Land use and stream dynamics - Jordan Lake Nutrient Study

Annual Report 2017

(Riveros-Iregui and Delesantro)

1. Introduction:

During Year 1, the watershed group of the Jordan Lake Nutrient Study project consisted of Dr. Larry Band (former Director of the IE), Dr. Jon Duncan (former research assistant professor at the IE), Dr. Diego Riveros-Iregui (assistant professor, Department of Geography), Dr. Javier Arce-Nazario (associate professor, Department of Geography), and 1st-year Ph.D. student Joseph Delesantro (Curriculum in Environment and Ecology). Because it has been shown that nutrient loading to headwater streams strongly mediates water quality downstream (Alexander et al., 2007), our group focused specifically on characterizing the spatial and temporal contributions of different land uses in headwater streams to nutrient loading in the Jordan Lake watershed. Thus, our objectives and tasks described in Sections 3 and 4 were intended to evaluate the range of hydrologic and water quality conditions that currently predominate upstream of Jordan Lake. We sought to capitalize on existing data records collected by various groups (including the Department of Environmental Quality and Duke University) and which have been made available to us, to go beyond the life of the current project and gain a more holistic understanding of water quality dynamics in the area.

2. Background and Context

The Jordan Lake watershed includes two major areas: the New Hope Arm which drains portions of the Research Triangle, and the Haw River, draining the majority of the watershed area, and including the urban areas of Burlington, Greensboro and a portion of Winston Salem. The Jordan Lake Rules were devised to achieve specific reductions in nitrogen, phosphorus and sediment loading from these areas (Jordan Rules, http://portal.ncdenr.org/web/jordanlake/read-the-rules). While the Haw River provides the bulk of nutrient and sediment loading due to its large drainage area, it drains into the lower basin of the reservoir, which does not contain water intakes. The New Hope Arm has both a larger percentage urban drainage area, and also drains into the shallower, upper portions of the reservoir where water intakes are located. Under some conditions, recirculation of the loading into the New Hope arm can occur, but the bulk is supplied from the surrounding drainage areas, and there is a larger percent reduction in loading from the contributing watersheds in Chatham, Orange, Durham and Wake Counties.

While the Jordan Lake Rules mandate reductions in annual load, methods of achieving loading targets are not specified and instead must be drawn from an approved list of practices. The efficiency of gaining load reductions can be very variable, and different methods are more effective for different nutrient sources, seasons, flow conditions and watershed position. In stream reduction methods generally are not effective at high flows, and would require mitigation at source locations. Therefore, timing and magnitude of nutrient delivery can vary substantially between adjacent land uses and urban/rural areas. If the bulk of nutrient and sediment loading occurs during high or low flow conditions, different stormwater control methods (SCM) selection and implementation would be required.

While large scale (subbasin) estimates of current and baseline loading are available, implementation of SCM will be planned and carried out for much smaller catchments, for which measurements are much more sparse. Thus, our measurements and modeling are focused on **small**, **representative catchments** distributed within the Jordan Lake watershed to quantify timing and magnitude of nutrient and sediment loading. We seek to inform watershed managers of the most effective SCM strategies for achieving target reductions, given limited resources.

3. Objectives and Guiding Questions:

A. Where and when within urban watersheds are nutrients (N, P) coming from and under what flow conditions?
B. How do hydrology, land-use, and sanitary infrastructure control nutrient loading?
C. How can we translate this knowledge to optimize nutrient management for urban watersheds and reservoirs in urbanizing watersheds?

4. Tasks (Specific to Year 1):

A. Cataloguing and reviewing existing water quality data sets collected throughout the Jordan Lake watershed to identify discernible spatial patterns of water quality.
B. Designing of a sampling network and strategy that will allow for spatial and temporal characterization of the major sources of nutrients and sediments to Jordan Lake in relation to land use, focusing in filling data gaps.
C. Purchasing, calibration, and deployment of field and analytical equipment.

5. Review of Existing Water Quality Data

Existing discharge data and water quality samples were collected by various entities over time, often in different locations and for different periods of time (see **Figure 1**). While this information is useful for background and context, the spatial and temporal resolution of the available data is insufficient to determine ***where*** and ***when*** nonpoint source pollution is delivered to the stream network, which is requirement for watershed management decisions. To address these challenges, we took advantage of two existing models: 1) the Jordan Lake model developed by TetraTech (TetraTech Inc, RTP, NC) and 2) a USGS model, SPAtially Referenced Regressions On Watershed attributes (SPARROW; Preston et al., 2011). The Jordan Lake model uses subbasins which are fairly large and not all that different from those with existing data. In fact, one of the determinants of the model subbasins was having existing data on which to calibrate the model. The SPARROW model has been developed at a finer spatial resolution (using catchments of the National Hydrography Dataset Plus [NHD+], produced by the Environmental Protection Agency [EPA]) and allows for separation of nutrient sources from urbanization, fertilizer application, etc., with the limitation that it is only available at an annual temporal resolution. We compared SPARROW and Jordan Lake model resolutions by upscaling from the small catchments in SPARROW to the Jordan Lake model subbasins, with the goal of estimating load of total nitrogen (**Figure 2**) and total phosphorous (**Figure 3**).

