

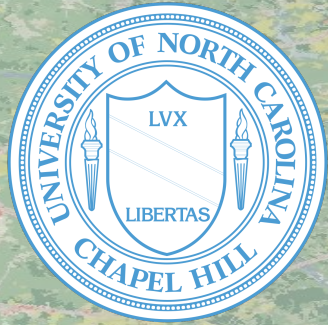
CONTROLS ON NITROGEN LOADING ALONG THE EXURBAN-URBAN GRADIENT OF THE NORTH CAROLINA PIEDMONT

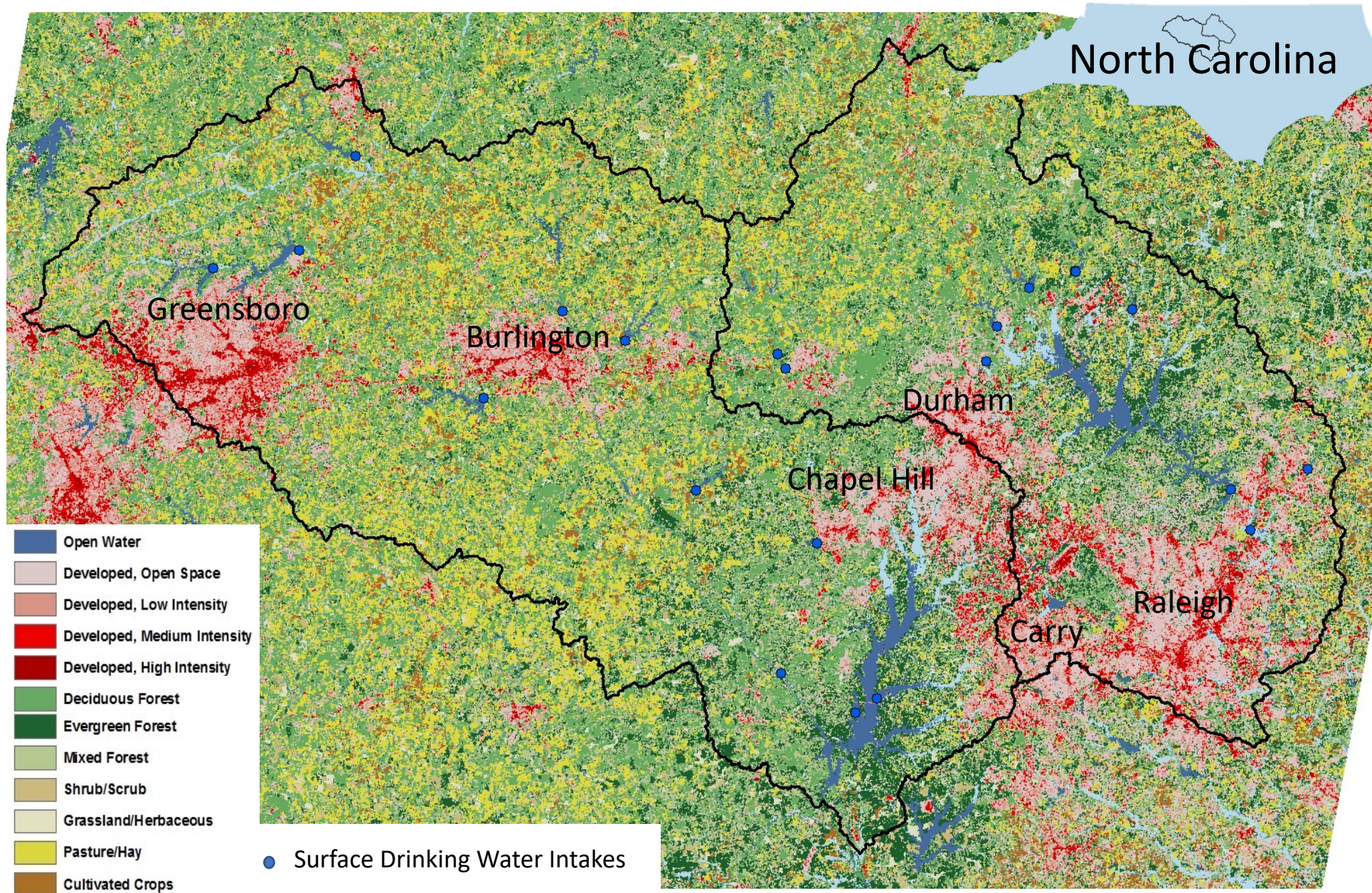
Joseph Delesantro

Postdoctoral Scholar, Penn State University

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Jonathan