Jordan Lake Nutrient Study

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1. Executive Summary:

Development is a significant and rapidly growing non-point source of nutrients to Jordan Lake Reservoir driving harmful algal blooms and eutrophication. The impairment of the Reservoir threatens the quality of drinking water and recreational value. In order for Jordan Lake Reservoir to continue to support growth and future development in the region, we need to reduce the impact of development throughout the watershed.

Development is highly variable across the Jordan Lake Watershed (JLW), spanning from rural to urban land cover, infrastructure, and development intensity. Across this range, nutrient sources vary greatly (e.g. septic systems, leaking and surcharging sewers, urban stormwater and atmospheric deposition), as does the hydrologic regime altered by impervious surface cover, vegetation and runoff connectivity (e.g. pipes, roads, ditches). Previous studies of nutrient loading have rarely utilized the high-resolution data needed to parse the effects of these variable developed landscapes, or sampled over sufficiently small catchments to characterize distinct development types. In-order to build a detailed understanding of nutrient loading in developed landscape and inform rule making for the management of nutrients in the Jordan Lake watershed we have outlined the following objectives:

A. Where and when within urban watersheds are nutrients coming from and under what flow conditions?
B. How do hydrology, climate, 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?

To address these objectives, we have combined high spatial resolution water chemistry (including major nutrients) sampling from 25 small watersheds with high temporal resolution, continuous monitoring water chemistry data from a subset of five watersheds. Sampling was designed to cover the range in development intensity and infrastructure within the Jordan Lake watershed, with a focus on low intensity watersheds that make up the majority of new and existing development. In addition to water chemistry sampling and instrumented continuous monitoring, we had a subset of samples from 12 watersheds analyzed for stable isotopes of nitrate, which provide evidence for the source of the nitrate. The continuous monitoring data also allows us to evaluate patterns in storm nutrient loading which allow us to infer the flow path and potential sources of nutrients. Our study identified the following relevant findings and we make several recommendations for rule making and management.

Relevant findings

- Wastewater is a significant contributor to baseflow nitrate loading across development intensity and both septic and sanitary sewer served watersheds.

- Stormwater is also an important source of nitrogen, constituting 20 – 48% of total loading and generally increasing with development intensity. The sources of stormwater N are a complex mix that includes fertilizer, atmospheric deposition and wastewater. This rapid high discharge loading constrains treatment options.
- There was a large range of septic watersheds loading with some watersheds exhibiting twice the dissolved nitrogen loading of comparable sewer severed watersheds. This variation was not explained with typical development metrics and additional analysis and research will be required to identify the drivers of septic served watershed loading.
- Per unit area loading of sanitary sewer served watersheds increased with development intensity; however, preliminary analysis suggests that per parcel, or per capita loading may be much larger for septic watersheds and stable across development intensity of sewer served watersheds.
- The sources, flow paths and timing of nutrient loading change with land-use and seasonal conditions.
- Forested watershed loading was significantly lower than that of developed landscapes.
- Extreme rainfall events such as hurricanes can contribute more than two months of nitrogen loading of normal (i.e., non-hurricane) periods based on minimum estimates.

2. Introduction:

Development is a significant and rapidly growing non-point source of nutrients to Jordan Lake Reservoir driving harmful algal blooms and eutrophication. The impairment of the Reservoir threatens the quality of drinking water and recreational value. In order for Jordan Lake Reservoir to continue to support growth and future development in the region, we need to reduce the impact of development throughout the watershed.

Many intentional and unintentional decisions create highly variable developed landscapes across watersheds that span from rural to urban and vary in land cover, infrastructure, and development intensity. Across this range, nutrient sources vary, as does the hydrologic regime altered by impervious surface cover, vegetation and hydrologic connectivity. Nutrient sources of non-point source pollution in developed landscapes include, atmospheric deposition, yard waste, lawn fertilizer, and wastewater among others. These nutrients become problematic when they come in contact with water and flow through the landscape into streams and rivers feeding Jordan Lake. Therefore the hydrology of developed landscape is potentially as important as the sources of nutrients. Developed landscapes generate significant stormflow from the direct runoff of rainfall from impervious surfaces and compacted soils. Road curbs and stormwater sewers connect the landscape and increase the speed of stormflow which reduces the opportunity for infiltration or nutrient removal. Nutrients in stormflow are often from surface sources such as lawn fertilizers, atmospheric deposition and yard waste. However, a portion of rainfall infiltrates and picks up additional nutrients from subsurface sources. This slower moving portion of stormflow is often referred to as event throughflow. The most important subsurface source of nutrients in urban landscapes is wastewater. Although we employ many techniques for treating and containing wastewater, these methods are known to fail occasionally or chronically leak at slow rates, releasing partially treated or untreated wastewater high in nitrogen (N) and phosphate (P). Wastewater can make its way into the groundwater which contributes significantly to streamflow during low-flow periods between storms known as baseflow, and recent research indicates can also contribute a substantial amount of storm event flow.

3. 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 stipulated in the Jordan Lake Rules.

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 typically not effective at high flows (unless substantial portions of flow can be stored in floodplains) 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. Identifying important sources of nutrients would allow focused reduction before loading occurs and reduce the need for difficult mitigation.

While large scale (sub-basin) 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. Likewise, specific sources of nutrients and their importance can't be isolated from large sub-basins which have mixed development and many sources. Thus, our measurements are focused on **small**, **representative catchments** distributed within the Jordan Lake watershed to quantify sources, timing and magnitude of nutrient loading. We seek to inform watershed management and SCM strategies for achieving target reductions, given limited resources.

4. Objectives and Guiding Questions:

A. Where and when within urban watersheds are nutrients coming from and under what flow conditions?
B. How do hydrology, climate, 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?

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 often insufficient to determine ***where, when*** and ***what*** nonpoint sources are loading pollution to the stream network, which is a 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 sub-basins which are fairly large and not all that different from those with existing data. In fact, one of the determinants of the model sub-basins 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 sub-basins, with the goal of estimating load of total nitrogen (**Figure 2**) and total phosphorous (**Figure 3**).

These existing model results (**Figures 2** and **3**) are useful because they highlight the spatial variability of nutrient loading in different sub-basins, but they remain too coarse to be applicable for watershed management or to develop cost-effective guiding plans or identify specific nutrient sources. It is therefore crucial to establish a finer scale of observation, both spatially and temporally, to determine ***when***, ***where*** and ***what*** 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.

6. Jordan Lake Watershed Geographic Characterization:

Land-use, land cover, infrastructure and geology was characterized across the Jordan Lake watershed. We obtained, catalogued, and reviewed road, stream, water feature, sanitary sewer, stormwater sewer, land cover, parcel and geologic mapping for the watershed. We estimated the position of septic systems as the centroid of parcels greater than 150 m from a sewer line and containing a building. We obtained limited septic data to validate these estimates for portions of Orange County. The National Hydrography Database NHD+ scale watersheds were used as the fundamental unit of landscape analysis. These watersheds are approximately 0.5 to 3 km^2. This small size provides the spatial resolution necessary to isolate important development features such as sanitary infrastructure or impervious surface cover (ISC). Numerous metrics of development, infrastructure and land-cover were calculated for each NHD+ watershed to allow us to characterize development in the whole Jordan Lake Watershed (Table 1).

Table 1: Key landscape metrics all developed Jordan Watershed NHD+ catchments.

Characterization	Description	Range	Median	Mean
Parcel Density	Parcels/km^2	80 - 1,497	190	250
Impervious Surface Cover	%, NLCD	0 - 78.4	8.8	13.5
Road Density	km/km^2	1.31 - 19.09	8.27	8.88
Sanitary Sewer Density	km/km^2	0 - 38.53	3.853	4.59
Septic Density	Units/km^2	0 - 333	16.2	33.5
Area	km^2	0.30 - 12.81	1.15	1.64
Forest Cover	%, NLCD	0 - 89	34	34

7. Methods:

Sampling was designed to cover a gradient from rural to urban development and optimize both spatial and temporal data collection. We collected two sets of water chemistry and flow data; a high spatial resolution, ***grab sampled*,** dataset comprised of discrete water quality samples at a total of 25 watersheds and a high temporal resolution, ***continuous monitoring***, dataset which utilizes deployed sensors to measure water chemistry and flow every 5 – 15 min at a subset of 5 watersheds. The grab sampled dataset provides data over a large range of developed land-use, infrastructure and geology. However, this discrete sampling can't cover the full range of flow conditions in developed environments due to rapid stormflow response to rainfall which is difficult to capture and often unsafe. The continuous monitoring allows us to capture the full range of environmental conditions and evaluate patterns in water chemistry and flow.

Site selection

Watersheds were selected for outflow sampling to span the range in development intensity, infrastructure and geologic basin with additional focus on low intensity residential development which is most common and also the largest component of new development. A total of 19 watersheds were selected in the Durham, Chapel Hill, Carrboro, and the Burlington area including Haw, Swepsonville, Graham, and Mebane. These sites are located in the Upper New Hope arm and Haw arm of the Jordan Lake watershed. A subset of five of these watersheds was selected for additional sampling in the form of continuous monitoring. Data from an additional 12 watersheds in the research Triangle region were pulled from existing data for analysis. Six of these watersheds were in the Raleigh Belt geologic basin which was found to have consistently higher loading than geologic basins in the Jordan Lake watershed and only the remaining six watersheds were included in analysis. Although some of these additional watersheds are outside the Jordan Lake watershed, they are representative of the development of the watershed (Blaszczak et. al. 2019).