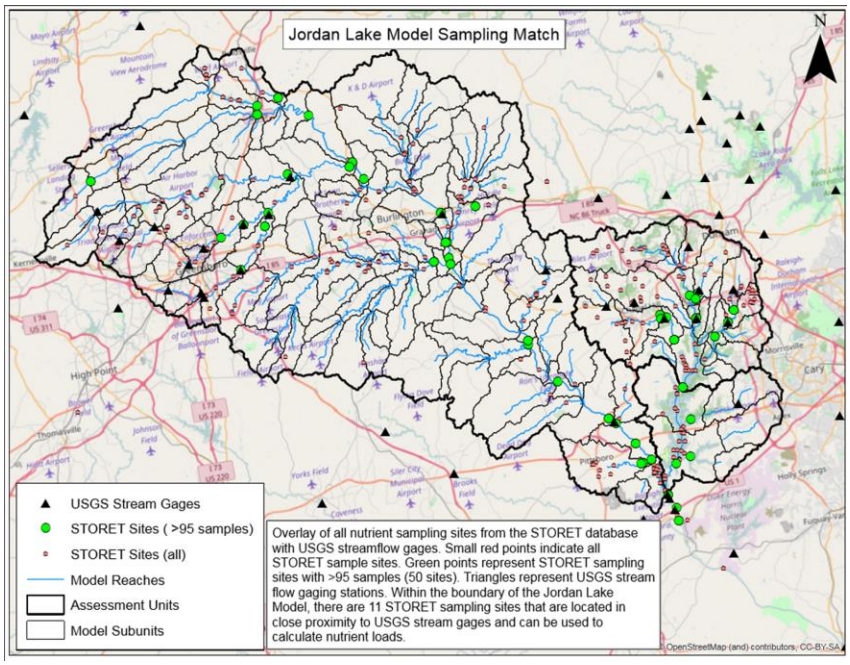

Figure 1. Map of storet and National Water Information System (NWIS) sites with ample water quality data

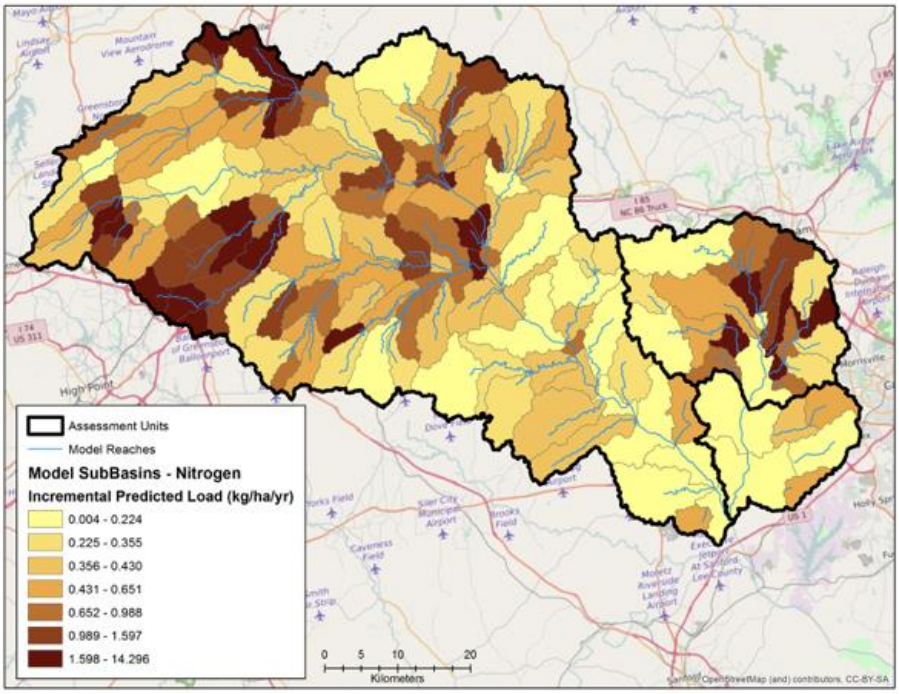

Figure 2. USGS SPARROW Model output of incremental predicted load of total nitrogen at the resolution of Jordan Lake Model Subbasins.

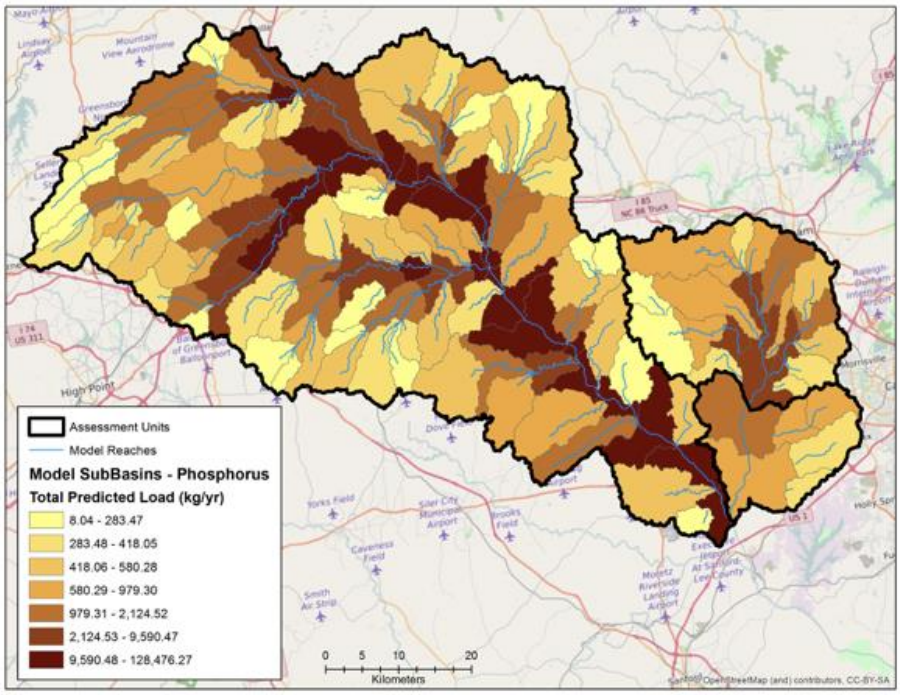

Figure 3. USGS SPARROW Model output of incremental predicted load of total phosphorus at the resolution of Jordan Lake Model Subbasins.