M. Duncan, Diego Riveros-Iregui, Keridwen M.
Whitmore, Joanna Blaszcak, Emily Bernhardt, Dean Urban,
Lawrence E. Band





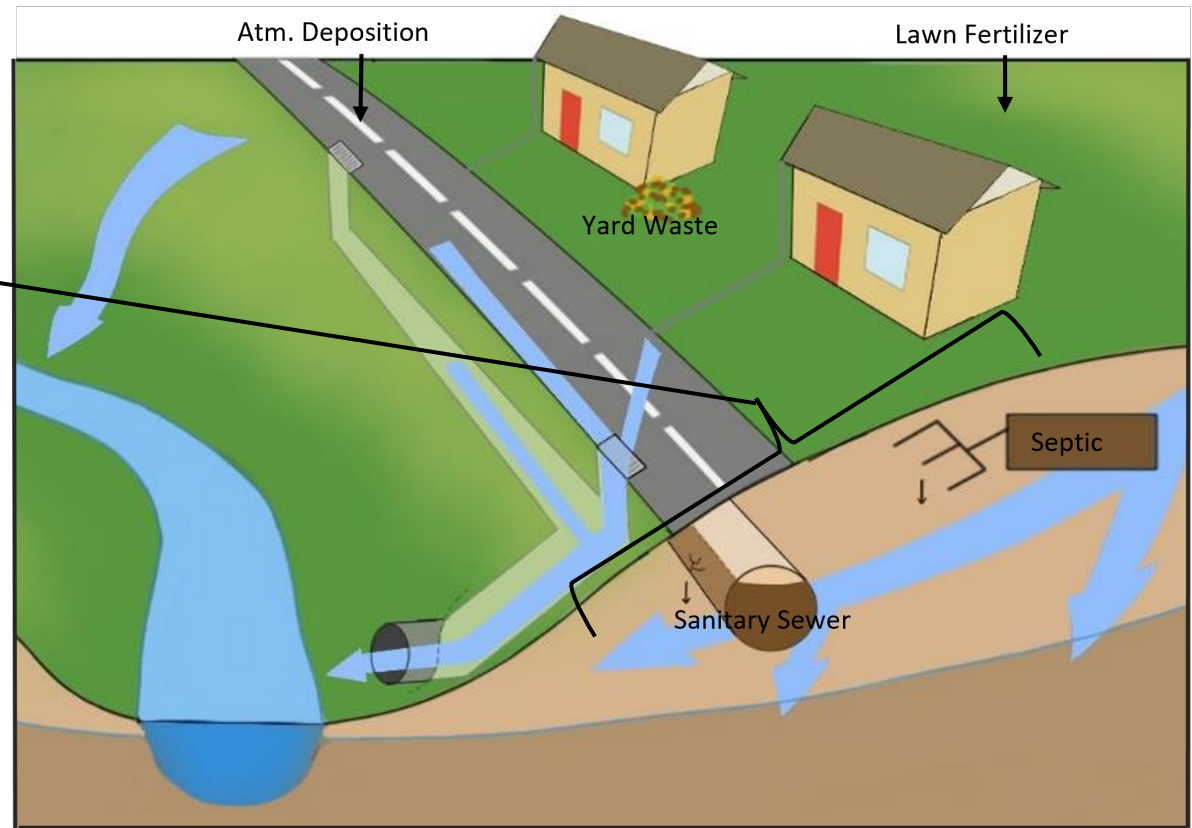
What are the dominant flow paths of nonpoint source nitrogen loading along the exurban-urban gradient?