Sites were initially selected from NHD+ watersheds based on geographic characterization metrics. All selected watersheds are headwater watersheds, meaning that streamflow originates within the study watershed and water chemistry is a reflection of the impacts within the watershed. Selected watersheds were re-delineated with QL2 Lidar Digital Elevation Models (DEM) and stormwater pipe maps were added to better generate watershed boundaries and flowpaths that account for storm sewer flow. Landscape metrics were re-calculated for the re-delineated watersheds. 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 **Figure 4**). By selecting small NHD+ scale watersheds we can select land-use specific watersheds to isolate important variables such as sanitary infrastructure or impervious surface cover (ISC).

Study watershed for continuous monitoring are forested (TH), rural on septic (RR), lower (BG), medium (BT), and higher development intensity (TY) on sanitary sewer. The TH watershed is nested within the RR watershed and the portion of RR that does not include TH is referred to as RRdev. Loading for RRdev is calculated by subtraction. The classification of these study watersheds is relative and because it was based on several factors such as ISC, parcel density, sanitary sewer density, septic density, and road density. These metrics for all sampled watersheds are reported in Table 2. Watersheds for continuous monitoring needed to be easily accessible and were limited to the Chapel Hill area in the Upper New Hope watershed.

Table 2: Key landscape metrics for study watersheds. Continuous monitored watersheds are highlighted in blue.

Site	Area (km^2)	ISC (%)	Forrest (%)	Road Dens. (km/km^2)	Parcel Dens. (par/km^2)	Sanitary Sewer Dens. (km/km^2)	Septic Dens. (sep/km^2)	Primary Sanitary Inf.	Geologic Basin	Study
Range	0.38 - 2.31	2.6 - 55.1	0.0 – 78.2	2.6 – 15.2	41 - 1209	0.0 – 13.1	0 - 308			
AH	1.53	7.0	59.2	4.11	102	1.22	25	Septic	Triassic	UNC
BA	1.06	15.3	21.6	7.85	290	5.62	22	Sewer	Carolina	UNC
BG	1.51	20.0	39.5	7.87	167	5.60	0	Sewer	Carolina	UNC
BT	0.99	24.0	26.6	9.56	311	7.18	0	Sewer	Carolina	UNC
CB	1.21	16.1	38.2	8.40	304	4.84	21	Mix	Carolina	UNC
CC	0.90	8.8	44.5	9.31	122	0.00	80	Septic	Carolina	UNC
CP	0.74	9.8	43.4	8.88	228	6.43	0	Sewer	Triassic	UNC
EW	2.31	26.4	39.0	7.40	274	5.44	6	Sewer	Triassic	UNC
FH	1.42	34.0	0.7	15.16	713	12.14	0	Sewer	Triassic	UNC
GC	1.62	55.1	0.0	14.70	668	13.08	0	Sewer	Triassic	Duke
HS	0.69	10.8	36.2	9.95	263	0.00	194	Septic	Carolina	UNC
LW	0.63	5.7	64.2	7.29	153	0.00	111	Septic	Carolina	UNC
MD	0.38	20.3	0.0	12.14	478	8.78	0	Sewer	Carolina	UNC
MT	0.91	5.4	78.2	2.60	51	0.00	21	NA	Triassic	Duke
RR	1.94	5.4	66.1	5.15	132	0.86	96	Septic	Carolina	UNC
RRdev	0.95	9.0	65.1	5.78	202	1.75	308	Septic	Carolina	UNC
SP	1.75	13.8	25.5	7.55	197	0.61	108	Septic	Carolina	UNC
TE	0.65	29.4	1.0	14.50	571	9.40	8	Sewer	Carolina	UNC
TH	0.99	2.6	76.2	4.54	41	0.00	13	NA	Carolina	UNC
TY	0.85	47.3	0.0	15.22	1210	12.63	0	Sewer	Carolina	UNC
W13	0.60	39.4	0.8	12.70	828	12.02	0	Sewer	Triassic	Duke
W22	0.95	16.9	27.4	5.80	258	5.90	0	Sewer	Triassic	Duke
W26	1.95	22.2	31.8	6.10	221	5.68	0	Sewer	Triassic	Duke
W42	1.10	23.0	48.2	3.60	487	5.14	9	Sewer	Triassic	Duke
WB	1.58	34.8	0.0	14.38	630	12.81	0	Sewer	Carolina	UNC
WG	0.64	8.2	38.0	7.29	200	0.00	135	Septic	Carolina	UNC

Water quality sampling

Grab sampling of 10 watersheds in Carrboro, Chapel Hill and Durham was conducted from July of 2017 to July of 2019. Grab sampling of 9 watersheds in the Burlington area including Haw, Swepsonville, Graham, and Mebane was conducted from Oct. 2017 to Dec. 2018 with additional sampling in Feb. and Apr. of 2019. Existing grab sampled data was collected from Nov. 2013 to Mar. of 2016 (Blaszczak et. al. 2019). Stream water samples were taken twice monthly during sampling periods at the outlet of the study watersheds and field filtered to 0.45 nm with a 0.7 prefilter into HDPE bottles. Samples were stored on ice in the field and frozen upon return to the lab. Samples were analyzed for major anion and cation concentrations (NO_3^--N, Cl^-, Br^-, Fl^-,SO_4^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+}; mg/L) on a Dionex ICS-2000 ion chromatograph (Dionex Corp., Sunnyvale, CA). We measured total dissolved nitrogen (TDN) concentrations (mg/L) with a Shimadzu TOC-VCPH with TNM-1 module (Shimadzu Corp., Kyoto, Japan) and soluble reactive phosphate (SRP) concentrations (mg/L) using EPA method 365.1 on a Lachat QuickChem 8500 automated system (Lachat Instruments, Loveland, CO, USA).

Flow at the 10 Carrboro, Chapel Hill and Durham watersheds was estimating by development of a water level–discharge rating curve. Submerged pressure transducers were deployed (HOBO U20, Bourne, MA) to measure water level every 5 min. Paired flow measurements were taken by a combination of velocity profiling by electromagnetic velocity sensors (Marsh-McBirney Flo-Mate, Frederick, Maryland), dilution gauging, and acoustic doppler profiling (SonTek IQ+, San Diego, California). Flow for the Burlington area watersheds was measured at the time of sampling by electromagnetic velocity profiling (Marsh-McBirney Flo-Mate, Frederick, Maryland).

All continuously monitored watersheds are in the Carrboro and Chapel Hill area and were also grab sampled throughout the sampling period. Continuous monitoring deployment period varied based on sensor availability and environmental conditions. Sensors are deployed submerged within steams at the watershed outflow and are controlled by CR1000 data loggers (Campbell Scientific, Logan UT). Water chemistry data was collected by in-situ UV and UV-Vis adsorption spectrometry (S::CAN Spectrolyser, Vienna, Ausria; Sea-Bird Scientific SUNA V1 and V2, Bellevue WA, US). The SUNA sensor measures exclusively $NO3^-$-N, while the S::CAN sensor is capable of measuring $NO3^-$-N, TDN, DOC among others. These sensors are site calibrated to water chemistry samples collected and run alongside grab samples. This ensures that the continuous monitoring and grab sampled datasets are consistent. Grab samples are sufficient to site calibrate the SUNA, however the S::CAN requires extensive sampling over a range of environmental conditions. ISCO 6712 autosamplers (Teledyne ISCO, Lincoln NE, USA) were used to autonomously collect key water chemistry samples for calibration. Keller Acculevel pressure transducers (Keller America, Newport News, VA, USA) provided real time water-level and ISCO automated samplers were triggered by program to sample along the rising and falling limbs of select storms across seasons. SUNA calibration was conducted by regression and S::CAN calibration was conducted by Partial Least Squares Regression (PLSR) (RMSE $<$ 0.07 mg/l).

Flow measurement at continuously monitored watersheds was more frequent than grab sampled watersheds and utilized deployed sensors to capture stormflow observations (SonTek IQ+). This allows us to modify the water level-discharge rating curve throughout time to provide a higher accuracy estimate of flow.

Stable isotopic analysis of $NO3^-$ was conducted on select low flow and stormflow water samples from the outflow of a subset of 12 study watersheds that spanned the range in sanitary infrastructure and development intensity. Frozen samples were analyzed using the denitrifier method at the University of Pittsburg Regional Stable Isotope Laboratory for Earth and Environmental Science Research. Low flow samples (n=40) were analyzed for $\delta^{15}N$-NO and $\delta^{18}O$-NO_3. Synoptic samples were selected for analysis to represent a range of seasonal and wetness conditions. Stormflow samples (n=40) were analyzed for $\delta^{15}N$-NO, $\delta^{18}O$-NO_3 and $\delta^{17}O$-NO_3. Stormflow samples were selected from the continuously monitored sites and were selected to represent different observed patterns in nitrogen loading.