These model results (**Figures 2** and **3**) are useful because they highlight the spatial variability of nutrient loading in different subbasins, but they remain too coarse to be applicable for watershed management or to develop cost-effective guiding plans. It is therefore crucial to establish a finer scale of observation, both spatially and temporally, to determine ***when*** and ***where*** nutrients are delivered to the stream network. While we have made use of existing empirical data and modeling results, our primary contribution is to collect new data at high temporal frequency and fine spatial resolutions to better identify the ***timing*** and ***magnitude*** of nutrient transport to the stream network. An ongoing and related project from Duke University (Dr. Emily Bernhardt, Principal Investigator) has focused on small land-use specific watersheds using state-of-the-art submersible sensors. Their study has revealed the importance of finer scale data, because it can be readily translated into information useful for stormwater managers.

Analysis of the existing data from these small land-use specific watersheds shows that the hydrology of watersheds is greatly altered along gradients of development intensity and that this causes shifts in nutrient loading patterns (Unpublished data, Delesantro, Blaszczak & Bernhardt, Duke University). Past and present flow conditions, time of year, impervious surface cover (ISC) and geology explain a significant amount of the variation in baseflow nitrate concentration among 10 sites along a gradient in ISC (GLM: $R^2 = 0.61$, $p<0.0001$). As development intensity increases, more surface runoff is generated resulting in concentration of event flows and reduced baseflow (or low water flow). In forested areas, or areas of low intensity development where subsurface pathways maintain baseflow, nitrate loading is strongly positively correlated to discharge during the wet season (**Figure 4**, left panel). This suggests that groundwater flowpaths intersect with nutrient sources and contribute to loading. Nitrate concentrations increase with winter baseflow suggesting that either nitrate concentration increases with height in the groundwater table, or that there are multiple groundwater flow paths with different nitrate

concentrations and variable contribution based on baseflow. During dry summer months, nutrient loading in these low development watersheds is best explained not by hydrology, but rather by time since the beginning of the growing season. This suggests that biotic uptake is an important regulating factor in summer nutrient loading.

The Duke University data for highly developed sites show very different trends in baseflow nutrient loading with no seasonality or impact of instantaneous flow. Baseflow in highly developed sites is much lower (3 to 4 times) than in low intensity developed areas. As a result, we would expect reduced transport of subsurface nutrient sources relative to low intensity developed sites. However, nitrate concentrations at baseflow increase with greater development intensity so some other flow path must supply nutrients. Antecedent flow conditions (mean flow over the past 15 days) predicts nutrient loading during baseflow at highly developed sites better than instantaneous discharge (**Figure 4**, right panel). This might suggest that during wet periods streams and subsurface pathways are loaded with nutrients from the surface that are then transported by baseflow.

While this preliminary analysis based on existing area in the region allows for identification of important controls of nutrient loading, the existing data only cover baseflow conditions and do not allow for quantification of nitrate loading during storms. Studies from analogous urban areas in Baltimore show that stormflow can account for the majority of total nutrient loading (Shields et. al., 2008), further supporting our rationale for collection of high temporal resolution data in the Jordan Lake watershed.

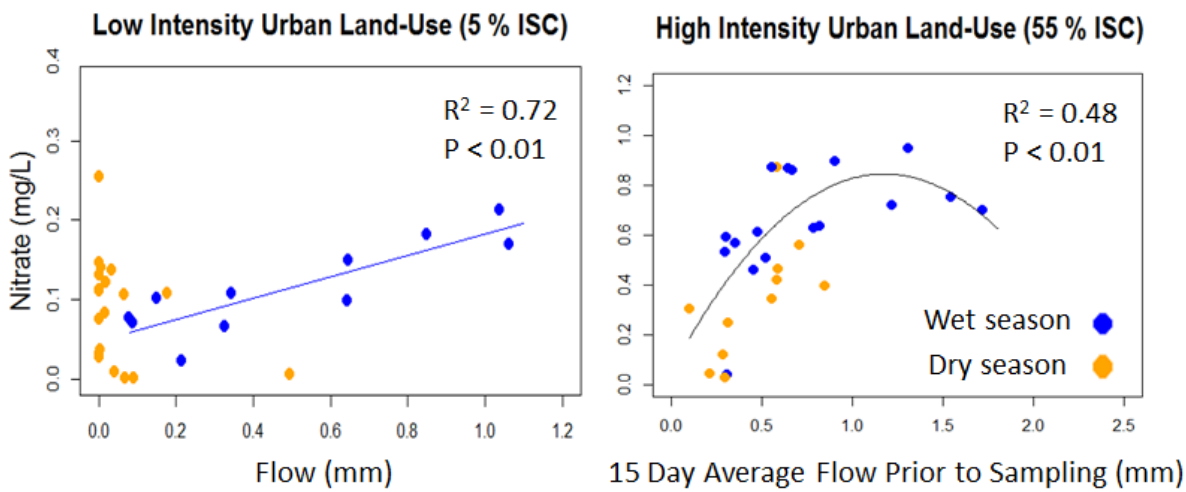

Figure 4. Existing water quality from single use catchments illustrating the change in drivers of nitrate loading at opposite ends of a gradient in impervious surface cover (Unpublished, Delesantro, Blaszczak, Bernhardt, Duke University).

