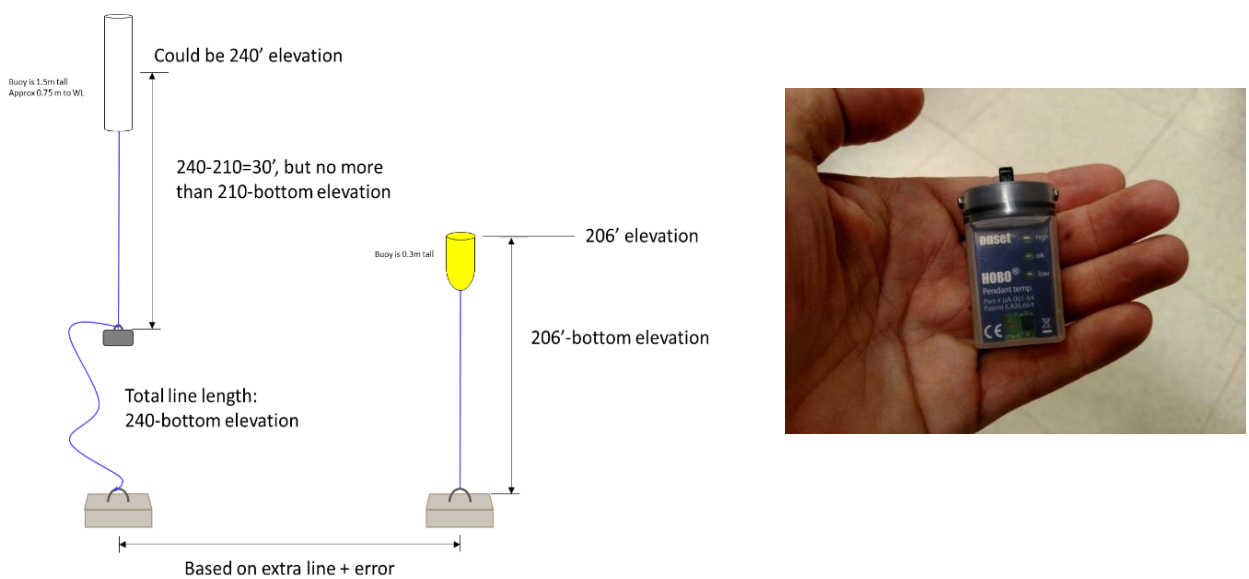

Figure 4. Moorings and typical Hobo sensor

Figure 5. Autonomous Vertical Profiler (AVP)

Figure 6a. AVP deployment location in the lower Haw River

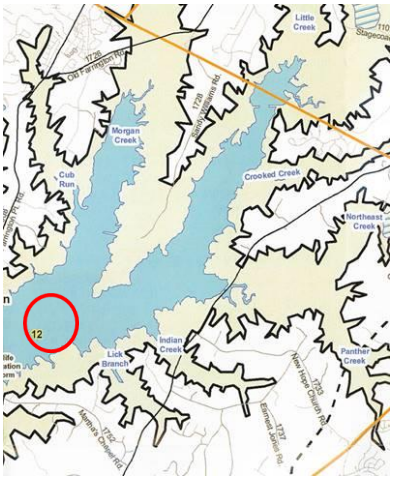

Figure 6b. AVP deployment location in the northeast portion of Jordan Lake

wind speed and direction and transmits data after each profile via a cell phone linkage to the Institute of Marine Sciences. These data are displayed in near real time at the website: jordanlakeobservatory.unc.edu. The AVP was deployed in the lower Haw River from May 17, 2017 through July 26, 2017 and in the upper section of the lake above the Farrington River causeway since July 26, 2017 (Figure 6). We expect to deploy a second AVP in the lake in the late summer or early fall.

<u>Algal / Nutrient Dynamics</u>

A series of bioassays and laboratory analysis using water collected from Jordan Lake are being conducted to:

- determine the degree of nitrogen (N) and phosphorus (P) limitation on phytoplankton productivity and biomass;
- determine the potential effectiveness of nutrient reduction (dilution) for reducing algal biomass / chlorophyll a in the lake;
- provide laboratory validation of observations from in situ instrumentation and determine additional parameters such as nutrient concentrations in the lake; and
- quantify phytoplankton productivity and the impact of light limitation on productivity and biomass.

Nutrient addition / dilution bioassays have been conducted on water collected in April 2017 and July 2017. Analyses of the April water samples are largely complete while analysis of the July samples are ongoing and expected by the end of September. Water for the initial bioassays was collected at 10:00 on April 24, 2017 from just upstream of the Farrington Rd causeway (NC DEQ DWR station CFR086F-see Figure 2b) using a diaphragm pump into ten - 20L polyethylene carboys. The carboys were quickly transferred to a darkened truck bed and transported to UNC-IMS. Upon arrival (approximately 14:30) the carboys were placed in the outdoor incubation ponds to maintain ambient temperature and light conditions. The following morning water from the carboys was homogenized in a 300L fiberglass tub prior to dispersing into 4L Cubitainers and performing experimental nutrient addition and dilution treatments.

Nutrient additions consisted of a full factorial design of N and P additions, including a control with no nutrients added, a N treatment (0.63 mg L^{-1} N-NO_3^- plus 0.07 mg L^{-1} N-NH_4^+), a P treatment (0.155 mg L^{-1} P-PO_4^{-3}) and a N plus P treatment (0.63 mg L^{-1} N-NO_3^- plus 0.07 mg L^{-1} N-NH_4^+ plus 0.155 mg L^{-1} P-PO_4^{-3}). Addition treatments were made to whole lake water as well as to lake water diluted by 10, 30, and 50 percent with a major ion solution that contained all the major salts of Jordan Lake water less N and P. A separate treatment consisting of addition of 1.4 mg L^{-1} dissolved silicate was additionally implemented to determine the potential of silicate limitation. Compared to other taxa, diatoms require significant amounts of silica for growth. Consequently, insufficient supplies of silica can impact both community level productivity and can lead to significant shifts in taxonomic structure, often favoring less desirable taxa such as cyanobacteria. Data from silica addition experiments are currently being analyzed and will determine whether phytoplankton productivity or community composition in Jordan Lake is affected by the availability of dissolved silica.

Phytoplankton growth in the nutrient addition and dilution bioassays was tracked by measurements of chlorophyll a and accessory photopigments using extraction followed by either fluorometric or high performance liquid chromatography (HPLC) techniques on day 0, day 1, day 3, and day 6 of the experiment. Analyses for chlorophyll *a* (Chl *a*), representing total phytoplankton biomass, are completed while accessory photopigment data are still being analyzed. Phytoplankton growth rates (μ in units d^{-1}) at each time point during the experiment were calculated as:

$$\mu = ln(C_t/C_0)/t$$

where *ln* is the natural logarithm, t is the length of time elapsed since the beginning of the experiment, C_t is the Chl *a* concentration at time t, and C_0 is the initial Chl *a* concentration. Using growth rates rather than biomass allows determination of the phytoplankton growth response that is not impacted by the reduction of biomass in the dilution treatments. Growth expressed in this manner is also consistent with the phytoplankton growth rates in many eutrophication models and therefore will facilitate incorporation of experimental results into such models. At each time point in the experiment, the effects of treatments on phytoplankton growth rates were analyzed using a three way ANOVA with dilution treated as a continuous variable and the addition or omission of N or P treated as categorical variables.

Water collected for the April and July bioassays was also used to determine the relationship between light availability and phytoplankton photosynthesis. Immediately upon delivery of lake water to UNC-IMS (~ 4.5 hours after collection), aliquots of water were dispensed into 20 mL borosilicate glass incubation vials. Photosynthesis was measured by $^{14}CO_2$ incorporation at 42 different light levels that span the range of light levels known to limit phytoplankton photosynthesis. The light gradient was produced by a photosynthetron which consists of a white light source, and a range of light reducing filters, and an aluminum heat sink that surrounds each vial to control temperature (Figure 7). Light delivery to water samples within each vial was measured using a Biospherical Instruments Model QSL-100 irradiance meter with a QSL-101 4 πsensor. Water was circulated through the heat sink to a temperature controlled water bath to maintain the water temperature present at the time of collection (20 °C on 24 April and 29 °C on 24 July). Samples were incubated in the photosynthetron for 1 hour and photosynthesis was determined by the amount of $^{14}CO_2$ incorporated according to standard methods. Photosynthesis was normalized by Chl *a* to express observed productivity in units of carbon produced per unit of phytoplankton biomass.

Figure 7. Photosynthetron set up for the measuring light vs. photosynthesis relationship. Note light increases from left to right within rows and also varies within columns.

Observed relationships between light and photosynthesis were used to model primary productivity within the vertical light gradient of the New Hope arm of Jordan Lake. Photosynthesis and light measurements were fit to a hyperbolic tangent model developed by Jassby and Platt (1976)

$$P^b = P^b_{max} \tanh(\alpha I / P^b_{max})$$

where P^b is the biomass normalized photosynthetic rate, P^b_{max} is the light-saturated photosynthetic rate, α is the initial light limited slope, and I is irradiance. Irradiance levels in the upper mixed layer of Jordan

Lake were determined based on extinction coefficients determined via depth profiles of PAR and upper mixed layer depths determined via analyses of temperature profiles. Depth profiles of Chl *a* were measured at the time of water collection (see above) and based on the lack of significant variability with depth were assumed constant throughout the upper mixed layer. Incident solar radiation integrated across wavelengths 200-1100 nm (W/m^2) were gathered from the nearby Remote Automated Weather System site at the Duke Forest and were converted to PAR in units of µmol photons/m^2/s by multiplying by 2.04. Using the equation above, productivity was calculated at 10 cm depth intervals every hour for the day of water collection. These values were then integrated across depth and time to produce an estimate of daily primary production in units of mg C/ m^2/ d.