Data analysis

Over the two-year course of data collection there were environmental and technical factors that lead to gaps in data or periods of low confidence data. These include drought and stream drying, hurricanes and flooding and sensor and power failures. These challenges are inherent to research in developed areas due to extreme flow events and disturbed landscapes. Interpolation of missing data occurred only at low flows where variation in loading is low. Continuous monitoring data was clipped to periods of high confidence data for this report. Additional data collection and modeling may allow us to constrain uncertainty and release additional data in the future.

For the continuous monitoring watersheds peak flow measurement were not captured for the TH or TY. At TH flow estimates are extrapolated for only 1.7% of the record. At TY there was significant erosion post hurricane Florence and we have not yet fully rebuilt the water level-discharge rating curve. TY peak flow was estimated by using rainfall data and the BT runoff ratio to estimate the total event flow volume for TY. Using the available rating curve and estimated volume, we solved for peak flow and added this estimate to the rating curve for the post-hurricane period. Because ISC is nearly twice as much at TY than BT, it is possible that this is a significant underestimation of stormflow and TY stormflow loading should be treated as a conservative estimate. Ongoing additional flow data collection will allow us to improve these estimates in the near future.

Loading during flooding events is an important part of total nutrient loading, however these events create many challenges for data collection. During the fall 2018 hurricanes sensors were removed from TY, BT, and TH where risk of loss was substantial. Sensors remained at BG and RR and continuously monitored throughout both storm events. Water levels exceeded the banks for significant periods of both events and we have no means to directly measure flow outside stream banks. In order to create a minimum estimate of flow, we ignored flow outside the banks, estimating flow for these periods as only in bank flow. Potential errors in nitrate concentration are negligible in comparison to flow estimates; however, high suspended sediment during these events created noisy nitrate concentration data which was smoothed. We note that our estimates should be considered as minimum loads for these over-bank events. We will refine these shortly by using stage and estimated inundation extent and flow velocities.

Over the period of this study, over 70 total individual storm events were captured at continuously monitored watersheds. Patterns in the co-variance of flow, nitrate concentration and nitrate loading were analyzed to infer primary flow paths of nutrient loading. Although multiple analysis involving flow-concentration hysteresis have been conducted, the final inference was drawn qualitatively based on strong patterns in the position of concentration and loading peaks relative to peak flow.

The water chemistry grab sampling and S::CAN sensors measure TDN and nitrate (NO_3^{3}), but the SUNA sensors and stable isotope analysis only measure nitrate. All analysis and values of nitrate are as nitrogen (NO_3^--N). All analyses are conducted on either nitrate as nitrogen (NO_3^--N) or TDN, never mixing parameters. Nitrate and TDN are well correlated (Adj $R^2 = 0.85$), and nitrate makes up 88% of TDN across sites. Therefore, in the discussion of generalized trends, we will refer to both TDN and nitrate-nitrogen loading as N-loading.

8. **Results:**

Trends in low flow N and P loading

Low flow water chemistry for 25 single land-use headwater watersheds in the Jordan and Falls Lake watersheds shows that nutrient pollution is impacted by sanitary infrastructure type, geology and development intensity. Low flow TDN and nitrate concentration and loading indicate that nutrient pollution increases with metrics of development intensity (i.e. ISC, road density, parcel density, sanitary sewer density) for watersheds within the urban service boundary served by sanitary sewer (**Figure 5**). Higher development intensity watersheds also generally show greater variation in sampled N concentration and load than low development intensity watersheds. Septic watershed concentration and loading does not respond to metrics of development intensity and is more variable than similar low development intensity watersheds on sewer (**Figure 5**). While mean low flow N loading was greater than the loading for comparable sanitary sewer watersheds (i.e. less than 300 parcels) the effect of sanitary infrastructure type on low flow N loading was non-significant due to the large variation in loading among septic watersheds (**Figure 7**). Watersheds within the Triassic and Carolina geologic basins which make up the Jordan Lake watershed have similar nutrient loading and response to development intensity; however, nutrient loading was significantly higher among Raleigh Belt watersheds. The Raleigh belt is not a part of the Jordan Lake watershed, but illustrates that geology is an important consideration in nutrient loading. Per unit area N-loading of sanitary sewer served watersheds increased with development intensity; however, preliminary analysis suggests that per parcel, or per capita loading may be much larger for septic watersheds and stable across development intensity of sewer served watersheds.

Soluble reactive phosphorus (SRP) loading increased dramatically with development intensity among high intensity development watersheds, but was relatively flat at lower intensity development (**Figure 6**). There were no significant differences in SRP loading with sanitary infrastructure and variation in loading was smaller among sites and through time at sites than N loading.

Assessment of sampling methods

Continuous monitoring of outflow of five subset watersheds indicates that total loading is not accurately represented by discrete water quality although general trends are consistent. The continuously monitored septic watershed had a median loading 40% less than the median of all the grab sampled septic watersheds. Due to the large range in loading observed from septic watersheds no single continuously monitored watershed could represent all septic watersheds. The low and medium development intensity watersheds on sanitary sewer are generally representative of urban development in the region although there is little sampling for comparison to the high intensity study watershed. Grab sampled predictions of total loading significantly underpredict the continuously monitored total loading; however, the grab sampling closely estimates the continuous monitoring observations of low flow loading.

Stormflow loading

The proportion of stormflow loading (stormflow loading/total loading) was much greater for the urban watersheds on sanitary sewer than for the rural septic watershed (Figure 9). Stormflow was responsible for 20% of nitrate loading at the septic watersheds while it was responsible for 40-48% of loading among the urban watersheds (**Figure 8**). Storm flow loading was highest at the high development intensity watershed (TY) and lowest at the rural watershed on septic; however, there was no significant difference between the stormflow loading of the low and medium intensity watersheds. This may be because there are two major Chapel Hill roads (MLK Blvd and Estes Dr) in the low intensity watershed despite otherwise low housing and building density. The stormflow loading for the Tanyard watershed is probably underestimated because high flow measurement was not practical and was therefore conservatively modeled. Stormflow from the forested watershed was responsible for 52% of total loading. Trends in flow and nitrate concentration relationships indicate that this is because at low flow forested nitrate concentration is very low, likely as a result of biotic uptake and removal.

Nitrate sources and contribution

Isotopic analysis suggests that the majority of nitrate loading from developed watersheds at low flow is derived from wastewater across seasons and infrastructure type (**Figure 9**). USGS isotopic studies indicate that there is a large overlapping range between soil N and wastewater N in their assessment ranging across the US. However, low flow forested watershed nitrate loading, which is expected to be primarily soil N, is 2.5 to 208 times lower than estimated monthly concentrations from grab sampled developed watersheds. The forested TH watershed is nested within the RR watershed and N loading per km^2 increases by 5.6 times between sampling points. Without evidence that soils in developed landscapes produce much greater nitrate than forested soils, it is reasonable to assume that the majority of nitrate in the overlapping soil N/wastewater N range is derived from wastewater. The nitrate contribution from wastewater is larger for septic watersheds than sanitary sewer served watersheds; however, the difference is not significant, suggesting that both septic and sewer served watersheds contribute significantly to N loading through leaking sanitary infrastructure at low flow.

Nitrate loading during stormflow is made up of a complex mix of sources. Isotopic analysis of stormflow water sampling was not sufficient to accurately partition loading sources; however, we can identify that wastewater, atmospheric deposition, fertilizer and soil are all important contributors. Throughout individual stormflow events, the sources of nitrate change rapidly and are mixed together. This rapid change and mixing obscures analysis and further sampling and laboratory analysis will be required to partition sources and identify patterns in source timing throughout stormflow events.

Seasonal and flow dependent drivers of loading

Inter-storm nitrate concentration patterns provide evidence for seasonal changes in nitrate loading based on land-use and sanitary infrastructure. **Figure 10** illustrates two examples of these different patterns based on the timing of the loading and concentration pattern relative to the event flow response. For this particular storm (7/22/18), subsurface flow paths and sources contribute significantly to loading at the septic watershed (**Figure 10** C. left hand graph) while rapid surface runoff and associated sources are significant sources at the low density urban watershed (**Figure 10** C. right hand graph). During dry periods, the septic watershed loading was driven by subsurface stormflow. During wet periods, low flow concentration and loading greatly increased at the septic watershed and stormflow resulted in less loading than stormflow in the dry period. This suggests that during dry periods, septic systems are not hydrologically connected to watershed streams at low flow, but are connected by stormflow resulting in large episodic pulses of N. However, during wet periods, septic systems are constantly hydrologically connected at low flow, resulting in consistent N loading. Patterns vary greatly for the urban watersheds on sanitary sewer. During dry periods, urban watershed loading is driven by fast moving surface runoff during stormflow. During wet periods loading is driven by both stormflow and highly elevated post storm N concentrations at low flows. This suggests that stormflow events during wet period hydrologically connect leaking sanitary sewer lines. The delay in increased concentration relative to stormflow suggests that stormwater may be infiltrating into wastewater pipes during events and slowly leaching out over the subsequent hours to days.