6. <u>Jordan Lake Watershed Geographic Data</u>

Land-use, land-cover and the infrastructure throughout the Jordan Lake watershed affect hydrology and sources and transport of nutrients. During Year 1, we obtained, catalogued, and reviewed road, stream, water feature, sanitary sewer and stormwater sewer mapping for the entire study area. We also obtained limited septic mapping and septic permitting records. We used these data to select sites for further sampling (**Figures 5** and **6**) and contextualize local sites within the entire watershed. Thus, one of our main tasks during Year 1 was to systematically

select sites that are characteristic and representative of the full gradient of land use that exist within the Jordan Lake watershed. Having achieved this task, we are now confident that we have developed a quantitative, geo-referenced basis for inter-catchment comparison during Years 2 and 3 and extrapolation to the larger watershed. Finally, in addition to aiding our current data collection and analysis, our geographic analysis will allow for the examination of additional, potential drivers of nutrient loading.

7. Sampling Design

The sampling plan was designed to identify control points for nutrient management. This requires a combination of high temporal resolution data with low spatial resolution (i.e., continuous sampling at a few sites) combined with coarse temporal resolution data with high spatial resolution (i.e., discrete sampling across multiple sites). Sampling is focused along gradients in both development intensity and sanitary infrastructure. Three levels of data collection will enhance our understanding of the factors controlling nutrient loading over a large spatial area. High intensity sampling, consisting of 4-6 endpoint sites, employs in-situ sensors to measure several parameters at 5 and 15 min intervals (**Table 1**). Medium intensity sampling consists of 11 sites (including those high intensity sampling sites) that fill in the gradient between high intensity endpoint sites. This sampling also employs in-situ sensors for high temporal resolution data; however, it has limited parameters in comparison to the high intensity sites. Finally, low intensity sampling will consist of periodic synoptic water quality sampling over a selection of 14 additional sites (25 total) spanning the Jordan Lake Watershed.

The high intensity sampling will highlight specific differences in nutrient loading between high and low density developed watersheds and watersheds on sanitary sewer vs septic systems. The high temporal resolution will allow for examination of nutrient loading changes throughout storm events. By filling in the space along the study's gradients, the medium intensity sampling will allow for statistical tests and evaluation of patterns in flow, conductance, and seasonal nutrient loading. The high and medium intensity sampling data will inform statistical and mechanistic models of nutrient loading based on environmental parameters, infrastructure and development intensity. The low intensity data collection will be used to evaluate model performance over the large spatial scale of the Jordan Lake watershed.

All observations are being collected regularly and a database has been built to store all data with redundancies and versioning. We are currently in the process of automating a large portion of the data cleaning and quality control. This will facilitate sharing of data available with the Jordan Lake Nutrient Management research group.

Table 1: Parameters and temporal interval for each sampling intensity. Grab sample analysis consists of anions, cations, ORP, NH3, TN and TOC.

Parameters	High Intensity Sampling	Medium Intensity Sampling	Low Intensity Sampling
Water Level	5 min	5 min	Monthly
Flow	5 min	5 min (where possible)	Monthly
Specific Conductance	5 min	5 min	Monthly
Temperature	5 min	5 min	Monthly
Nitrate	5 - 15 min		Monthly
Dissolved Organic Carbon	5 - 15 min		Monthly

Turbidity	5 - 15 min		
Grab Sample	bi-weekly	bi-weekly	Monthly

8. Site Location and Instrumented Sites

High and medium intensity sampling sites are depicted in **Figures 5** and **6**. These sites are located in the Upper New Hope arm of the Jordan Lake watershed. The rapid urban growth in the area and long residence time of the New Hope arm of the lake cause the area to have a large contribution to lake nutrient loading and eutrophication. Current Jordan Rules indicate that the New Hope arm area will require the most severe cutbacks to meet nutrient management goals (Jordan Water Supply Nutrient Strategy Rules, Section 15A NCAC 02B .0262). Focusing initially in this area also allows us to employ resource and time intensive sampling techniques due to its proximity to UNC. These sampling techniques focus on the underlying hydrology of nutrient loading and solute transport. Given the region's shared climate, similar soils and geology, these findings will be applicable to the entire Jordan Lake watershed. We improve the approach of many previous studies by combining spatially distributed, high temporal resolution measurements of water quality and hydrologic dynamics to evaluate the mechanisms controlling nutrient loading in the Jordan Lake watershed.