Depth profiles of important water quality parameters were collected at the time and location of the bioassay water samples and during servicing of the *in situ* moorings. In each case, temperature, conductivity, pH, dissolved oxygen, in vivo fluorescence, and PAR were measured at 0.5 m depth intervals. Discrete water samples were also collected at 1 m depth intervals during the bioassay sampling and at surface, mid-depth and near bottom during the servicing trips. Upon return to IMS, these were analyzed in the laboratory for dissolved nutrients, Chl *a* by acetone extraction, and fluorometrically-determined Chl *a*.

Results

Water Circulation and Exchange

The ADCPs and moorings are scheduled to be serviced in late October at which time we will download the data collected during the previous six months and begin to evaluate the water circulation and exchange along the lake. Evidence of water movement from the Haw River arm into the New Hope Creek arm of the lake following a major discharge event is evident from the *in situ* water quality parameter sampling and is discussed below.

In Situ Water Quality Parameters

The 70-day AVP deployment in the lower Haw River was characterized by “normal” Haw River flow rates ranging from 250 – 1000 cubic ft per second that were interrupted by two major discharge events, beginning on May 23rd and June 20th, during which the inflow from the Haw River and from the creeks surrounding the New Hope Creek arm of the lake increased to more than 10 times their normal flow rates, Figure 8.

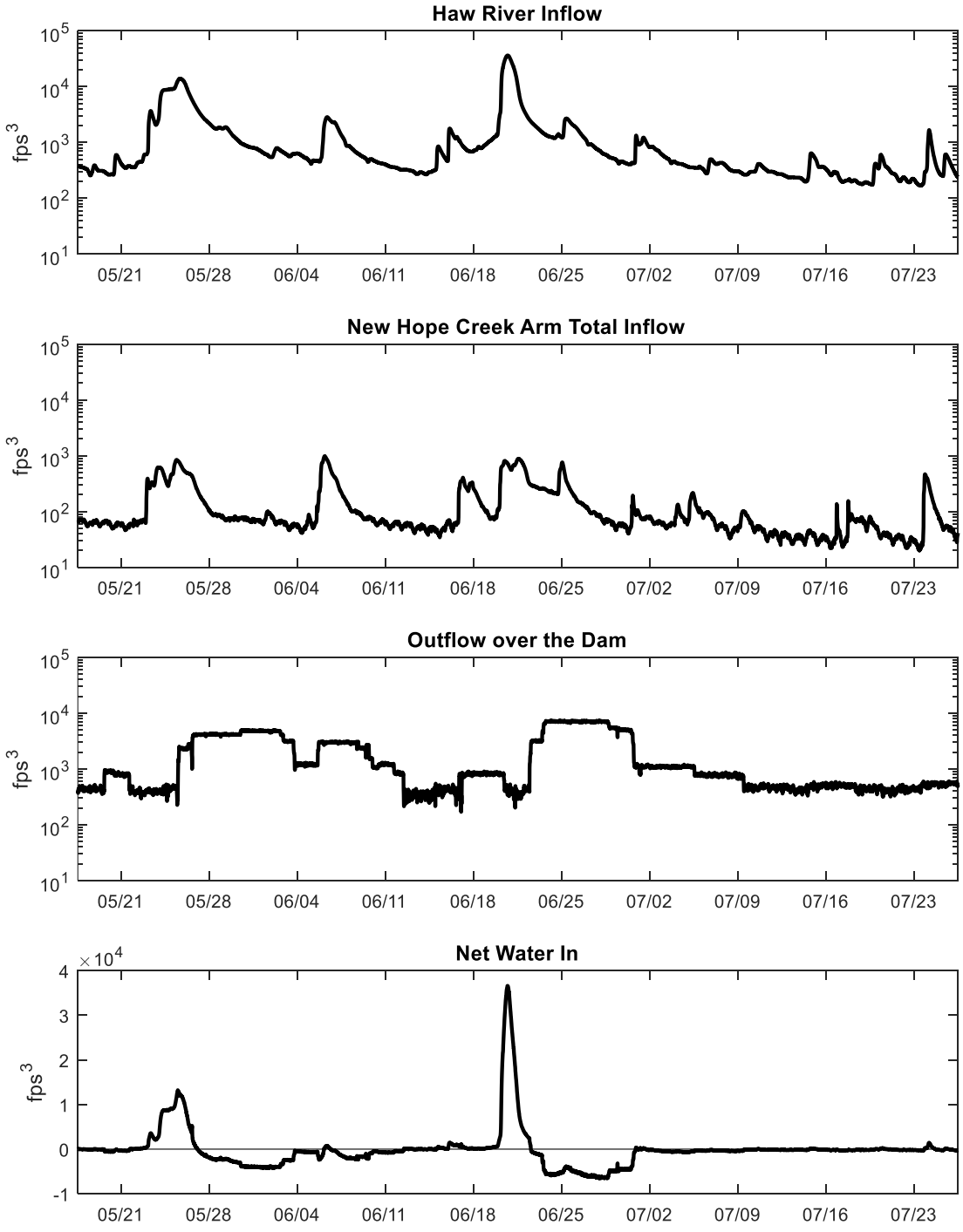

Figure 8. Jordan Lake inflows and outflows during the Lower Haw River AVP deployment

During normal flow warm weather conditions, the lower Haw River stratifies thermally with a relatively sharp thermocline two to three meters below the surface, Figures 9, 10. Algal biomass, as represented by in vivo chlorophyll fluorescence, is concentrated above the thermocline and diurnal cycles of dissolved oxygen and pH suggest significant primary productivity is occurring in this part of the water column during mid-day. Oxygen levels are depleted and turbidity is highest below the thermocline.

Water associated with the two major discharge events was highly turbid, 8-10 degrees C colder, lower in specific conductivity, pH, and in vivo fluorescence and higher in dissolved oxygen that the prevailing conditions at the AVP site, Figures 9, 11. There was evidence during the first discharge event that Haw River water initially flowed into the lake near mid-depth, (at a vertical level where the density of the river inflow matched that of the lake), although in both cases it quickly impacted the entire water column, Figure 9, 11. The physical change that these events imposed on the water column was extreme and persisted for approximately a week, after which turbidity levels returned to more normal values, the water column re-stratified thermally, and a diurnal cycle re-emerged typical of normal flow warm weather conditions as described above, Figure 11.

The major discharge events were also a source of substantial debris input to the Haw River arm of the lake, Figure 12. This debris ends up along the shore and on the lake bottom. Semi-annual cleanup events are organized to help remove tires, plastics, and other trash from the shore, e.g., cleanjordanlake.org. The extent that the debris directly impacts water quality in the lake appears to be largely undocumented.

Additional *in situ* water quality data was collected using instruments deployed from the boat when the moorings were cleaned on 5/18, 6/21, 7/13 and 7/27, 2017, Figures 13-16. On 5/18 the lake was thermally stratified at all four sites, turbidity was in the range of 10 NTUs and uniform through the water column, except at the Farrington Road causeway where it increased to above 30 NTUs below approximately 4 m depth. In vivo fluorescence was high near the surface in the lower Haw River and the S-bend, relatively uniform at the Hwy 64 causeway and had a small mid-depth maximum at Farrington Rd. Dissolved oxygen was supersaturated near the surface and declined with depth at all four sites. Light penetration was greatest of the four sampling dates at three of the four sites (Figure 17), with light reaching one percent of the surface value (considered the “compensation depth”, below which oxygen consumption by respiration and decomposition exceeds oxygen production by photosynthesis) at between 2.9 and 4 m below the surface, (Table 2). Sampling on 6/21 occurred during the second major discharge event. Minimal stratification existed at all of the sites and turbidity of approximately 120 NTUs existed through the water column at both the lower Haw River and the S-bend indicating that highly turbid water entering from the Haw River was being pushed from the Haw River arm to the New Hope Creek arm of the lake. The one percent light level at these two locations was greatly reduced to 1.9 to 0.9 m below the surface. It does not appear that this turbid water had been transported up the lake to the Hwy 64 causeway by the date of this sampling. The well-mixed water column is also evident in the *in vivo* fluorescence and dissolved oxygen levels at the Haw River and S-bend sites. Near bottom oxygen depletion is evident at the Hwy 64 causeway. Given the nearly homogeneous thermal structure at this location, this suggest active respiration is occurring in the lower water column or the bottom sediments. Water column properties during the latter two trips, 7/13 and 7/27 were similar throughout