Hurricane N loading

While not originally planned within this project, our instrumentation was deployed during the heavy rains brought by Hurricanes Florence (Sept 15, 2018) and Michael (Oct 10, 2018) and allowed to assess stream nitrate dynamics during these unusual periods. Conservative estimates of nitrate loading for both hurricanes suggest that large storms can have a disproportionate impact on nutrient loading (**Figure 11**). Flooding event data has high uncertainty and this data is a minimum loading accounting for uncertainty in flow and sensor estimates of nitrate. Even so, our estimates show that extreme events are an important component of nutrient loading. Hurricane Florence nitrate loading was greater than 25.2 kg for BG and 9.5 kg for RR, or 2.0 and 1.6 months loading under normal flow conditions respectively (at least). Hurricane Michael nitrate loading was greater than 16.8 kg for BG and 11.2 kg for RR, or 1.4 and 1.9 months loading under normal flow conditions respectively (at least). Continued analysis of this data will aim to constrain uncertainty and provide an estimated loading range for flooding events. Nonetheless, the high spatial and temporal variability of hurricanes can make it challenging to characterize the full effects that these events can have on water quality.

9. Recommendations:

Wastewater

Summary of findings: Wastewater is a significant contributor to non-point source nitrate loading across land-use and septic or sanitary sewer severed watersheds. Septic systems are designed to discharge partially treated wastewater into the ground where natural soil processes remove the majority remaining nutrients, but during wetter periods and storms, nutrients are transported faster, reducing treatment in the soil and resulting in greater N-loading. There was a large range in N-loading from septic watersheds that was not explained by development features or household density. Septic system performance and location relative to streams and flow paths may be of greater importance. Additional analysis of collected data will be conducted to assess this hypothesis; however, additional study will likely be necessary. Sanitary sewers are meant to contain wastewater and transport it for treatment, but they are known to leak and surcharge. This results in low flow nitrate contribution from wastewater that is lower than that in septic watersheds, but still accounts for the majority of low flow N-loading at these watersheds. The extent and degree of leaks is unknown, however among the seven sewer served watersheds that were sampled over the course of a year for this analysis, significant wastewater derived nitrate was nearly ubiquitous.

Implications: Storm water control measures must be coupled with sanitary infrastructure upgrades and maintenance. Distancing sanitary infrastructure from streams should be evaluated as a potential mitigation. Sanitary sewer trunk lines often run in close proximity to streams and at low points in the landscape. This means that even minor leaks may have a direct nexus to streams and the very presence of the sewer lines prevents the planting of vegetated riparian buffers which may mediate this loading.

Stormwater

Summary of findings: Stormflow is also of great importance, accounting for 20 – 48% of total N-loading across the continuously monitored developed watersheds and generally increasing with development intensity. The many negative impacts of stormwater are well documented and stormflow contributes to nutrient loading in ways not investigated by this study such as suspended sediment transport and reduced stream health and uptake.

Implications: Because stormwater moves rapidly at high volumes, nutrient treatment options are often constrained relative to low-flow loading. Stormwater control measures can provide some reductions and they can be an important part of watershed scale planning and restoration. Connecting streams to floodplains will allow riparian buffers to provide treatment of stormwater and increases the potential treatment time by slowing flow.

Forrest Cover

Summary of findings: Forested watershed loading was 2.5 to 208 times lower than developed watershed loading and trends in concentration and flow suggest significant biotic N uptake and removal especially at low flow. Although previous work has shown moderate total organic nitrogen (TKN) loading from forested watersheds it also indicates low nitrate and ammonium loading (Boggs et. al. 2013). Much of the TKN is in the form of suspended solids and may change form, but is not immediately available to algae and may be buried in reservoirs.

Implications: Conservation of reservoir watersheds through easements and development limits is a common method for protecting the quality of drinking water sources. These findings highlight the importance of this practice. Effective stream restoration could be a powerful tool for managing nutrients; however, it must be approached at the watershed scale with reduction of stormwater and include reconnection to floodplains and wetlands.

Nutrient loading mechanisms

Summary of findings: The mechanisms and timing of N-loading change with land-use and throughout the year based on rainfall and seasonal conditions. Loading can occur over different time scales based on the flow path that N loading takes. This is highly sensitive to the location of sources (e.g. surface vs subsurface and potentially proximity to streams) and also to the seasonal wetness conditions.

Implications: These factors are important consideration for optimizing the implementation of storm water control measures and best management practices as a part of larger regional nutrient management. Recommendations may change based on targeted landscapes, seasons or flows. For example, if we wish to target spring nutrient loading to reduce summer eutrophication, our results suggest that in rural areas low flow loading should be targeted. Stream restoration and forest cover may be good options. Likewise in urban areas stormflow and throughflow loading should be targeted. This may require a combination of bio-retention, riparian buffers and enhanced sewer maintenance to trim storm peaks, but ensure treatment and retention of nutrient in subsurface flow. Future publication will detail these findings on the hydrologic processes driving nutrient loading and the effects of land-use and hydroclimate.

Extreme Events

Summary of findings: In 2018 North Carolina was hit by two major hurricanes which transported months' worth of nitrate from study watersheds in a few days. Very few previous studies have been able to quantify hurricane loading especially at inland headwater watersheds.

Implications: Climate change projections predict an increase in the number of extreme rainfall events which will have profound impacts on nutrient loading. Because of the high discharge of flood event loading, these nutrients are not just an issue for Jordan Lake, but the entirety of the Cape Fear River and estuary. Increased extreme event loading should be considered in management plans and future projections.

10. References

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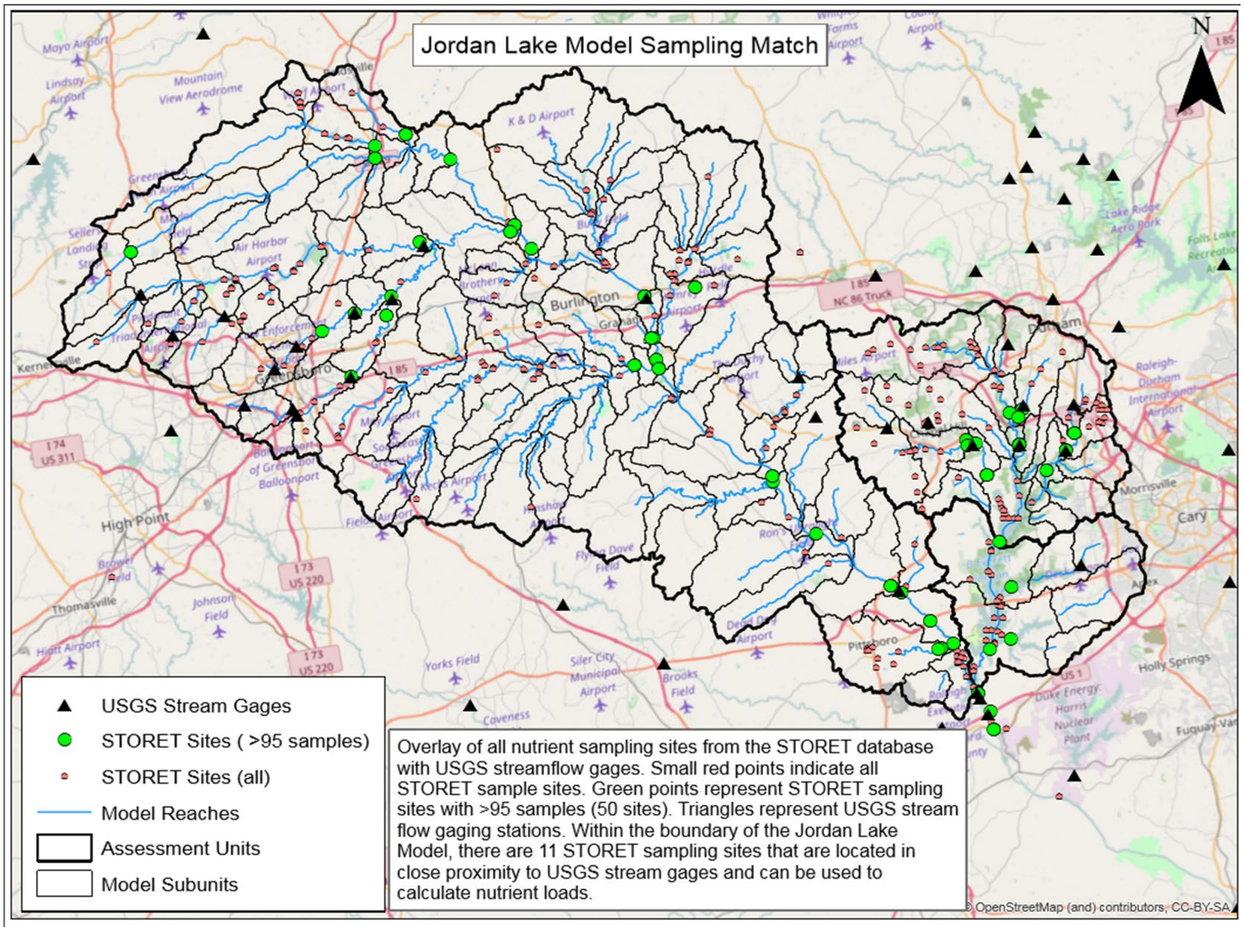

Figure 1. Map of storet and National Water Information System (NWIS) sites with ample water quality data