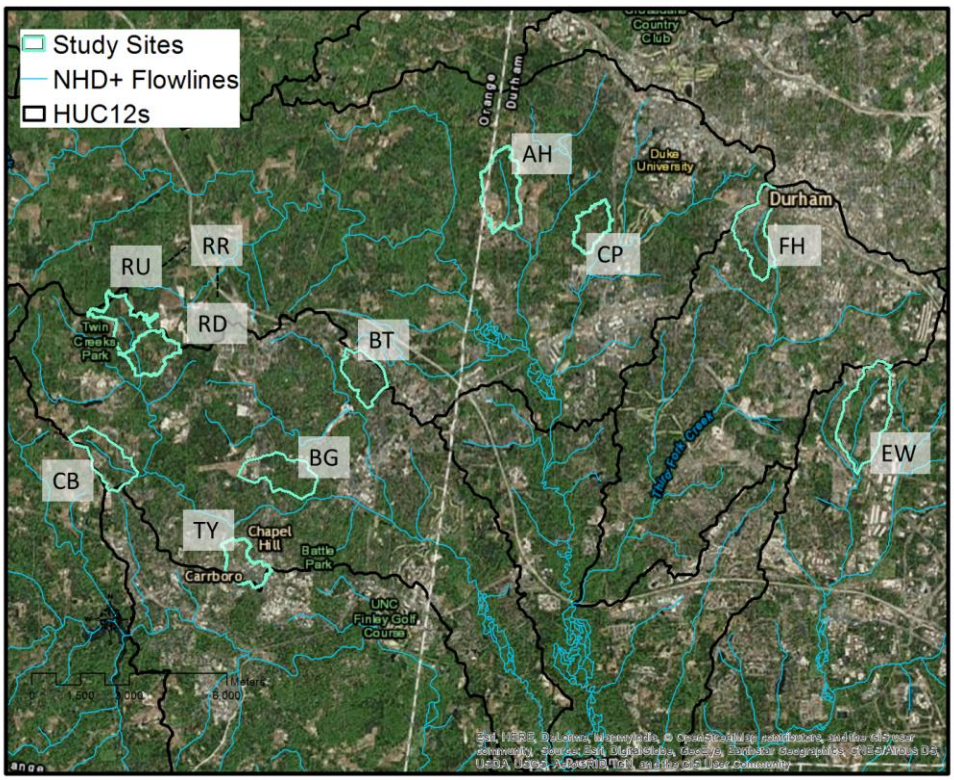

Figure 5. Site location and instrumented watersheds for this study. See **Table 2** for catchment characteristics.

Selected sites cover the range in urban development and sanitary infrastructure. Low density residential watersheds with similar land-cover and land-use metrics, but different sanitary

infrastructure are selected to investigate the effects of sanitary sewers systems and septic systems on urban nutrient loading. Sites along the gradient in development intensity allow us to investigate the effects of hydrologic connectivity, due to impervious surfaces and stormwater infrastructure, on hydrologic pathways and nutrient loading.

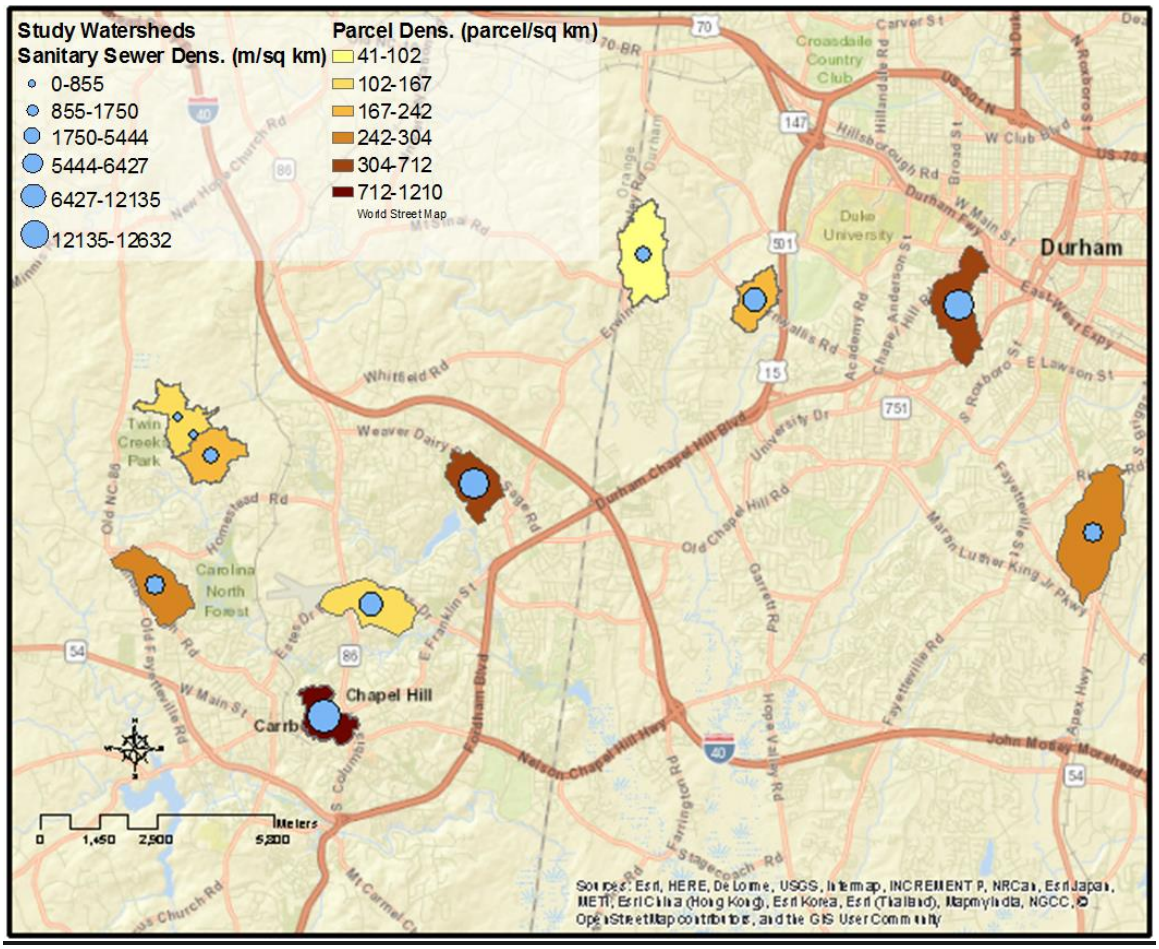

Figure 6. Sanitary sewer density (blue circles) and parcel density (shades) of instrumented watersheds in this study. See **Table 2** for site characteristics and **Figure 5** for site ID.

9. Instrumentation

The physical characteristics and land use attributes of the watersheds selected for this study are summarized in **Table 2** (each individual watershed can be observed in **Figures 5** and **6**). Watersheds range in area from 0.74 to 2.31 km^2, road density (~4 to ~15 km/km^2), parcel density (41 to 1209 parcels/km^2), and density of sanitary sewer (0 to ~13 km/km^2). The continuous sampling conducted at each of these watersheds (summarized in **Table 3**) will be compared with discrete sampling (i.e., synoptic) across other watersheds in the Jordan Lake watershed with similar distributions of physical characteristics and land use attributes.

Table 2: Key preliminary statistics for study watersheds.