What are the primary sources of nonpoint source nitrogen loading to streams along the exurban-urban gradient?

What landscape features control nitrogen loading in developed watersheds?
Where is nitrogen coming from?

How is nitrogen transported to streams in developed watersheds?

- Humans convert food to wastewater
- And we depend on sanitary infrastructure to contain and treat this nitrogen source



Bernhardt et al.: Urban Impacts on Surface Water Nitrogen Loading

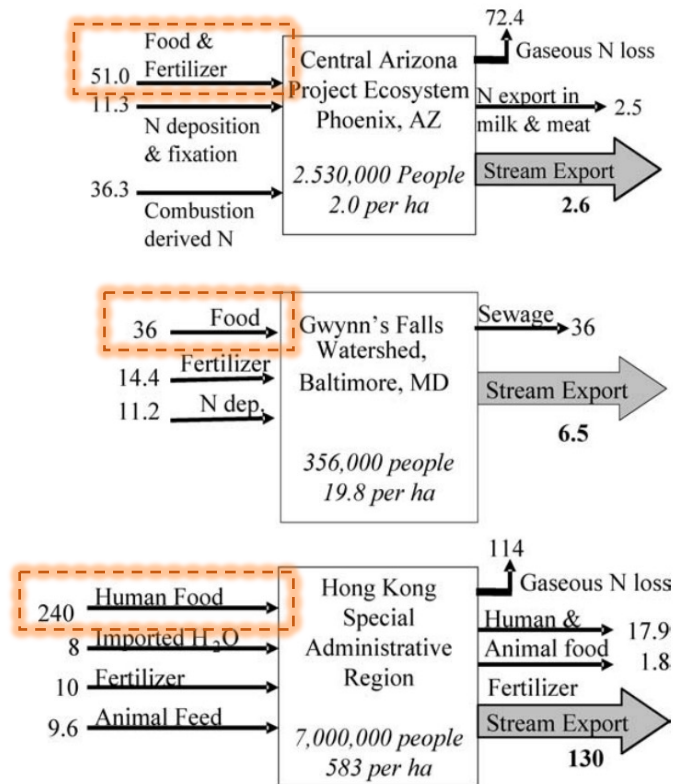


Figure 2. Compiled mass balance estimates for three cities (data in kg N ha⁻¹ y⁻¹) arranged in order of increasing population density. Data for Phoenix from Baker *et al.* 2001, for Baltimore from Groffman *et al.* 2004, and for Hong-Kong from Warren-Rhodes and Koenig 2001. Note the discrepancies between the types of fluxes measured in each study.

Bernhardt, E. S., Band, L. E., Walsh, C. J., & Berke, P. E. (2008). Understanding, managing, and minimizing urban impacts on surface water nitrogen loading. *Annals of the New York Academy of Sciences*, 1134, 61–96.