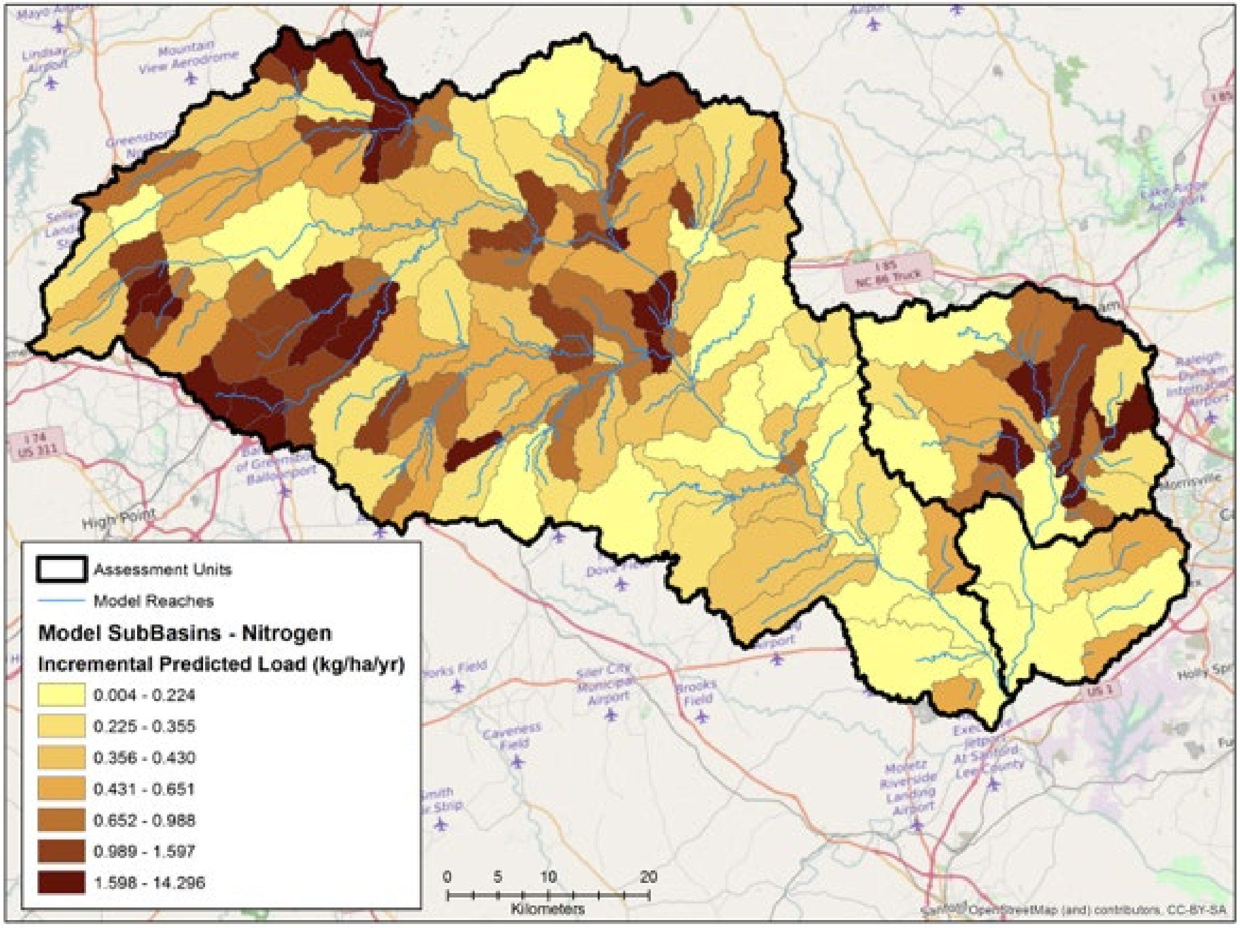

Figure 2. USGS SPARROW Model output of incremental predicted load of total nitrogen at the resolution of Jordan Lake Model Subbasins.

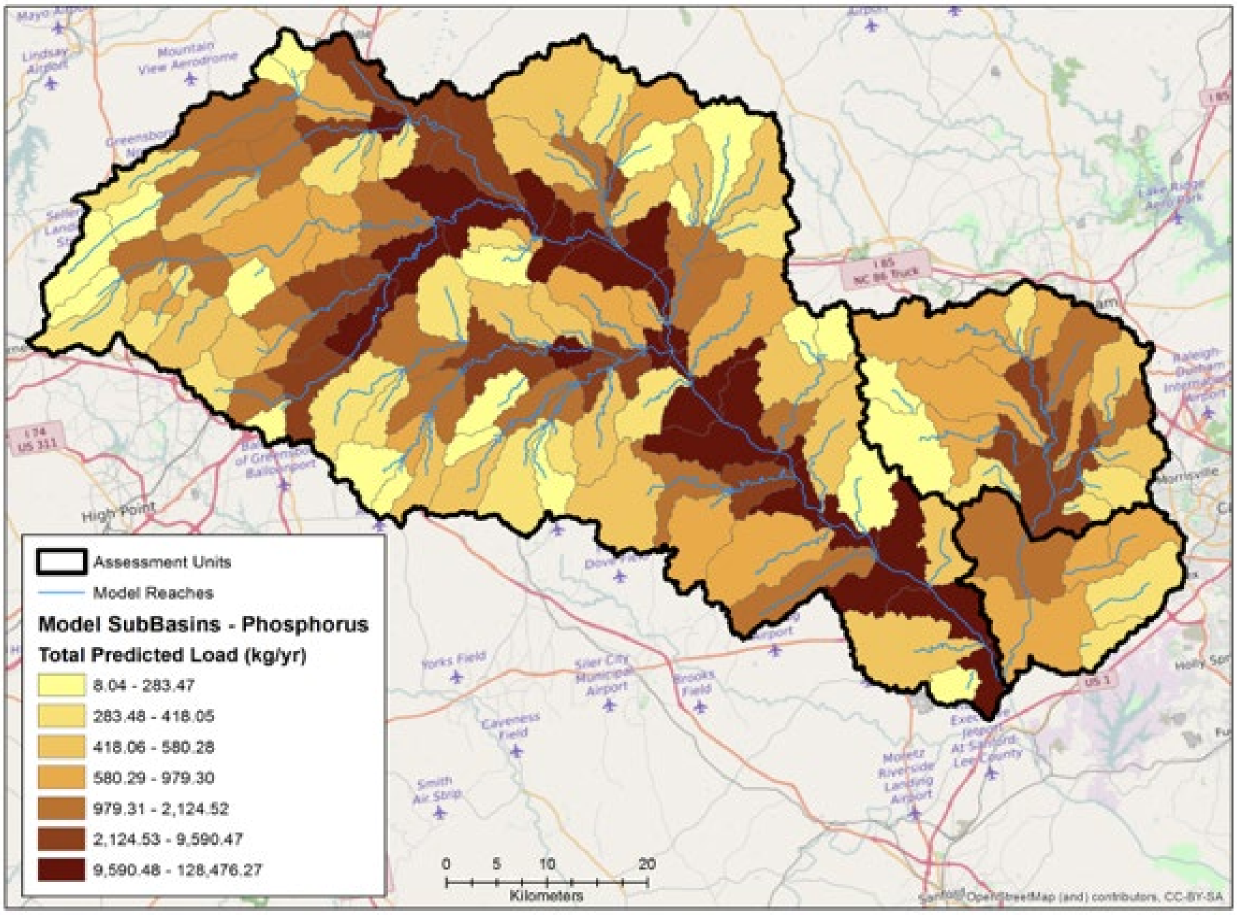

Figure 3. USGS SPARROW Model output of incremental predicted load of total phosphorus at the resolution of Jordan Lake Model Subbasins.