Watershed Name	ID	Area (sq km)	Road Density (m/ sq km)	Parcel Density (parcel/sq km)	Sanitary Sewer Density (m/sq km)
Cobblestone	CB	1.21	8403.42	304.48	4841.87
Roger's Road	RR	1.94	5146.45	131.59	855.36
Roger's Road Up	RU	0.99	4543.28	41.37	0.00
Roger's Road Down	RD	0.95	5777.89	242.94	1750.81
Tanyard Branch	TY	0.85	15217.82	1209.90	12631.56
Booker Trib	BT	0.99	9557.36	310.53	7177.56
Burlage	BG	1.31	7870.13	167.23	5597.61
Arrowhead	AH	1.53	4110.97	102.34	1221.48
Emory Woods	EW	2.31	7400.80	273.50	5444.61
Forest Hills	FH	1.42	15157.22	712.63	12135.62
Colony Park	CP	0.74	8879.83	228.01	6427.27

Selected study watershed designation along urban/rural gradient is summarized in **Table 3**. In this table, we also summarized the status of data collection to date, which includes: a) existing data (prior to this study); b) current data being collected through this study (including instrument deployment date); and c) planned data collection to begin in Year 2. Frequency of data collection ranges from every 5 min to every hour.

Table 3: Watershed designation, existing data, current and planned data collection through this study, and instrument deployment date.

Watershed Name	ID	City	Urban Dev.	Sanitary System	Existing Data	Current Data Collection	Planned Data Collection	Deploy. Date
Cobblestone	CB	Chapel Hill	Med. Dens.	Mixed	SC, Stage, WQ	SC, Stage, WQ	SC, Stage, WQ	6/28/2017
Roger's Road	RR	Chapel Hill	Low Dens.	Septic		SC, Flow, WQ HR	SC, Flow, WQ HR	7/7/2017
Roger's Road Up	RU	Chapel Hill	Forested	NA		SC, Flow, WQ	SC, Flow, WQ	7/7/2017
Roger's Road Dn	RD	Chapel Hill	Med. Dens.	Septic		SC, Flow, WQ	SC, Flow, WQ	7/7/2017
Tanyard Branch	TY	Chapel Hill	High Dens.	Sewer	SC, WQ LR	SC, Stage, WQ	SC, Stage, WQ	7/17/2017
Booker Trib	BT	Chapel Hill	Med. Dens.	Sewer	SC, Flow, WQ		SC, Flow, WQ HR	
Burlage	BG	Chapel Hill	Low Dens.	Sewer	SC, WQ	SC, Stage, WQ	SC, Flow, WQ HR	6/28/2017
Little Creek	LC	Chapel Hill	Med. Dens.	Mixed	SC, WQ LR		SC, Flow, WQ HR	
Arrowhead	AH	Durham	Low Dens.	Septic		SC, Stage, WQ	SC, Flow, WQ	8/7/2017
Emory Woods	EW	Durham	Low Dens.	Sewer	SC, Flow, WQ	SC, Stage, WQ	SC, Flow, WQ	8/4/2017
Forest Hills	FH	Durham	High Dens.	Sewer	SC, WQ		SC, Flow, WQ HR	
Colony Park	CP	Durham	Low Dens.	Sewer			SC, Stage, WQ	

10. Preliminary Findings

Year 1 focused on site selection, landscape analysis, experimental design, instrument purchases, calibration, testing, and deployment. Field data collection began toward the end of Year 1 (**Table 3**). The newly deployed automated sensors will allow for data collection at time intervals ranging from every 5 min to every hour - day and night - for the next two years. This means that, based on the sampling design described in the previous sections, we are now in a position to build a highly detailed dataset of both the hydrologic and nutrient dynamics in headwater streams in the Jordan Lake Watershed. This high-temporal resolution information will be key for comparisons with lower-resolution information collected through this study across other areas of Jordan Lake watershed, and with information collected by other water quality groups prior to the beginning of this project. Currently, every deployed sensor is collecting anywhere from ~20 to ~300 measurements per day. The largest nutrient datasets in the region using traditional sampling methods have around 200 measurements spanning decades, the equivalent of 2 days of nitrate measurements at a single high intensity sampling station in this study. This project capitalizes on new technology, which will allow for examination of nutrient loading at temporal resolutions that were not possible before. Below we provide examples of the capabilities of the new sensors, and the type of datasets that this project is now rapidly building.

Figure 7 shows a comparison of three different streams in the Jordan River watershed, each with a different land use: (top panel) forested land cover, (middle panel) low development land cover, and (bottom panel) high development land cover. Of particular note in these preliminary results are:

1) The stream located in the forested land cover shows the lowest (~120 uS/cm) baseflow specific conductance (SC; green line) across the three sites. SC is a measure of dissolved ions in the water, and road salt, for example, contributes to the increase of SC in stream waters. (Other factors contributing to SC are the proportions of groundwater vs. rainfall in stream water, as groundwater that has been in contact with soils and rock tends to have higher SC than rainfall, which generally has a low SC - except in the case of acid rain). On the other hand, the stream located in the high development land cover shows the highest SC (~400 uS/cm). Furthermore, changes in specific conductance occur differently depending varies with changes in hydrologic conditions. Increases in specific conductance typically occur more slowly than decreases in specific conductance, which can be driven by dilution from new rainfall.

2) The response of water level (blue line) to precipitation varies for each land cover. While the high development stream shows ‘flashy’ (i.e., rapid) responses to precipitation, the response of the forested stream is more buffered. On the other hand, the effects of water demand by evapotranspiration are seen as diel fluctuations in water level, which appear more noticeable in the forested stream that in the other two streams, likely as a result of greater vegetation cover.