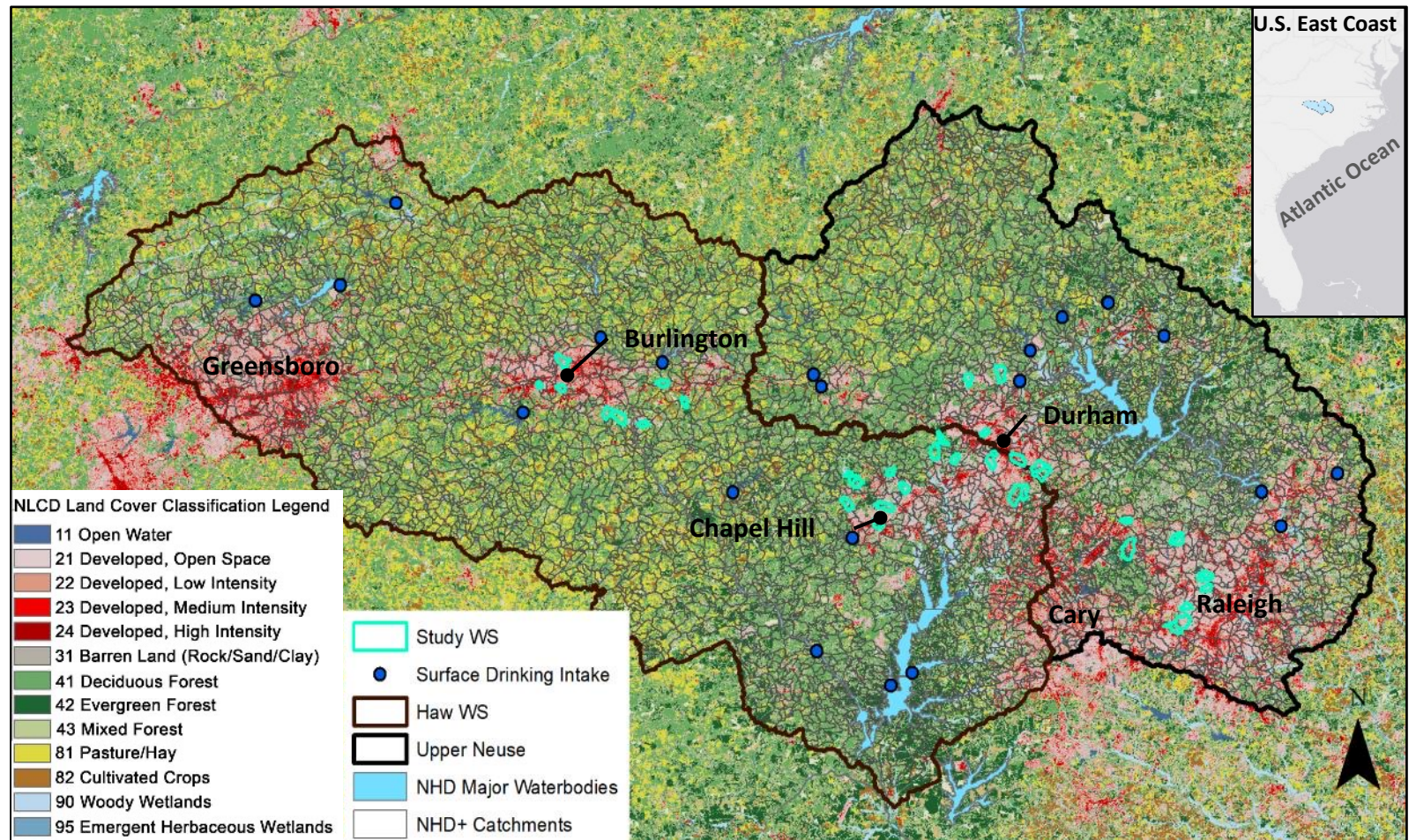
Baker, L. A., Hope, D., Xu, Y., Edmonds, J., & Lauver, L. (2001). Nitrogen balance for the Central Arizona-Phoenix (CAP) ecosystem. *Ecosystems*, 4(6), 582–602.

Groffman, P. M., Law, N. L., Belt, K. T., Band, L. E., & Fisher, G. T. (2004). Nitrogen Fluxes and Retention in Urban Watershed Ecosystems. *Ecosystems*, 7(4), 393–403.

Warren-Rhodes, K. & A. Koenig. (2001). Ecosystem appropriation by Hong Kong and its implications for sustainable development. *Ecol. Econ.* 39: 347–359.