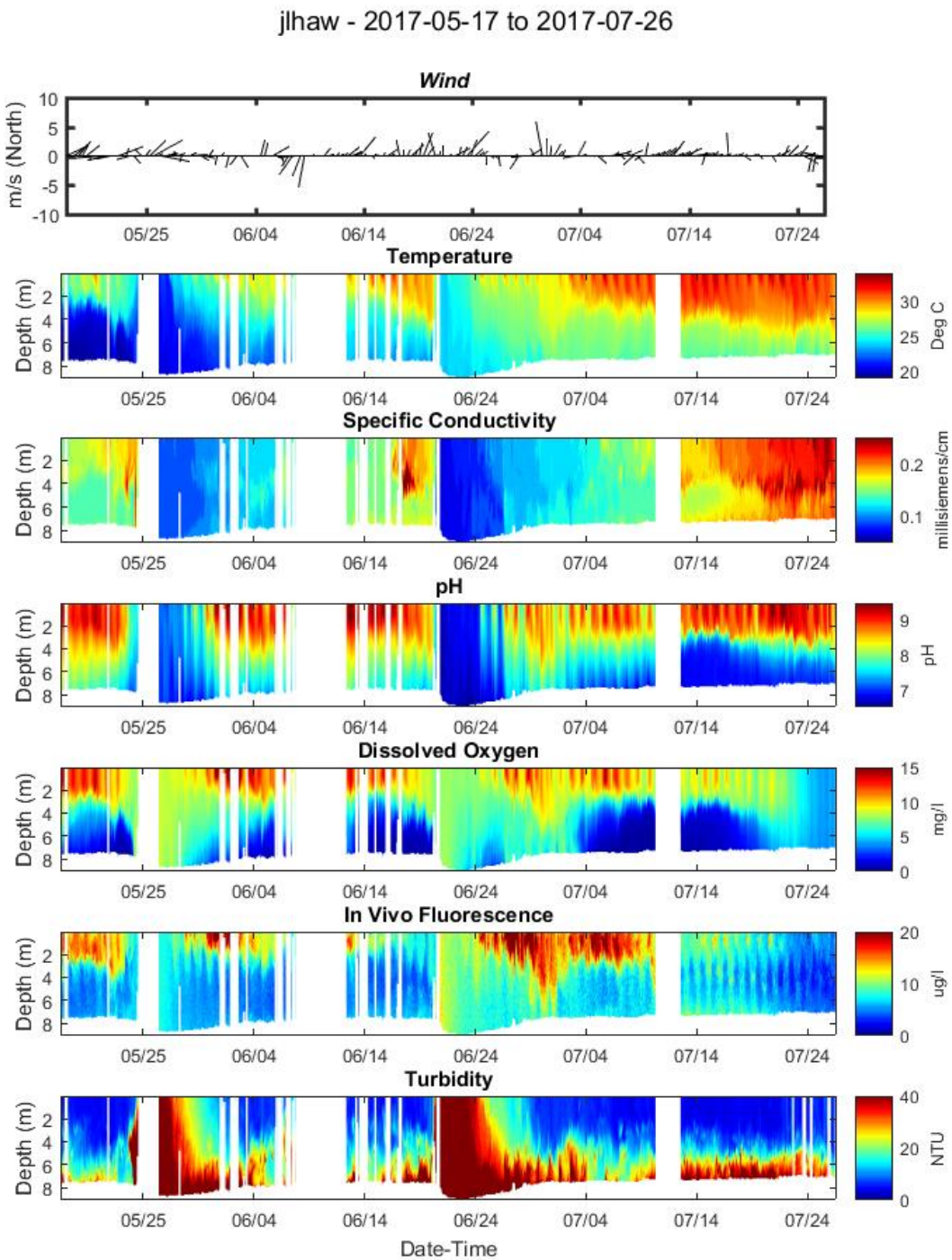

Figure 9. Water quality parameters observed during the full AVP deployment in the lower Haw River. Vertical white stripes indicated periods when the profiler was not functioning.

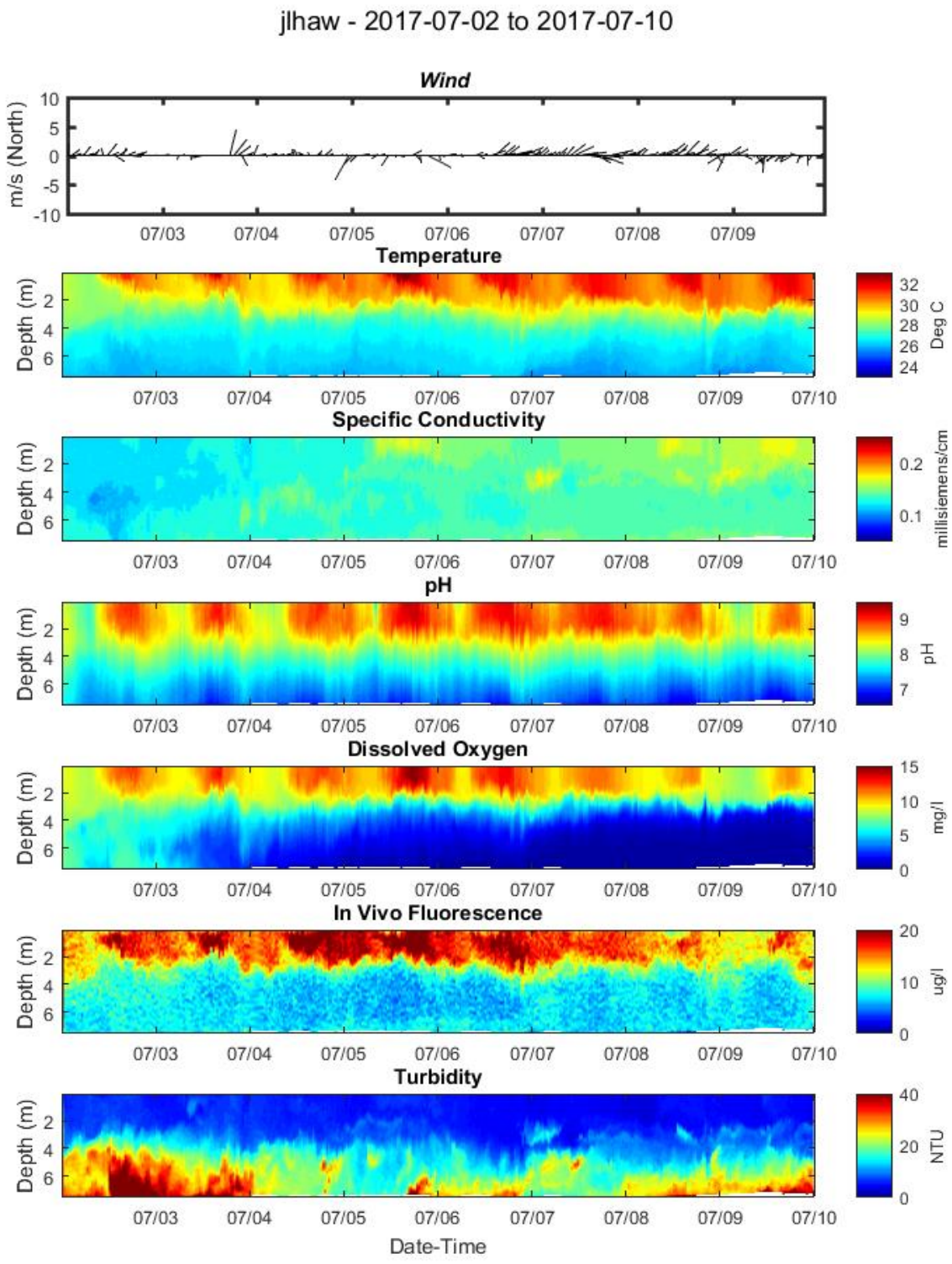

Figure10. Water quality parameters observed by the AVP deployment in the lower Haw River during a period of normal flow, warm weather conditions.

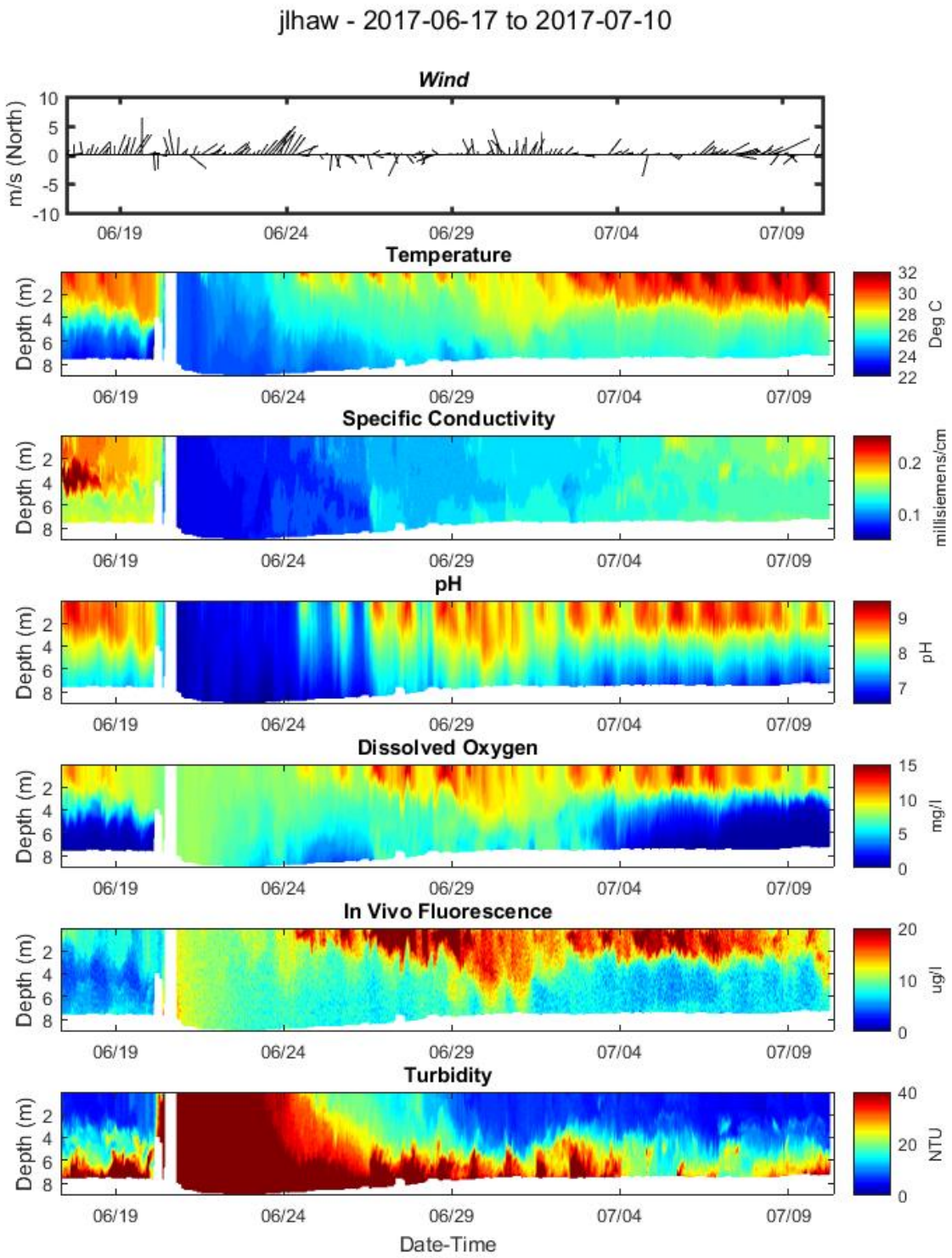

Figure 11. Water quality parameters observed by the AVP deployment in the lower Haw River during and following the second major flow event.