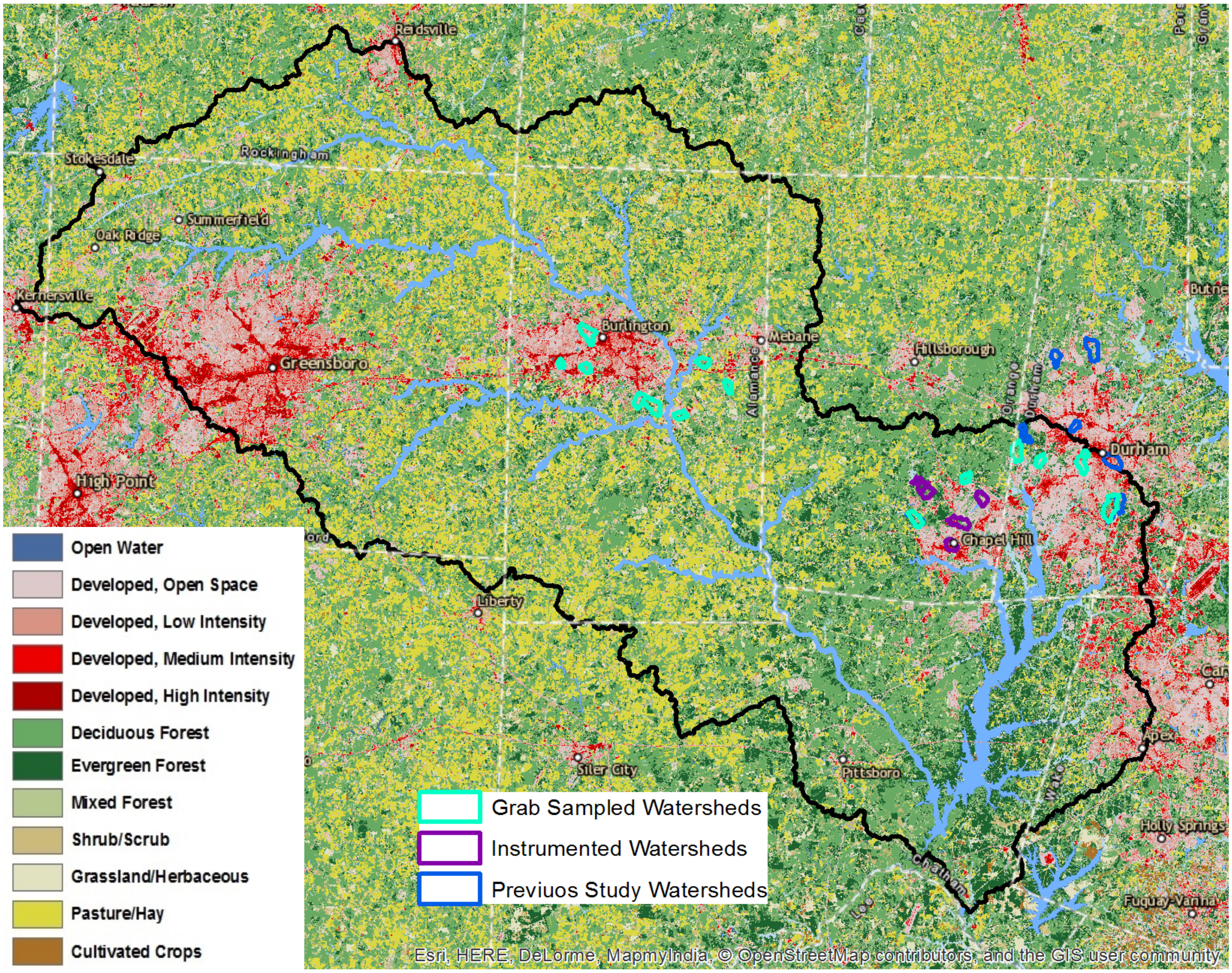

Figure 4. Study watershed locations for grab sampled watersheds, continuously monitored instrumented watersheds and previous studied watersheds. See **Table 2** for catchment characteristics.

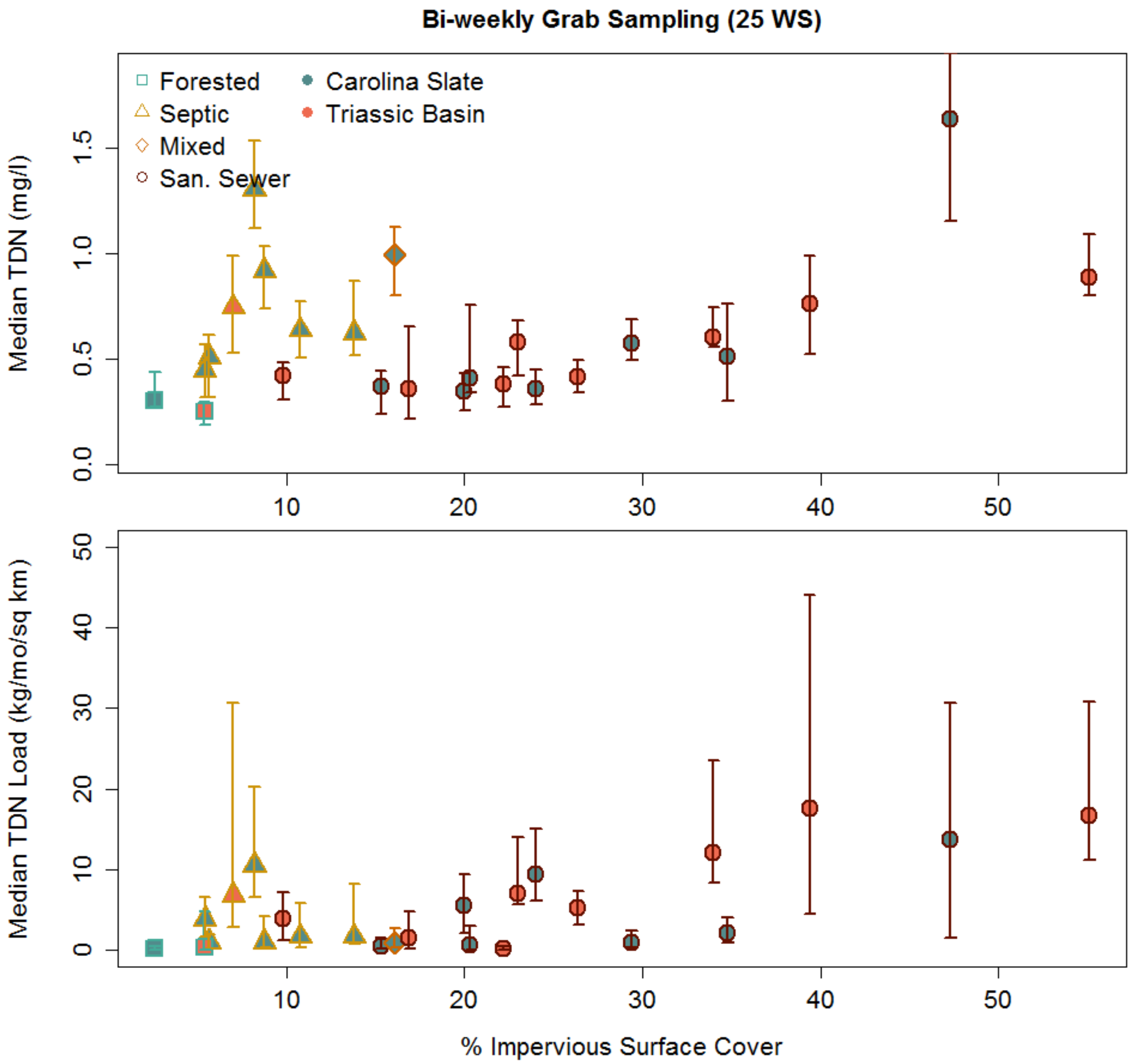

Figure 5. Median TDN concentration and loading with the interquartile range for 31 twice monthly sampled single land-use watersheds. All watersheds have greater than 12 months of sampling covering all seasons. Shapes depict land-use and infrastructure of developed watersheds while the fill col indicates the underlying geologic basin.

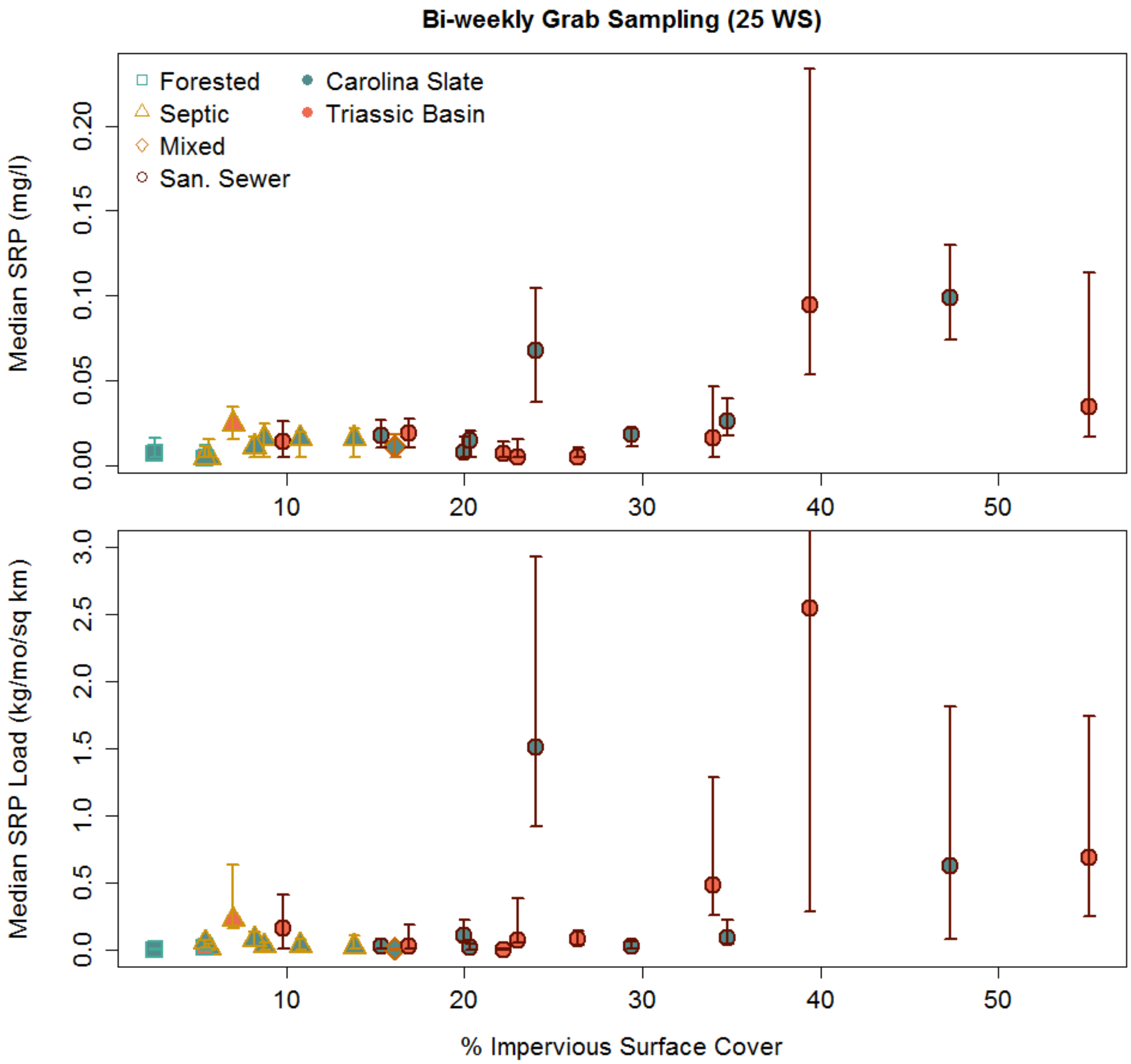

Figure 6. Median SRP concentration and loading with the interquartile range for 31 twice monthly sampled single land-use watersheds. All watersheds have greater than 12 months of sampling covering all seasons. Shapes depict land-use and infrastructure of developed watersheds while the fill col indicates the underlying geologic basin.