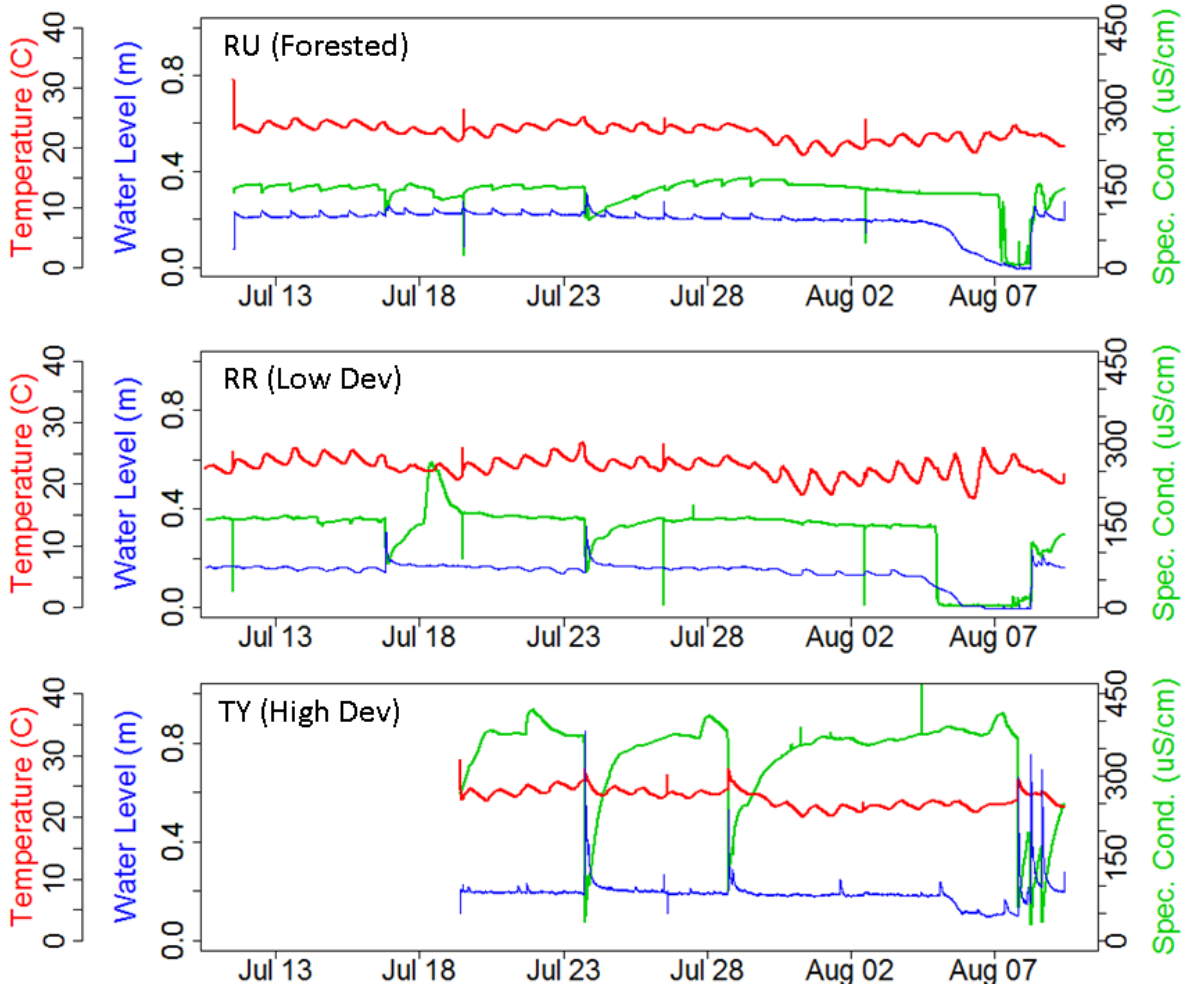

Figure 7. Comparison of medium intensity sampling instrumentation data across a gradient in development from forested (top) to low development (middle) to high development (bottom). These data demonstrate the role of urban development on mediating the dynamics and magnitude of several variables, including temperature (red), water level (blue), and specific conductance (green), across watersheds that have been developed to various degrees.

Figure 8 shows 5-min measurements of rainfall, water level, nitrate (NO_3^-), and turbidity at a low-density development watershed on septic systems. Of particular note in these preliminary results are:

1) In this low-density development watershed, the stream responds very rapidly and essentially synchronously to precipitation.
2) Equally, NO_3^- and turbidity respond synchronously to precipitation. However, prior to rainfall (i.e., during baseflow) NO_3^- and turbidity behave differently with NO_3^- exhibiting clear diel dynamics and a subtle decrease during the 5 days leading to the first rainfall event. These in-stream dynamics are important because they are indicative of biological activity that is consuming stream NO_3^-, thereby effectively removing and decreasing its concentration. This project seeks to characterize these biological dynamics across all

proposed stream and assess the natural capacity of the streams to regulate their own nutrient content prior to reaching Jordan Lake.

3) Nitrate concentrations are higher than similar urban headwater catchments on sanitary sewer. The average baseflow Nitrate concentration of 9 previously sampled watersheds in the Jordan and Neuse watersheds with similar ISC and road density was 0.19 mg/L (Unpublished, Delesantro, Blaszczak, Bernhardt) while the Roger's Road average at baseflow during the short period of record is 0.56 mg/L. While more data will be necessary to confirm this trend, it suggests that septic systems are large sources of nutrients in headwater catchments.