Figure 12. Pictures of debris near the AVP on June 20, 2017 during the second major discharge event.

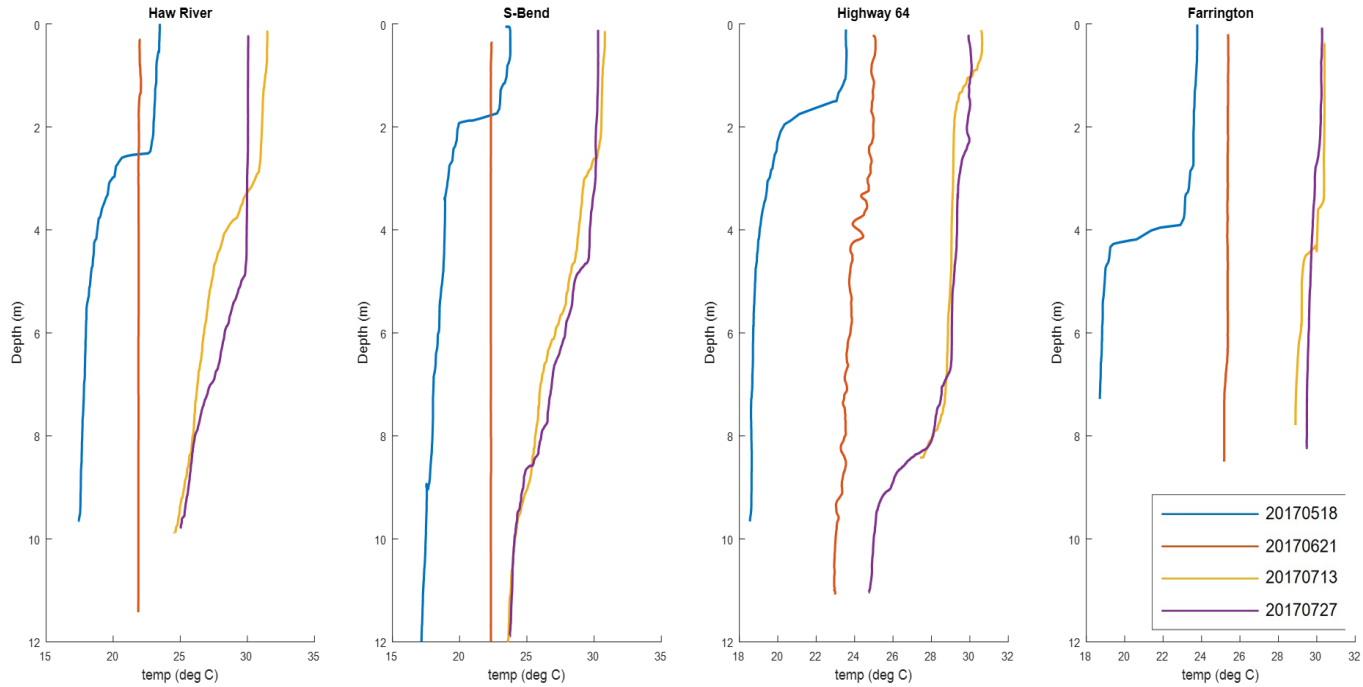

Figure 13. Water temperature profiles measured at the four mooring sites during trips to clean the moored sensors on 5/18, 6/21, 7/13 and 7/27, 2017

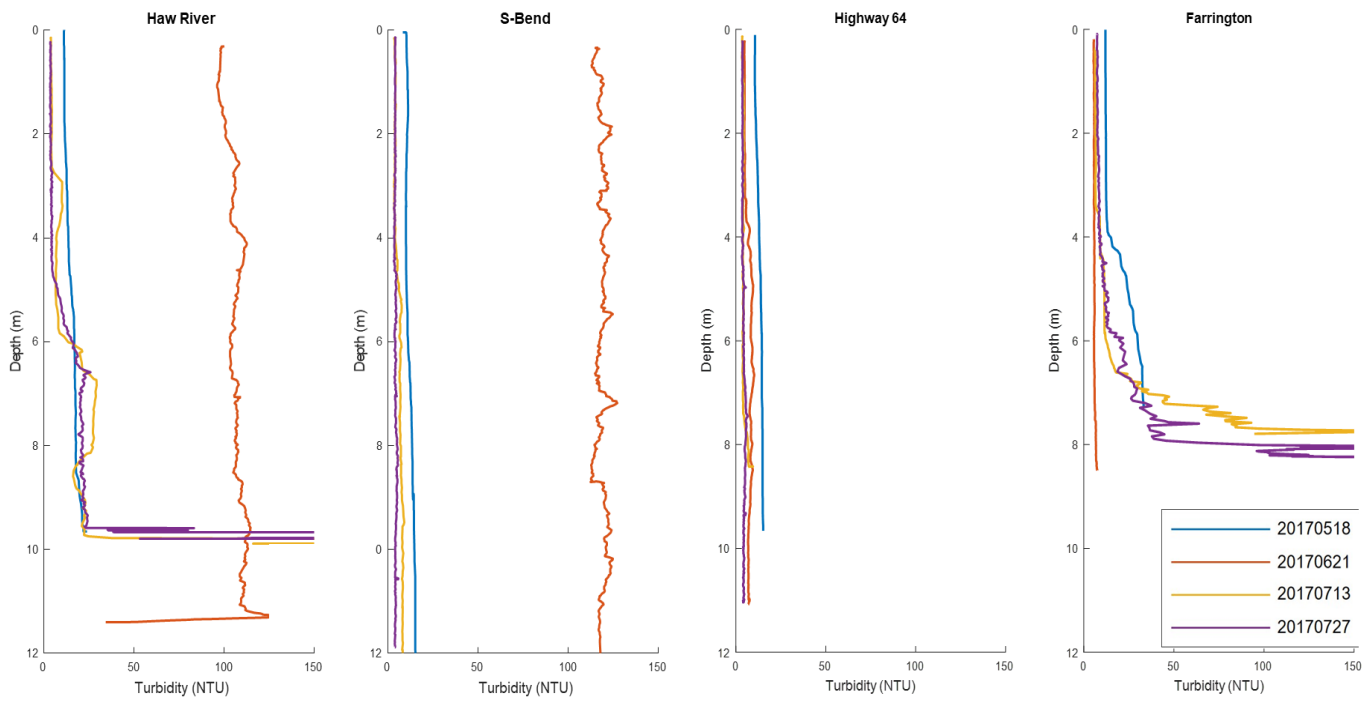

Figure 14. Turbidity profiles measured at the four mooring sites during trips to clean the moored sensors on 5/18, 6/21, 7/13 and 7/27, 2017