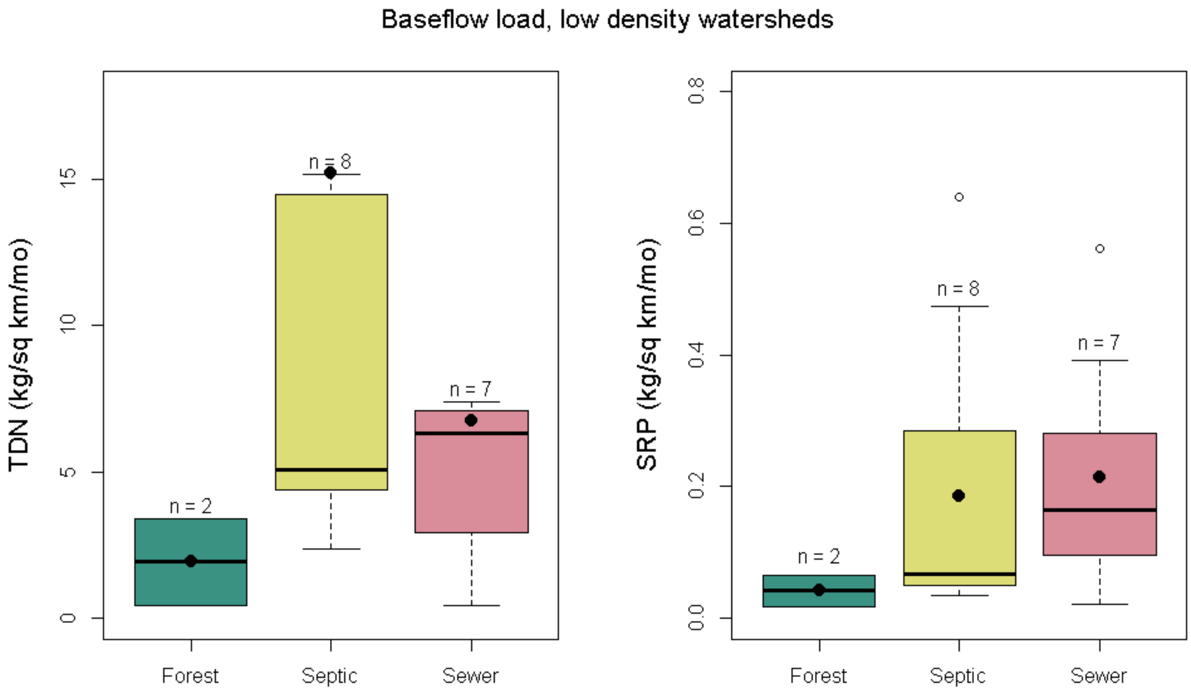

Figure 7. Boxplots of total dissolved nitrogen (TDN) and soluble reactive phosphorous (SRP) loading for watersheds with less than 300 parcels per km^2. Means are depicted by the solid points.

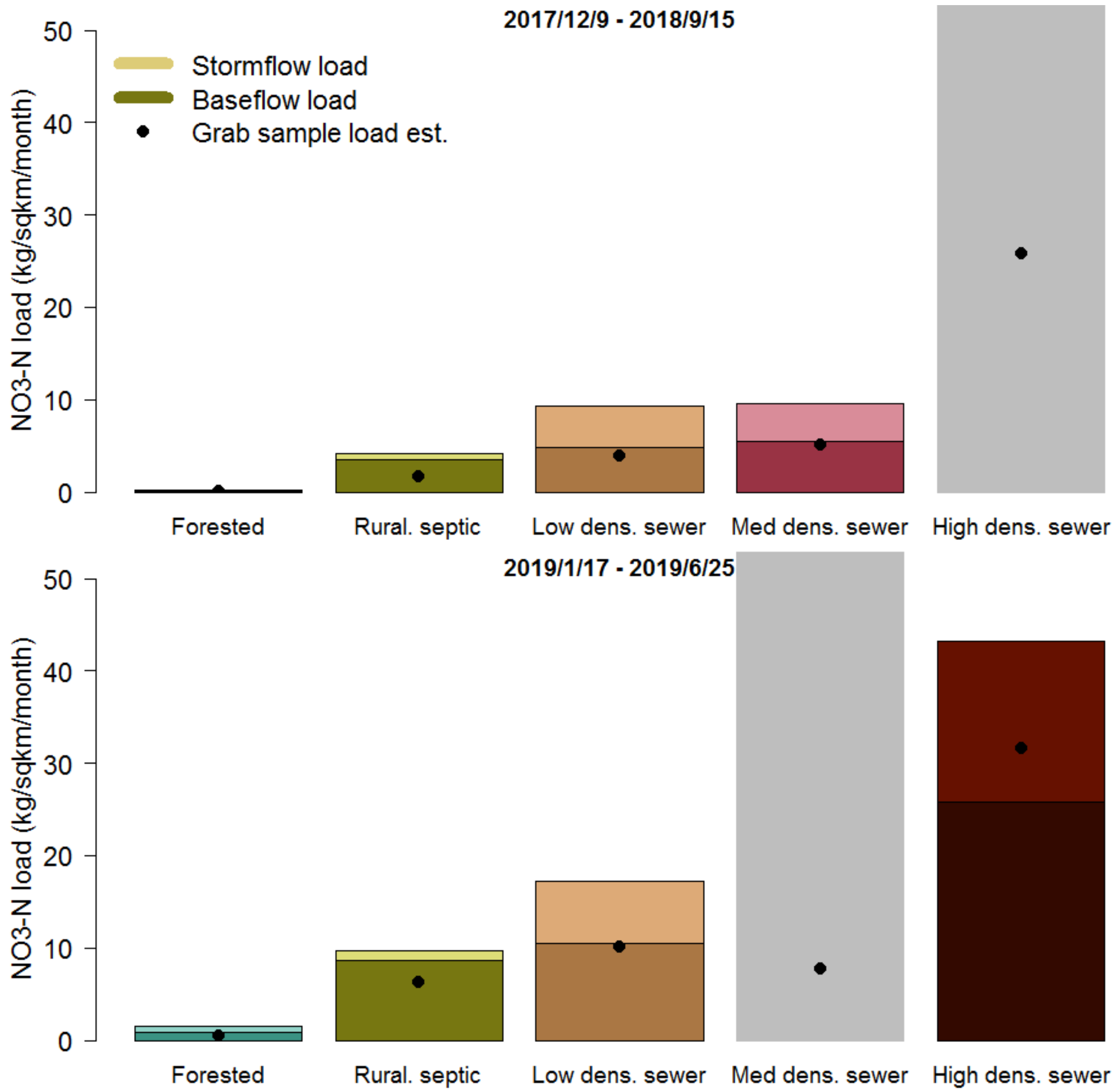

Figure 8. Total loading for two periods of high confidence continuous monitoring data. Study watersheds are TH, RRdev, BG, BT, and TY respectively. Light colors represent stormflow loading while paired dark colors represent low flow (baseflow) loading. Data is missing for the high-density watershed in the first period and 44 days of data have been removed in QA/QC. Data is missing for the medium density watershed in the second period and 6 days of data have been removed for QA/QC. Points represent the grab sampled based estimate for nitrate loading. Peak flow for TY is estimated and therefore TY stormflow loading is a conservative estimate and is likely higher. The 2019 period of data was wetter (127 mm/mo rainfall) than the 2017/2018 period (91 mm/mo rainfall) which started in drought.