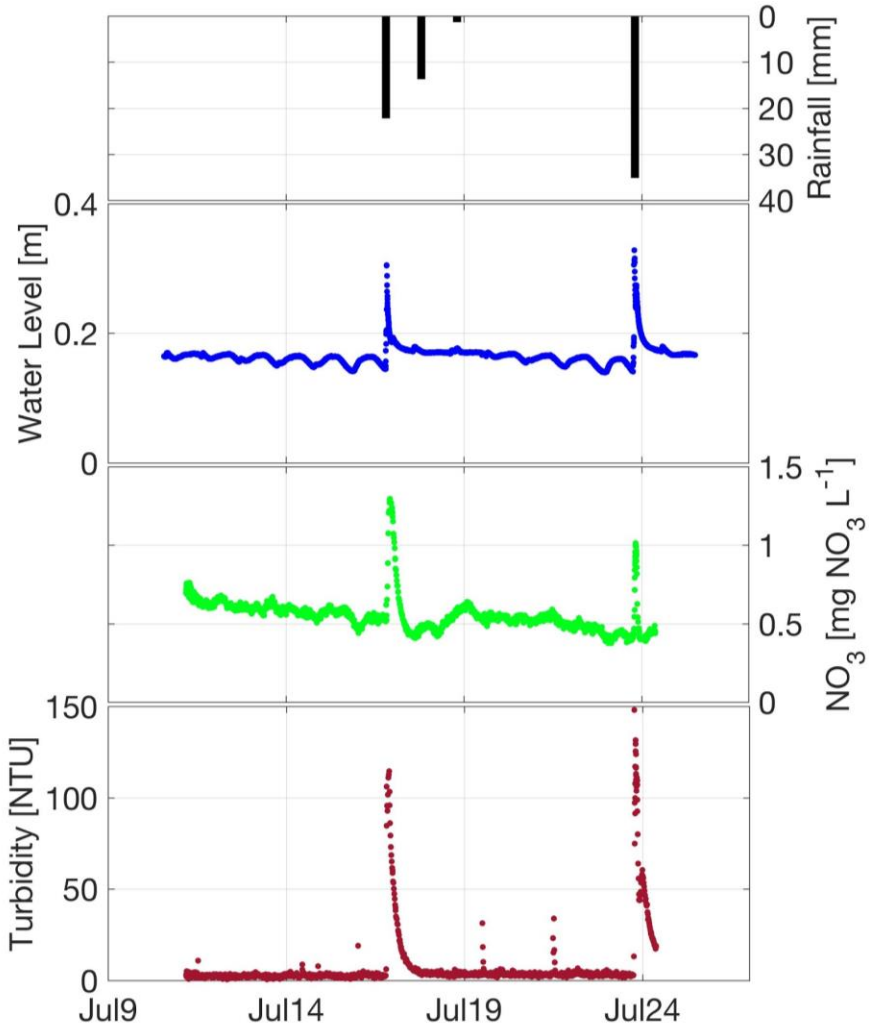

Figure 8. High intensity data collection for a watershed on septic systems with low density development. Nitrate exhibits rapid and large concentration increases in the stream during storm events with little to no dilution from rainfall.

Finally, **Figure 9** shows 15-min measurements of water level (m) and nitrate (mg/l) during 22 hours during a storm on July 16, 2017. The observed pattern, known as 'hysteresis', demonstrates that the relationship between water level and nitrate is non-linear as the two variables are out of phase with each other. Characterization of this non-linear behavior between hydrologic dynamics and nitrate loading is critical to accurately estimate nitrate loading during baseflow and stormflow conditions.

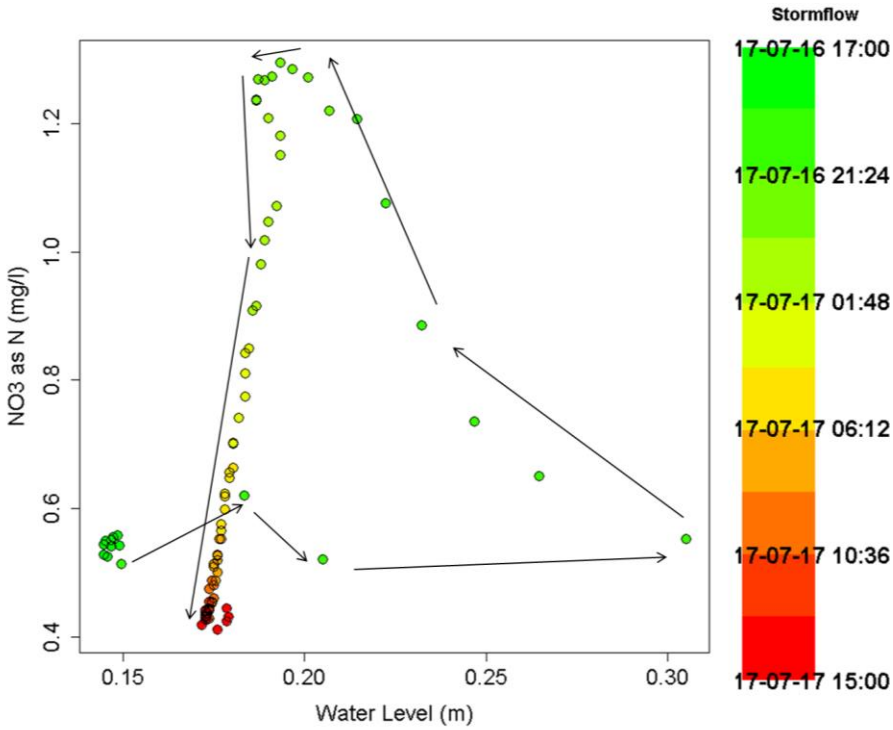

Figure 9. High temporal resolution measurements of water level (m) and nitrate (mg/l) during the July 16, 2017 storm (total rainfall 0.86 inches). Arrows indicate the progression of the measurements and colors indicate the date/time of day.

References:

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