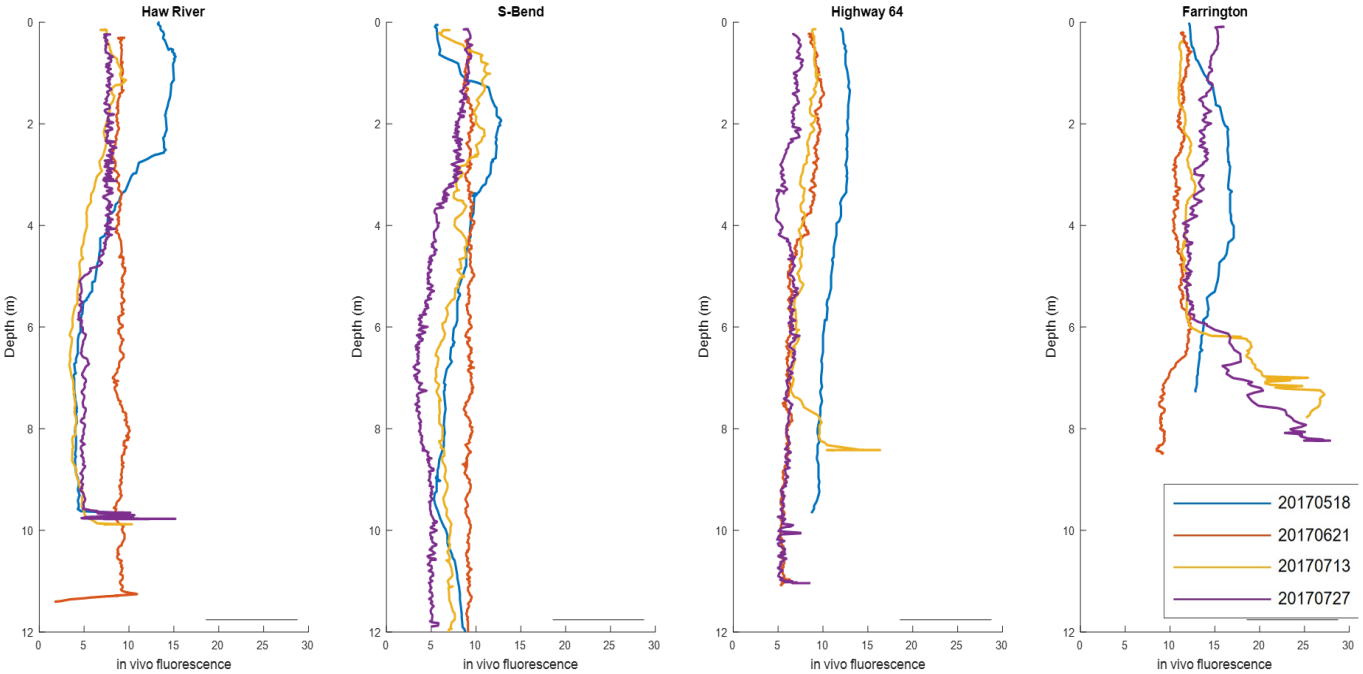

Figure 15. In vivo fluorescence profiles measured at the four mooring sites during trips to clean the moored sensors on 5/18, 6/21, 7/13 and 7/27, 2017

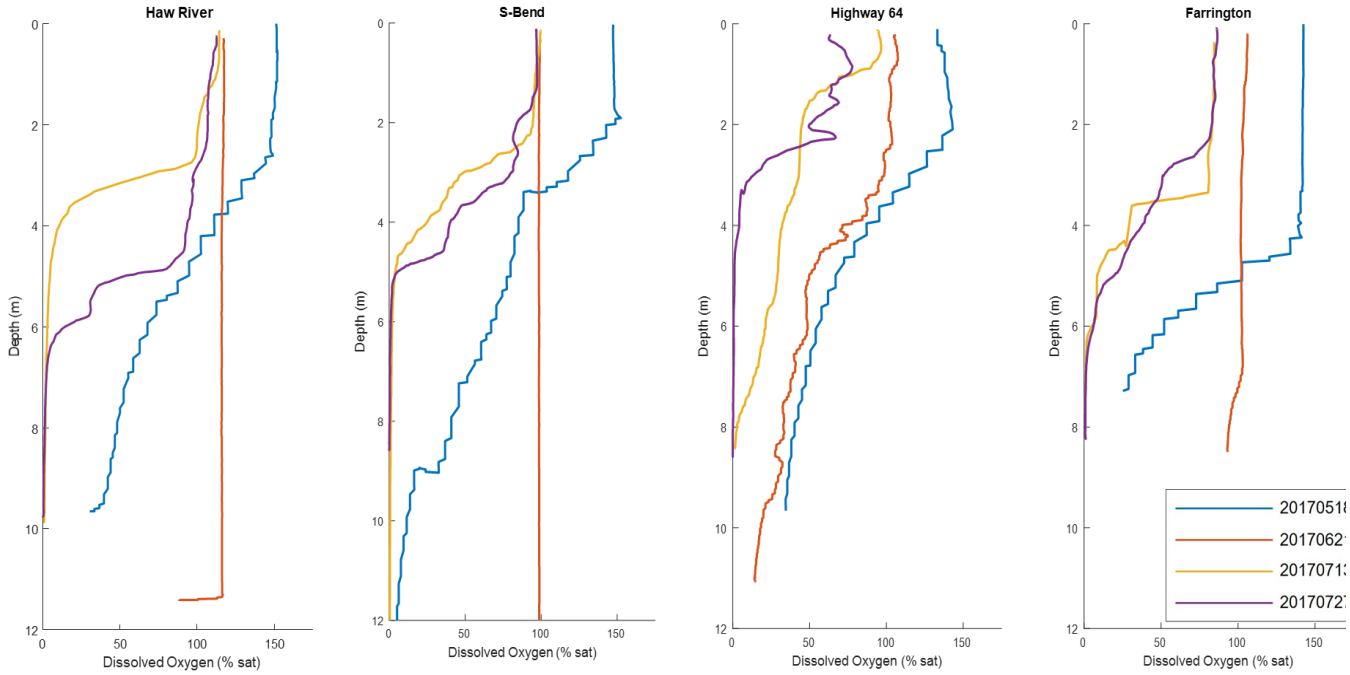

Figure 16. Dissolved oxygen profiles measured at the four mooring sites during trips to clean the moored sensors on 5/18, 6/21, 7/13 and 7/27, 2017

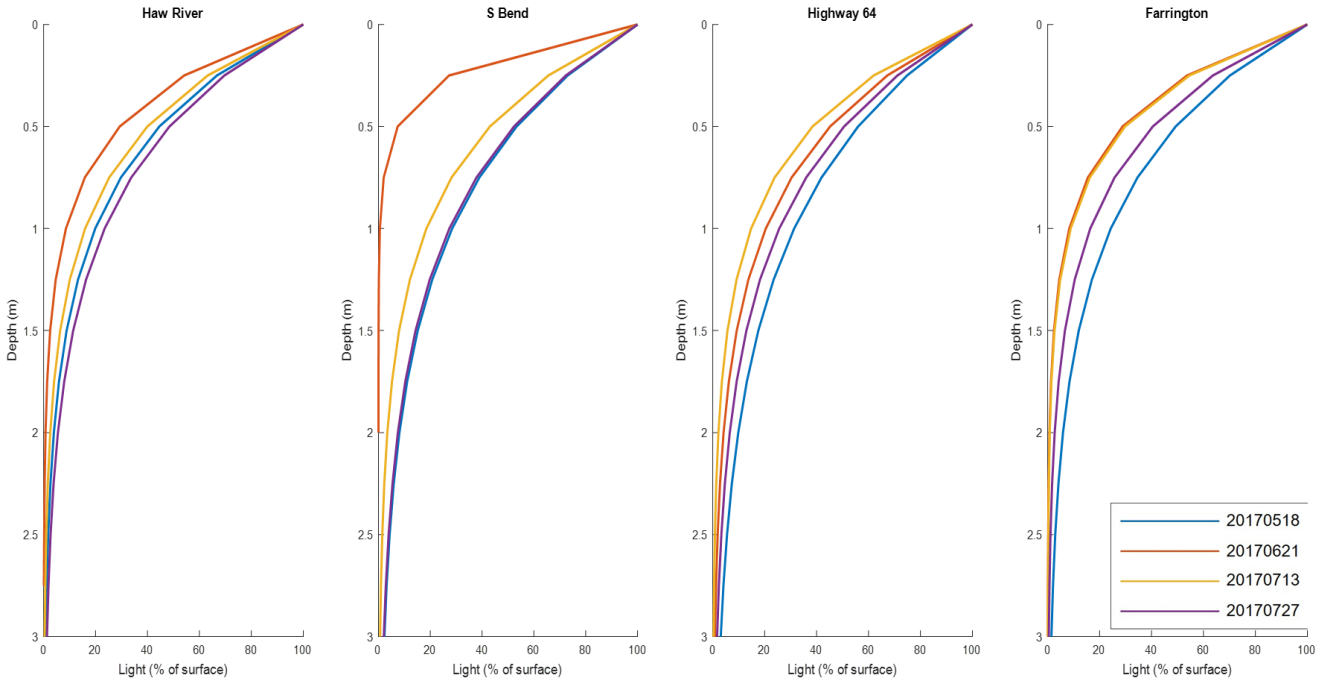

Figure 17. Exponential extinction curves fit to light profiles measured at the four mooring sites during trips to clean the moored sensors on 5/18, 6/21, 7/13 and 7/27, 2017

Table 2. Results from fitting exponential extinction curves to light profiles measured at the four mooring sites during trips to clean the moored sensors

Extinction coefficient (m^{-1})

Date	Haw River	S Bend	Hwy 64	Farrington Rd
2017-05-18	1.6	1.3	1.2	1.4
2017-06-21	2.5	5.2	1.6	2.5
2017-07-12	1.8	1.7	1.9	2.4
2017-07-27	1.5	1.3	1.4	1.8

Depth to the 1% light level (m)

Date	Haw River	S Bend	Hwy 64	Farrington Rd
2017-05-18	2.9	3.7	4.0	3.3
2017-06-21	1.9	0.9	2.9	1.9
2017-07-12	2.5	2.7	2.4	1.9
2017-07-27	3.2	3.6	3.4	2.6

the lake and reflective of normal flow warm weather conditions. In both cases the thermocline was more diffuse and somewhat deeper than on 5/18. Turbidity was lower than the other dates, except very near the bottom at the Haw River mooring site (possibly due to the instrument hitting and stirring up the bottom sediment) and over the lower 1-2 meters at the Farrington Rd causeways. In vivo fluorescence was highest near the bottom at the Hwy 64 and Farrington Rd causeways and otherwise was higher in the near surface waters. Dissolved oxygen approached saturation near the surface and zero below the thermocline. One percent light depths ranged from 1.9 to 3.6 m.