Across the 6975 km² study area:

- Population density of developed sub catchments is low, with a median of 390 per/km²
- There is a large overlap in the population density use of septic and sewers systems encompassing the median population density.
- 25% of the population is served by septic systems.
- Sanitary sewers are preferentially placed near streams, 91.1% of sanitary sewer volume was within 200ft of a stream

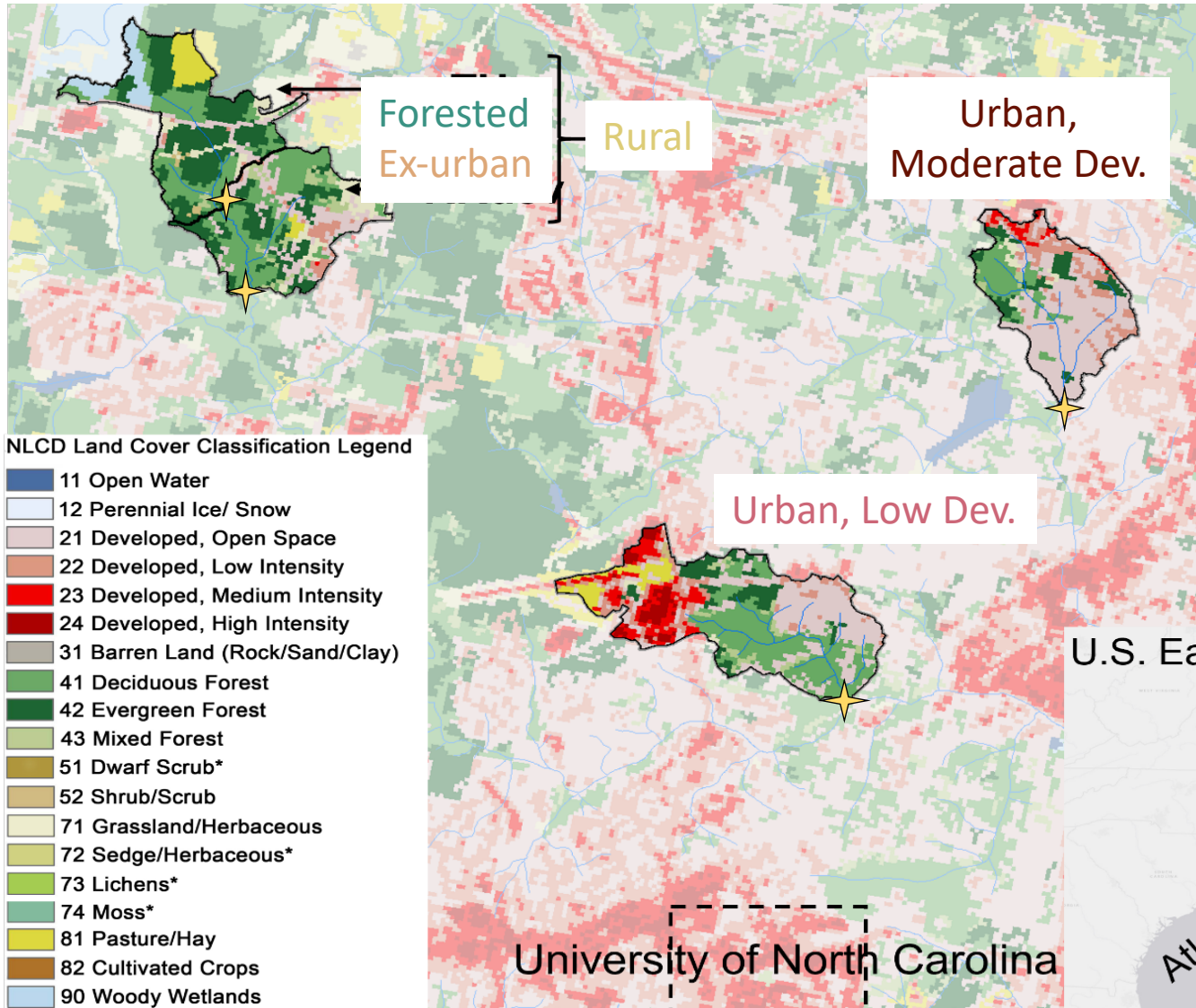


Read more about development patterns in the NC Piedmont:

Delesantro, J. M., Blaszcak, J. R., Duncan, J. M., Bernhardt, E. S., Riveros-iregui, D., Urban, D. L., & Band, L. E. (2021). Characterizing and classifying urban watersheds with compositional and structural attributes, (August), 1–20. <https://doi.org/10.1002/hyp.14339>

What are the dominant flow paths of nonpoint source nitrogen loading along the exurban-urban gradient?