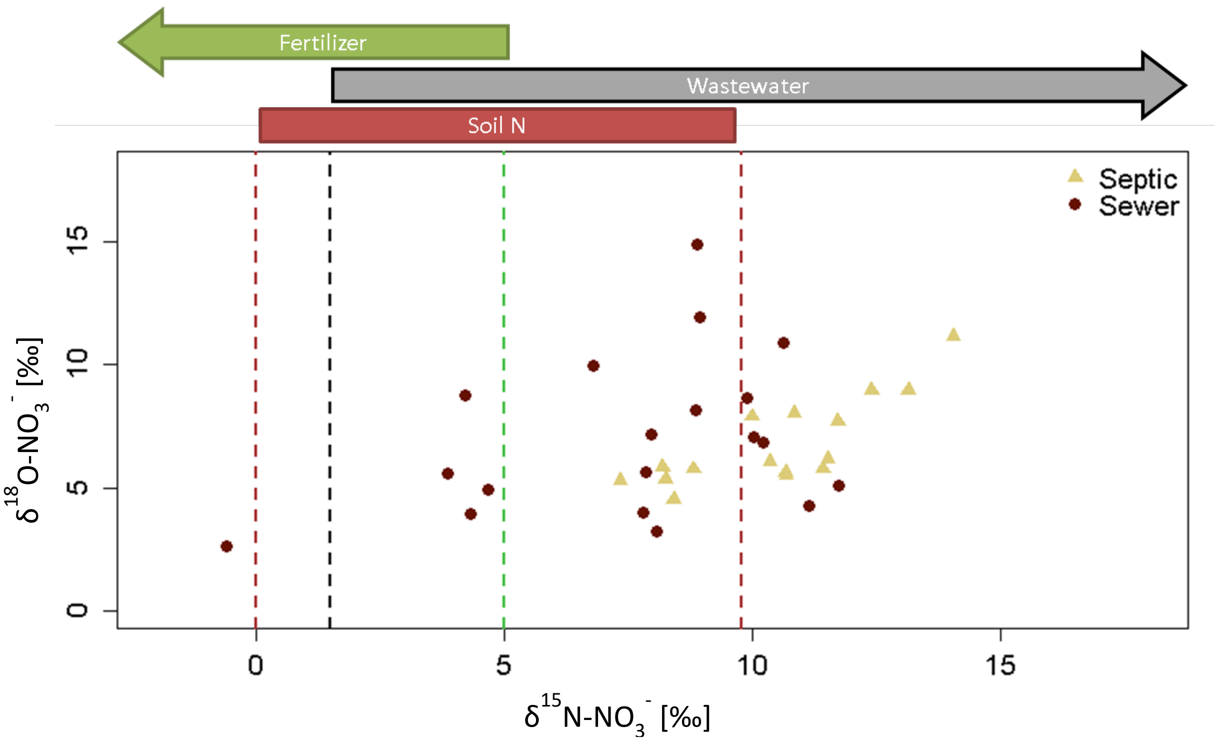

Figure 9. Baseflow sampled nitrate dual isotope analysis spanning 12 watershed and four seasons from Nov 2017 to Sept 2018. Ranges denote the source of nitrate based on Kendall et al. 2007. There is a large overlap between the ranges for each nitrate source. Because soil N concentration are low in the absence of sanitary infrastructure results suggest that much of the sampled nitrate is derived from wastewater.

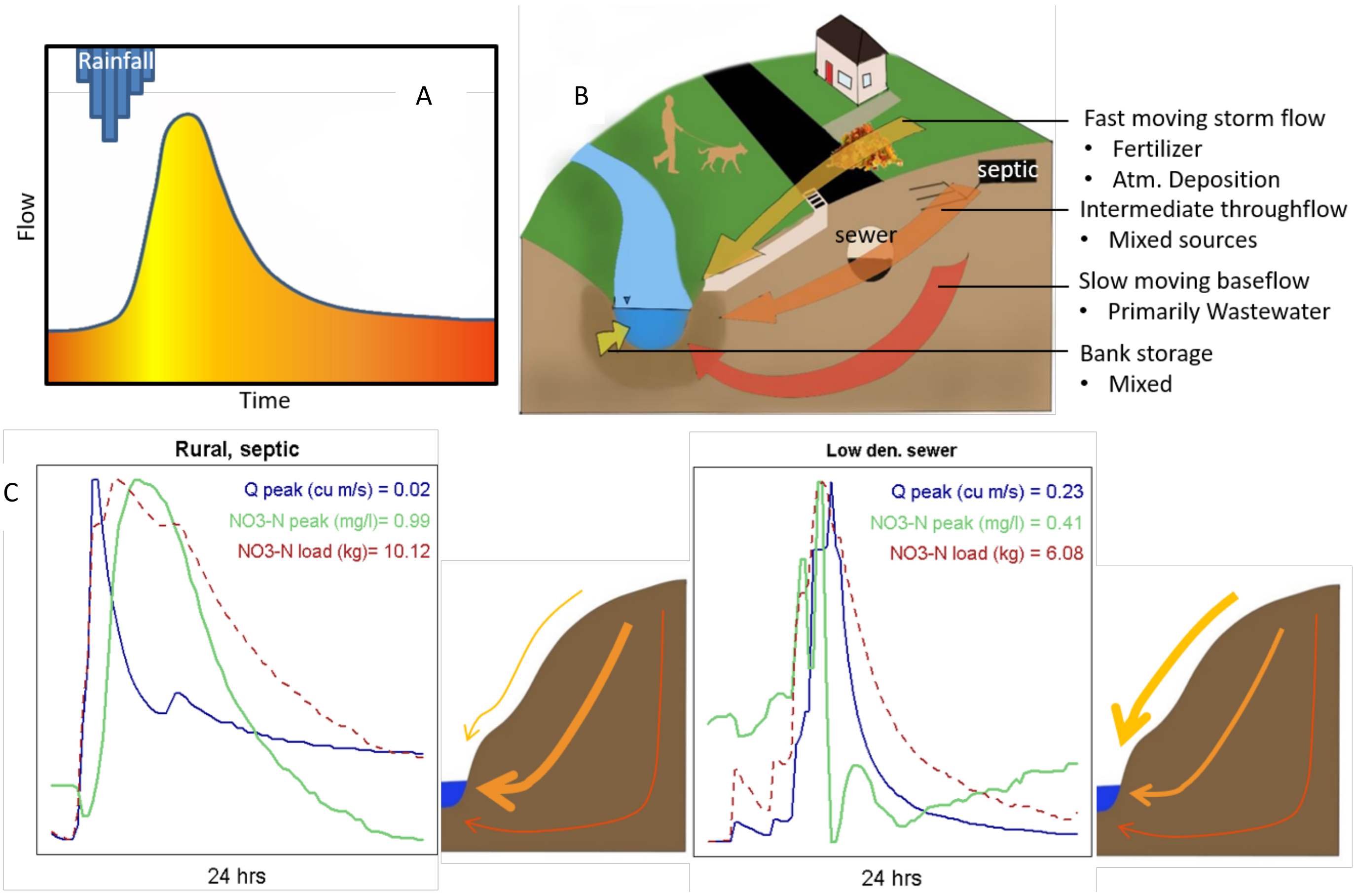

Figure 10. A representation of how the timing of flow, nitrate and loading informs our understanding about the flow paths and potential sources of nitrate loading. A. depicts a generalized hydrograph; colors correspond to arrows of flow on B. B. depicts how nutrients flow into streams with yellow representing fast flow paths and red representing slow flow paths. C. shows two sample hydro-chemo graphs of nitrate loading for a dry season storm (7/22/18, 0.6 in) with hillslope representations of load transport. Larger arrows indicate larger flow-path contribution.

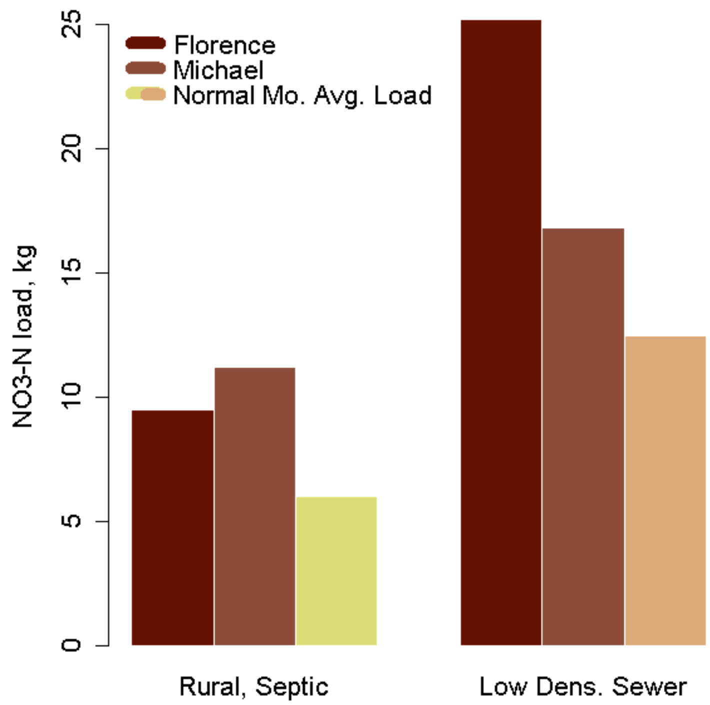

Figure 11. Bar graph comparing the average nitrate load for a normal month at the continuously monitored rural watershed and low-density urban watershed to the loading from the single rainfall events from hurricanes Florence and Michael. Estimates are a minimum, not accounting for over bank flow, and true hurricane loading could be substantially higher.