Algal / Nutrient Dynamics

No significant effects of dilution on phytoplankton growth were observed at any of the time points, Figure 18. In the absence of N additions, phytoplankton biomass declined within all dilution levels and at all time points. The decline in biomass was significantly less in the N addition treatments than in the control and growth was positive only in the N + P treatments. Later in the experiment, growth was positive only in the N plus P treatments with higher levels (30 and 50% dilution).

Based on the lack of a significant response to nutrient dilution, it appears that the vast majority of nutrients were contained within the phytoplankton rather than in bioavailable dissolved forms within the water. Nutrient concentrations measured at the beginning of the experiment confirmed that dissolved inorganic nitrogen (DIN) levels were low (~0.1 mg/L) and phosphate concentrations were below the limits of detection. The primary source of nutrients sustaining phytoplankton growth was likely remineralization which can at best maintain constant biomass levels over time, and cannot by

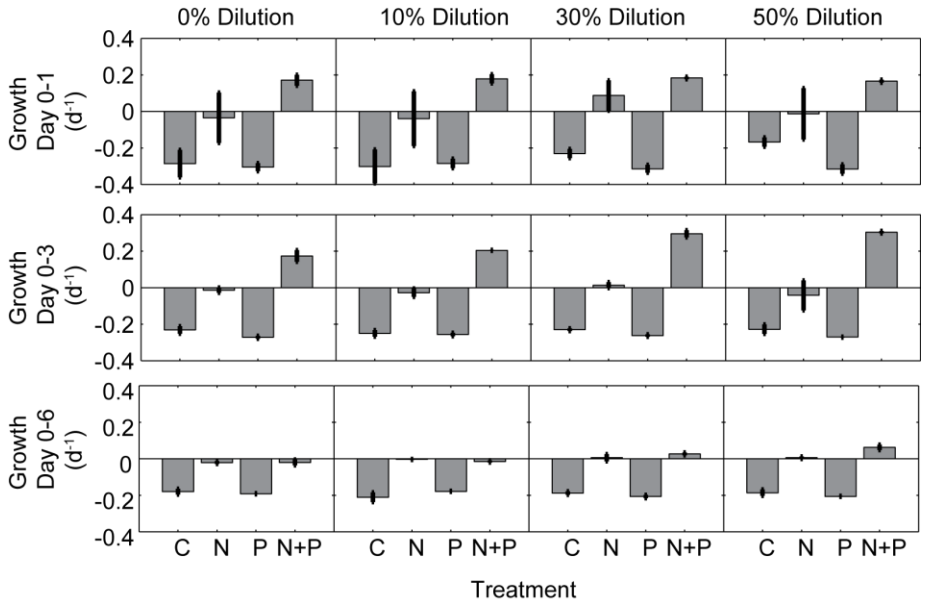

Figure 18. Phytoplankton growth responses to nutrient addition and dilution treatments within the April 2017 bioassay. C = control. N = N addition, P = P addition, N + P = both N and P addition. Bars represent the mean of triplicate values. Error bars are standard deviations.

definition result in increased biomass. Despite very low initial phosphate concentrations, it appeared that the supply of recycled N exerted a primary control on phytoplankton growth during the experiments. This is not uncommon due to the capacity of phytoplankton to strongly modulate their internal stores of P in response to decreases in availability, and due to the relatively faster rates of cycling of P compared to N. The lack of a positive growth response to N additions alone indicates that the phytoplankton growth requirements for N and P were very close to being balanced (i.e. N and P co-limitation). By adding N, the phytoplankton were forced to P limitation. This is consistent with the strong positive growth achieved in the N plus P treatments, and is common for the response of phytoplankton communities fueled by internal nutrient cycling. Over the full six day experiment, the occurrence of positive growth rates only in the higher dilution treatments was likely due to the smaller initial biomass and reduced competition for added nutrients in the more dilute treatments. Overall, the spring 2017 bioassay experiment indicated N and P co-limitation, a condition observed in numerous eutrophic freshwater lakes and reservoirs (Elser et al. 2007; Paerl et al., 2016).

Results from the photosynthesis vs irradiance analysis indicated that photosynthesis increased rapidly as PAR increased up to about 50 µmol photons/ m^2/s and began to saturate at higher values, Figure 19. The value of P_{max} divided by α, known as I_k, provides the irradiance at which photosynthesis is nearly saturated. In this case I_k = 45 µmol photons/ m^2/s which is a relatively low value for phytoplankton assemblages. The Jordan Lake Nutrient Response Model TetraTech (2002) assumed an I_k near 500 µmol photons/ m^2/s. It is instructive to examine how this significant difference in parameterization of the photosynthetic response to light affects estimates of daily production.

Figure 20 shows the modeled light field over the course of 24 April 2017. The depth at which light becomes limiting (i.e. below I_k) is shown for both measured values of I_k and currently assumed values of I_k. A much larger fraction of the water column has saturating irradiance conditions than was assumed in

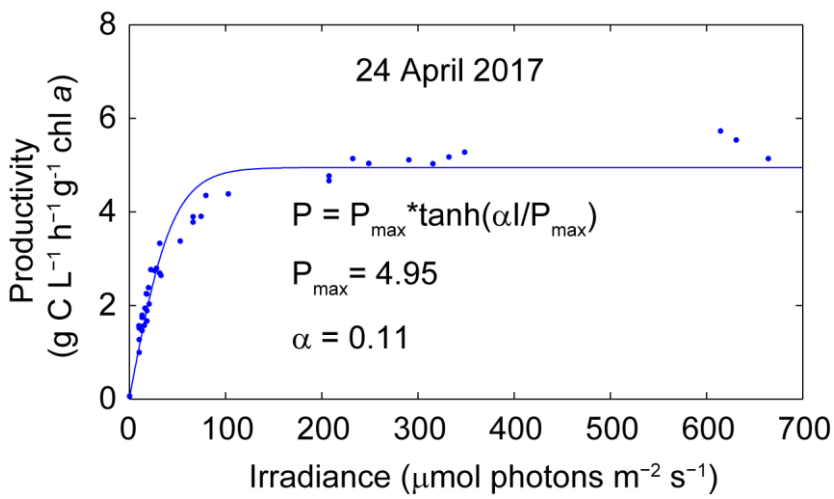

Figure 19. Productivity versus irradiance measured by a photosynthetron from Jordan Lake water collected on 24 April 2017 at NC DEQ station CPF086F.

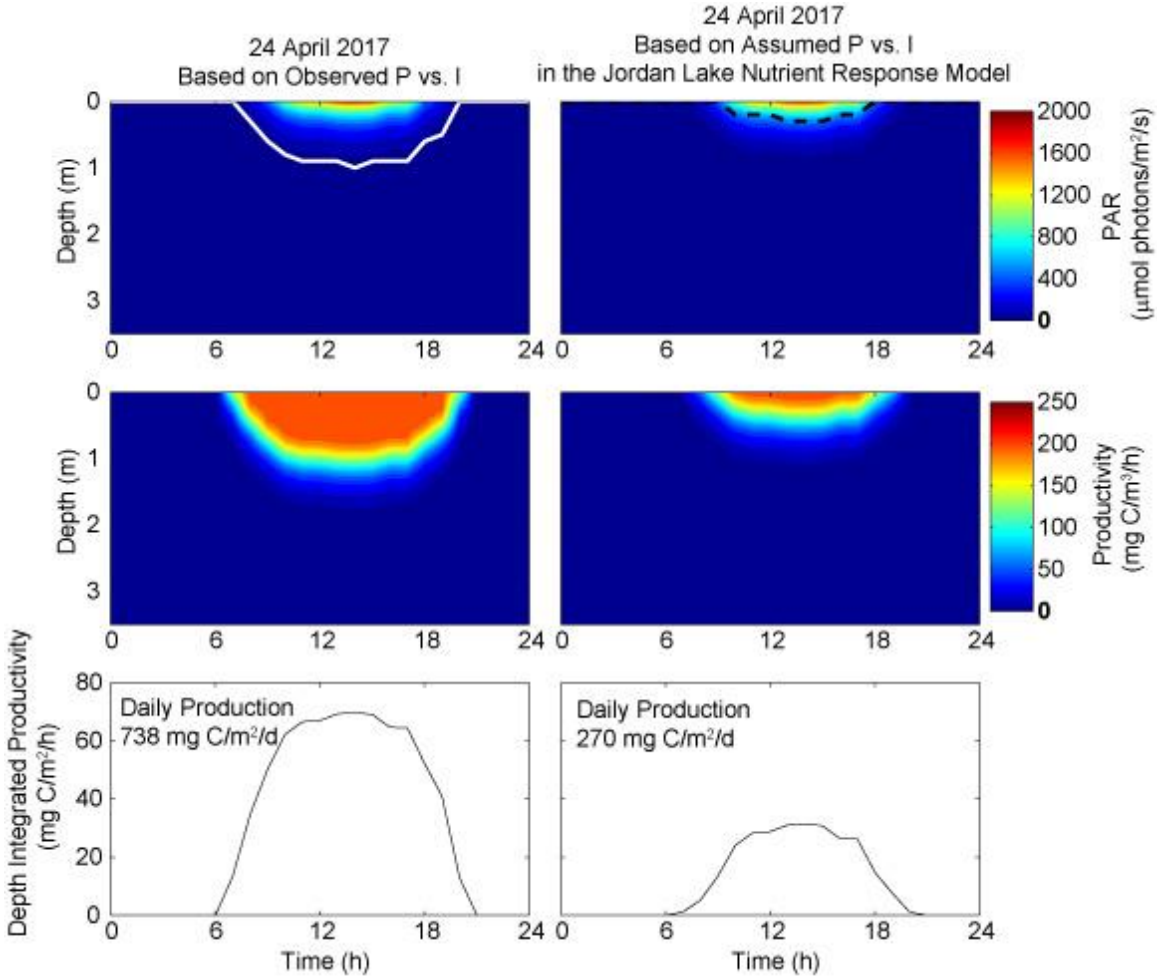

Figure 20. Comparison of phytoplankton primary productivity estimates based on measured photosynthesis/ irradiance relationship (left column) versus the photosynthesis/irradiance relationship assumed in the current nutrient response model for Jordan Lake. Modeled temporal and vertical variation in photosynthetically active radiation during the day of 24 April 2017 based on measured light attenuation and incident irradiance (top rows). White solid line (top left panel) and black dashed line (top right panel) represent the depth of measured versus assumed saturating light intensity, respectively. Modeled temporal and vertical variation in productivity based on modeled PAR and either the measured relationship between PAR and photosynthesis (left column middle row) or assumed relationship (right column middle row). Daily depth integrated primary production based on measured (left column) or assumed (right column) relationship between PAR and photosynthesis.

the Nutrient Response Model. Calculations of water column production strongly reflect this difference with daily production being nearly three times higher when based on measured versus assumed photosynthetic responses to the vertical gradients of light.

These results suggest that the springtime phytoplankton community is well adapted to the low light availability of the relatively turbid conditions of the upper New Hope Creek arm of the lake. The large discrepancy between modeled productivity based on measured light responses compared to assumed responses in the Nutrient Response Model suggests that these productivity vs. light response measurements can significantly improve the parameterizations in the model and therefore its ability to represent phytoplankton growth and productivity in Jordan Lake.

Ambient temperatures at the sampling station indicated a well-mixed water column on both days water was collected for the above described studies, although subtle decreases in dissolved oxygen and pH with depth were apparent (Figure 21). Turbidity was elevated near the bottom in April and *in vivo* fluorescence of chlorophyll (Chl *a* IVF) was higher near the surface and at mid-depths in both profiles. Nutrient profiles also demonstrated some vertical heterogeneity within the water column (Figure 22). Phosphate and silicate in particular showed distinct maxima at depth. The nearly uniform vertical temperature structure but vertically varying profiles of other parameters suggests that biological processes (e.g. photosynthesis, respiration, remineralization) were operating on time scales faster than the mixing. Elevated silica and phosphate at depth are consistent with a deep layer where rates of remineralization exceeded uptake by phytoplankton. These features indicate 1) deep water may be significant source of nutrients to the well-lit surface waters and 2) homogeneity of density structure is not sufficient to indicate homogeneity of chemical and biological properties of the water column. Chlorophyll *a* values derived from fluorometric measurements of acetone extracted pigments from discrete depth profile samples were more than twice as high as values produced by *in vivo* fluorescence (Figures 21 and 22). Based on laboratory derived Chl *a* values, levels present in Jordan Lake at this

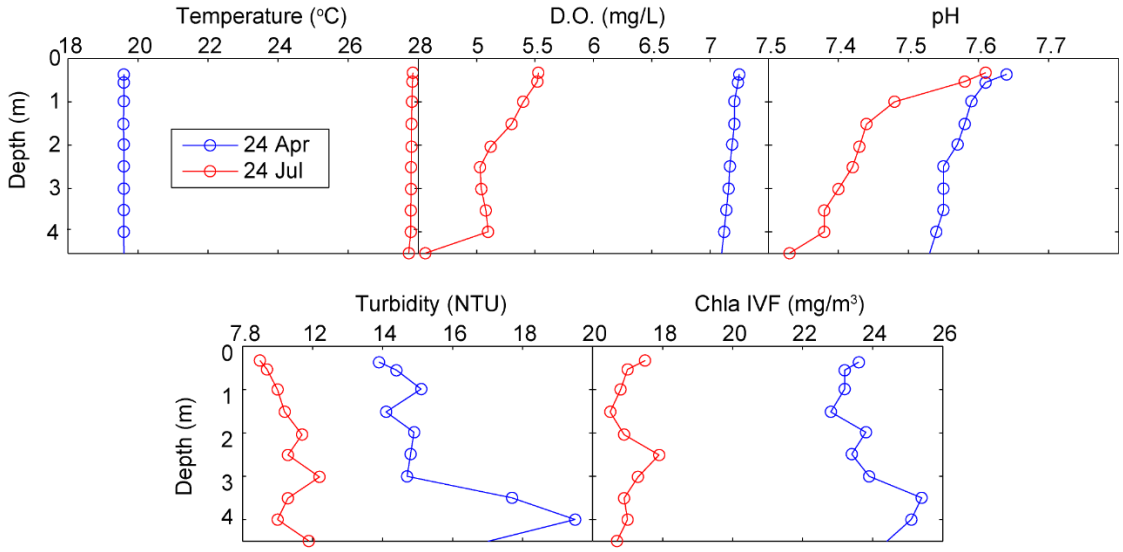

Figure 21. Depth profiles of hydrographic, chemical and biological properties of the water column at site CFR086F at the time of the water collection for nutrient limitation bioassays.

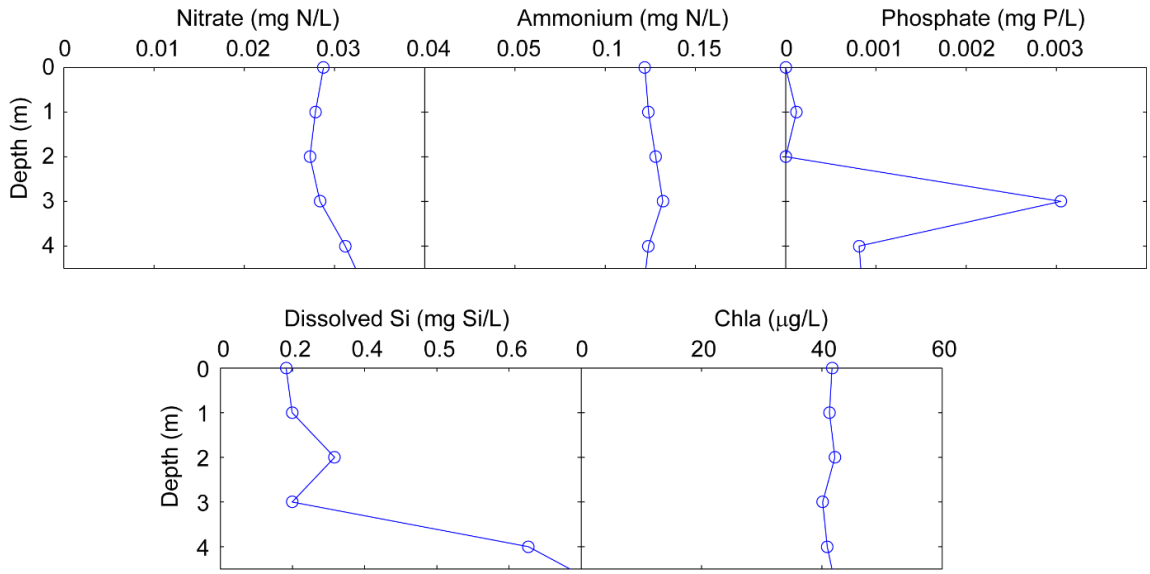

Figure 22. Depth profiles of dissolved nutrients and chlorophyll a at station CFR086F on 24 April 2017 during water collection for the April 2017 nutrient limitation bioassay study.

sample site exceeded the NC State "acceptable" chlorophyll a level of 40 µg/l on April 24, 2017. The disagreement between *in vivo* fluorescence measures of chlorophyll a and laboratory measurements of acetone extracted Chl *a* is common, and indicates that *in vivo* fluorescence should not by itself be used as a measure of Chl *a* without proper post-calibration.

Depth profiles of nutrients collected at the four mooring sites on 5/18 and 6/21 showed strong variation in nutrient concentrations between stations and with depth, Figure 23. In May, 2017 nitrate and phosphate concentrations were highest nearest the Haw River; nitrate decreased with increasing distance from the Haw River. Nitrate and ammonium consistently increased with depth. In June, higher nitrate and ammonium concentrations were observed in the narrows (s-bend), followed by the Haw River, and subsequently decreased upstream in the New Hope Creek arm. In the vertical dimension, nitrate, ammonium, and phosphate were homogenously distributed at all stations except at the HWY 64 station which contained bottom waters with elevated nitrate, phosphate and ammonium.

As noted previously, water and associated constituents from the second major discharge event appeared to have been transported from the Haw River arm into the lower portion of the New Hope Creek arm by the sampling date. In particular this led to higher turbidity, Figure 14, and higher nitrate and ammonium, Figure 23, at the S-bend than in the lower Haw River. It is not clear whether elevated near bottom values of nitrate, phosphate, and ammonium at the HWY 64 causeway reflect up lake transport of bottom water that may have originated in the Haw River arm or whether they reflect more local water column and benthic processes.

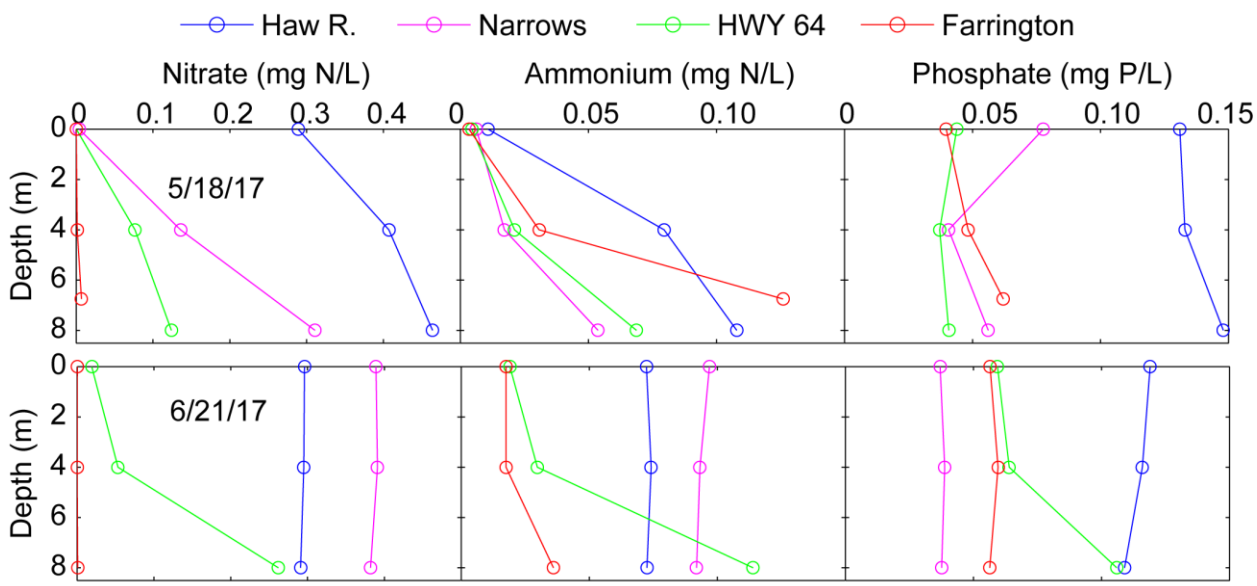

Figure 23. Depth profiles of dissolved nutrients measured at four stations that span the Haw River arm to upper New Hope arm of Jordan Lake.

Conclusions to Date and Management Implications

A multi-prong observational program has been initiated to help clarify the impacts of watershed input on key processes controlling water quality in Jordan Lake and to help inform management actions designed to improve water quality in the lake.

Over the 70 day period from May 17, 2017 through July 26, 2017 the AVP was deployed in the lower Haw River, this location was found to be characterized by two very different states. One state reflects normal flow, warm weather conditions, during which the water column is thermally stratified at a depth 2-3 m below surface which roughly corresponds to the extent of the euphotic zone (based on the 1 percent light level). Near surface waters were highly productive, with *in vivo* Chl *a* fluorescence of 15 – 25 µg / l. If the results showing *in vivo* fluorescence equal to roughly half of laboratory derived Chl *a* in the upper New Hope Creek arm can be generalized to the entire lake, Chl-a levels in the lower Haw River are frequently exceeding the state's Chl *a* standard of 40 µg / l. High photosynthetic productivity in the surface waters is supported by observations of supersaturated dissolved oxygen levels and elevated pH. Below the thermocline, respiration and mineralization rapidly deplete dissolved oxygen in the water column. Haw River water typically has the highest concentrations of nitrate, ammonium and phosphate of the four locations along the lake that were sampled. The second state reflects major runoff events, two of which occurred during the AVP deployment. During these events, the Haw River discharge increases by more than 10 times normal and is characterized by colder temperatures, very high turbidity and substantial amounts of floating debris. The river water initially enters the ambient water column near or below the thermocline, but quickly subsume the entire depth. The physical impacts last for roughly a week, although it is not known how long nutrient levels remain elevated in the water column.

Due to the relatively small volume of the Haw River arm of the lake, these waters are rapidly transported up into the southern end of the much larger New Hope Creek arm of the lake. At this point, it is unclear how far they may penetrate up the New Hope Creek arm and therefore to what extent they impact nutrient and light availability and ultimately phytoplankton growth in the larger lake. The effect of the extensive amount of debris accompanying major runoff events on the overall lake water quality is also unclear. The AVP has recently been moved to the end of the lake north of the Farrington Rd causeway and will provide a more complete picture of the response of that end of the lake.

Boat-based water quality profiles associated with water collection for the nutrient addition / dilution studies and cleaning of moored sensors at four locations in the lake indicate similar behavior to the normal flow, warm weather results found in the lower Haw River, with a thermally stratified water column, elevated biomass, dissolved oxygen and pH in the near surface and low oxygen near bottom. However, even in instances when the water column was not thermally stratified, vertically varying profiles of dissolved oxygen and nutrients were found suggesting that biological processes (e.g. photosynthesis, respiration, mineralization) were operating on time scales faster than vertical mixing. Elevated silica and phosphate at depth are consistent with a deep layer where rates of mineralization exceeded uptake by phytoplankton. Upward mixing of nutrient rich bottom waters may be a significant source of nutrients fueling phytoplankton growth.

At the time of the spring nutrient limitation bioassays, nitrogen was the most limiting (for algal growth) nutrient, with no significant response to phosphorus additions alone. Nitrogen plus phosphorus additions yielded the largest algal growth response, indicating that availability of *both* N and P play important roles in controlling algal production. A lack of response to dilution treatments indicated that the major source of nitrogen and phosphorus was through recycling of the N and P within the phytoplankton community. This finding was corroborated by nutrient measurements that showed small quantities of bioavailable dissolved nitrogen and phosphorous forms at the beginning of the experiment. These results support the nutrient addition bioassay results, pointing to N being the most limiting nutrient at the time of the experiment. However, the fact that N+P yielded highest growth responses point to the lake being close to “co-limited” by these nutrients (also see Paerl et al., 2016). Results from photosynthesis versus irradiance studies showed that the phytoplankton community of Jordan Lake is much more highly adapted to low irradiance conditions than assumed in previous modeling studies of the lake. Therefore these studies may have overestimated the light saturation level by nearly an order of magnitude with potentially significant consequences for model outputs of phytoplankton growth.

Proposed management actions in Jordan Lake have been based on water quality improvements predicted by the Jordan Lake Nutrient Response Model (TetraTech 2002) to occur in response to nutrient input reductions. The understanding gained from the current study will be most helpful for framing future management actions and for improving the predictive skill of the existing or any subsequent model of the system.

Important management implications of our work thus far include:

- the results from the spring bioassay indicate that phytoplankton in the upper New Hope Creek arm of the lake are likely co-limited by N and P. This suggests that efforts to reduce phytoplankton biomass will need to address both N and P. Summer and fall bioassays will determine whether this holds true for the entire phytoplankton growth period.

- the Jordan Lake Nutrient Response Model (TetraTech 2002) assumed that light limitation is a significantly greater impediment to nutrient utilization and biomass formation than found to be the case in the water collected from the upper New Hope Creek arm during April 2017. Rather, phytoplankton were much better adapted to growing in low light than represented in the model. Similar evaluations throughout the year and at other locations in the lake could greatly improve this aspect of the model and thereby enable more robust predictions of questions such as how fast can phytoplankton respond to pulses of nutrients from the tributaries given that such pulses are also associated with high loads of suspended particulates and color;

- considerable uncertainty remains regarding the source of nutrients fueling phytoplankton growth and productivity in various sections of the lake. Understanding the relative roles of horizontal and vertical transport, remineralization in the water column, sediment – water column exchange, is critical for making effective management decisions. Observations to date indicate elevated concentrations of nutrients (ammonium and phosphate) at depth suggesting nutrient inputs from the sediments may be significant. Because sediment nutrient fluxes can take years to decades to reach equilibrium with changes in external loading to reservoirs, a greater understanding of sediment fluxes will provide a clearer picture of the types of water quality improvements that should be expected under given load reduction scenarios. Additionally, depending on the distance Haw River nutrients can be transported upstream into the New Hope Creek arm, water quality management of the New Hope Creek arm will need to consider nutrient loads coming from the much larger Haw River watershed as well as the Upper and Lower New Hope Creek watersheds;

- predicting phytoplankton growth and productivity throughout a waterbody like Jordan Lake requires representing a large number of physical, chemical and biological processes including: nutrient inputs, transport, mixing, vertical stratification, sediment water column exchange, light penetration, biological uptake, growth and regeneration, etc. While relationships have been developed for many of these processes either from first principals or laboratory analyses, there is often very little *in situ* data for model calibration / validation in such systems. The data being collected by this program will provide a unique opportunity to improve the Nutrient Response Model and make it a more robust tool for use in future management decisions; and

- major disrupters in the Haw River arm of the lake appear to be large episodic discharge events. Understanding the significance of these events in the overall water quality of the lake is essential for making effective management decisions.

References cited:

Elser, J. J., M. E. S. Bracken, E. E. Cleland, D. S. Gruner, W. S. Harpole, H. Hillebrand, J. T. Bgai, E. W. Seabloom, J. B. Shurin, and J. E. Smith. 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecol Lett 10**:** 1124-1134.

Paerl, H. W., J.T. Scott, M.J. McCarthy, S.E. Newell, W.S. Gardner, K.E. Havens, D.K. Hoffman, S.W. Wilhelm and W.A. Wurtsbaugh. 2016. It takes two to tango: When and where dual nutrient (N & P) reductions are needed to protect lakes and downstream ecosystems. Environmental Science & Technology 50: 10805−10813.

Tetra Tech, 2014, Lake B. Everett Jordan Watershed Model Report

Tetra Tech, 2002, Jordan Lake Nutrient Response Model (final), https://ncdenr.s3.amazonaws.com/s3fs-public/Water%20Quality/Planning/TMDL/FINAL%20TMDLS/Cape%20Fear/Jordan%20Related/JordanLakeNRMFinal.pdf