To investigate nitrogen loading across flows:



Metric	Units	Study WS ID				
		TH	RR	RRdev	BG	BT
Area	SqKM	0.99	1.94	0.95	1.51	0.95
Agg. Landcover	%	7.94	5.25	2.39	5.3	0.19
Forested Landcover	%	60.83	62.3	64.09	40.83	25.87
ISC (NLCD)	%	0.81	2.28	3.83	15.71	10.9
ISC (hand drawn)	%	1.57	3.77	6.9	20.03	23.22
All Developed Landcover	%	0.81	3.86	7.08	24.64	20.4
Road Density	km/km ²	2.59	3.64	4.75	5.6	7.43
Stormwater Pipe Dens	km/km ²	0.09	0.25	0.42	1.11	2.78
Sanitary Sewer Density	km/km ²	0	0.43	0.88	5.13	7.36
Septic System Density	per km ²	13	94	180	3	0
Sewer TWI		0	0.88	1.23	0.67	1.01
Population Density	per km ²	30	259	498	313	887
Parcel Density	per km ²	13	85	161	113	276

U.S. East Coasts



↖
Solar
Panels

Autosampler for
storm samples

Datalogger

Batteries

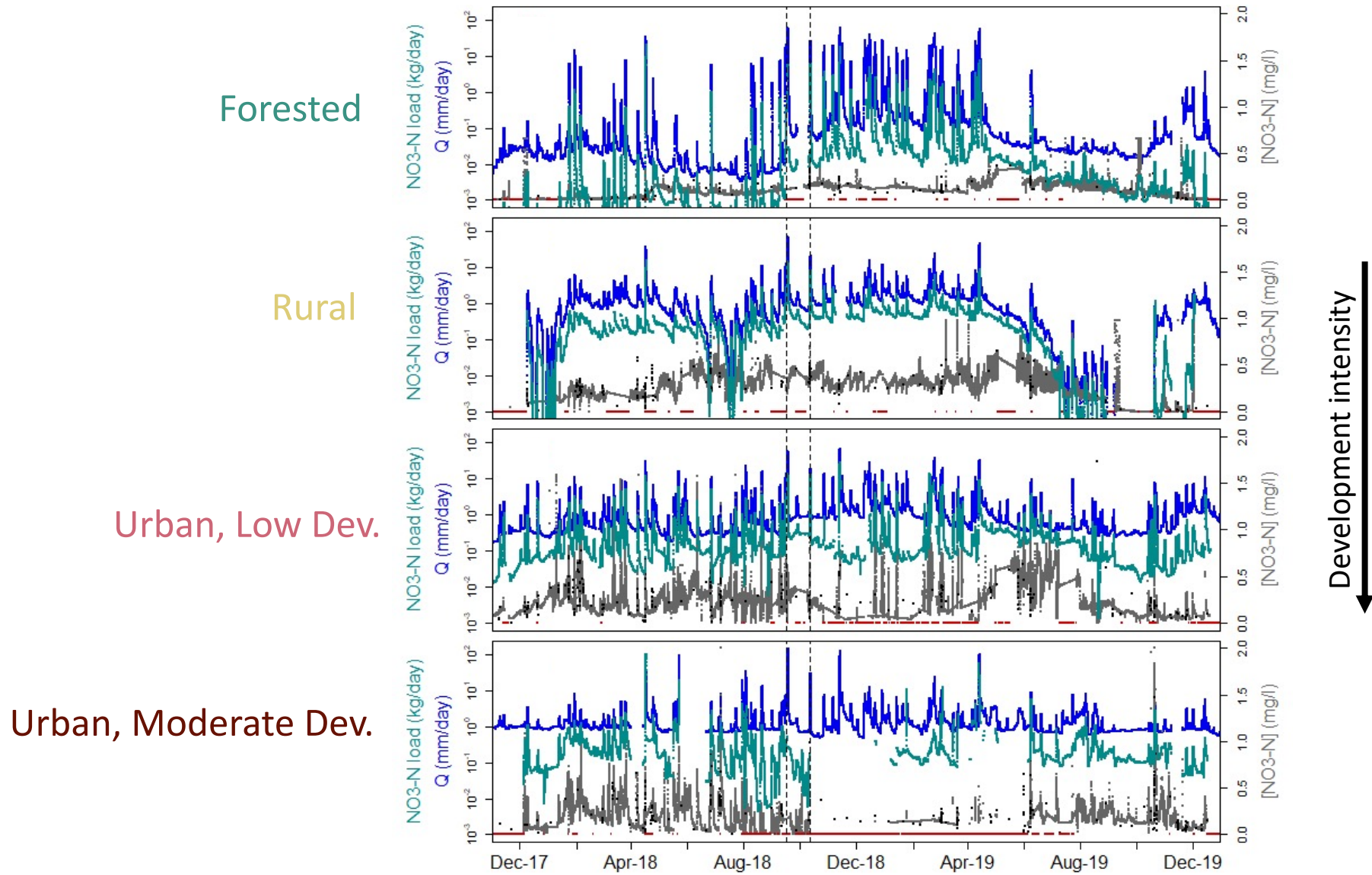
Spectrometer

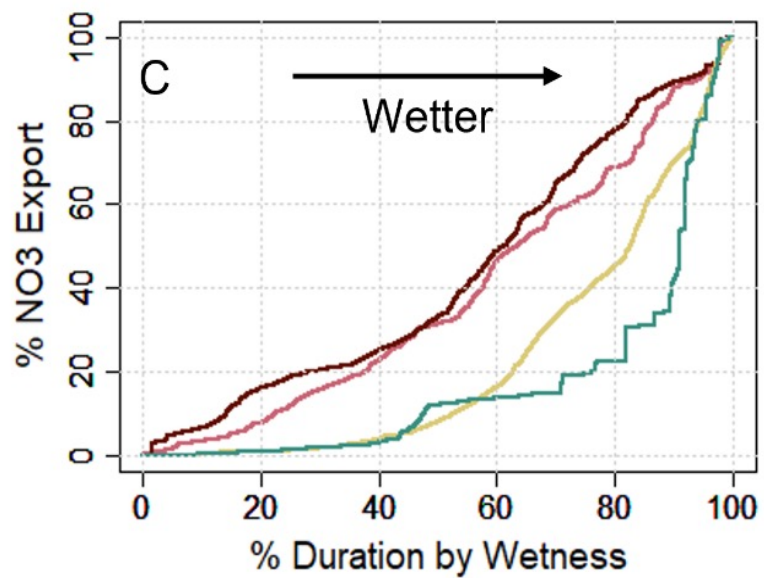
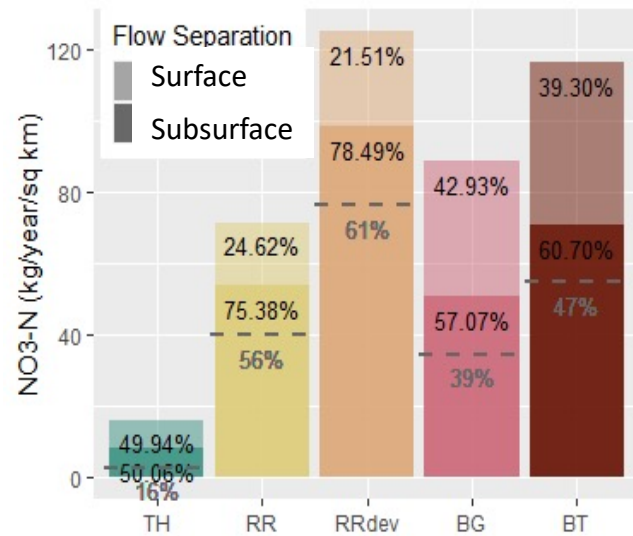
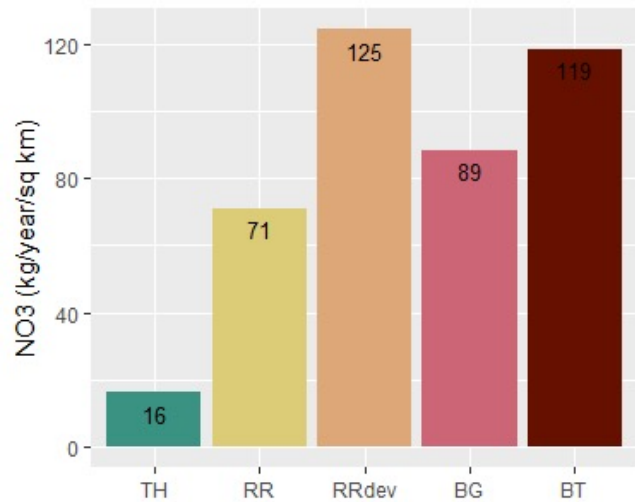
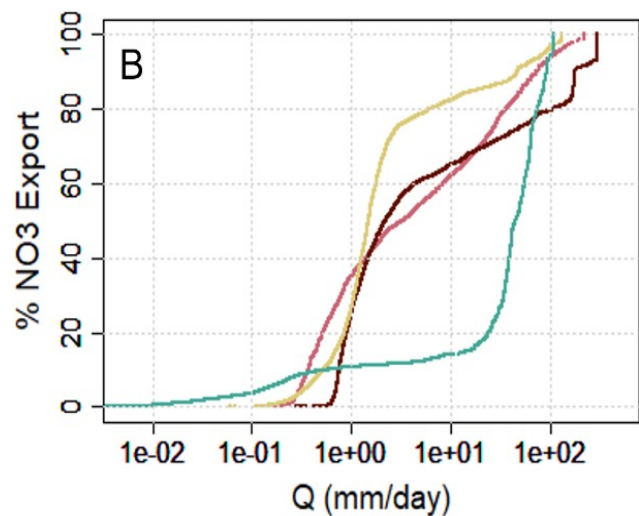
Water Level

Flow Sensor →

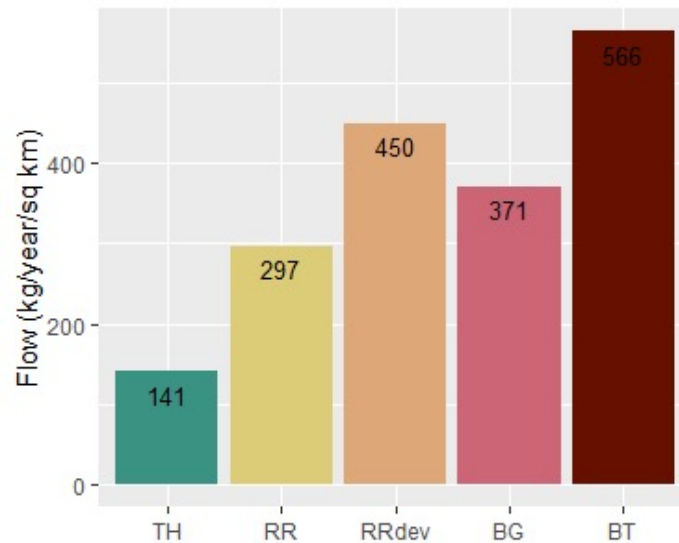
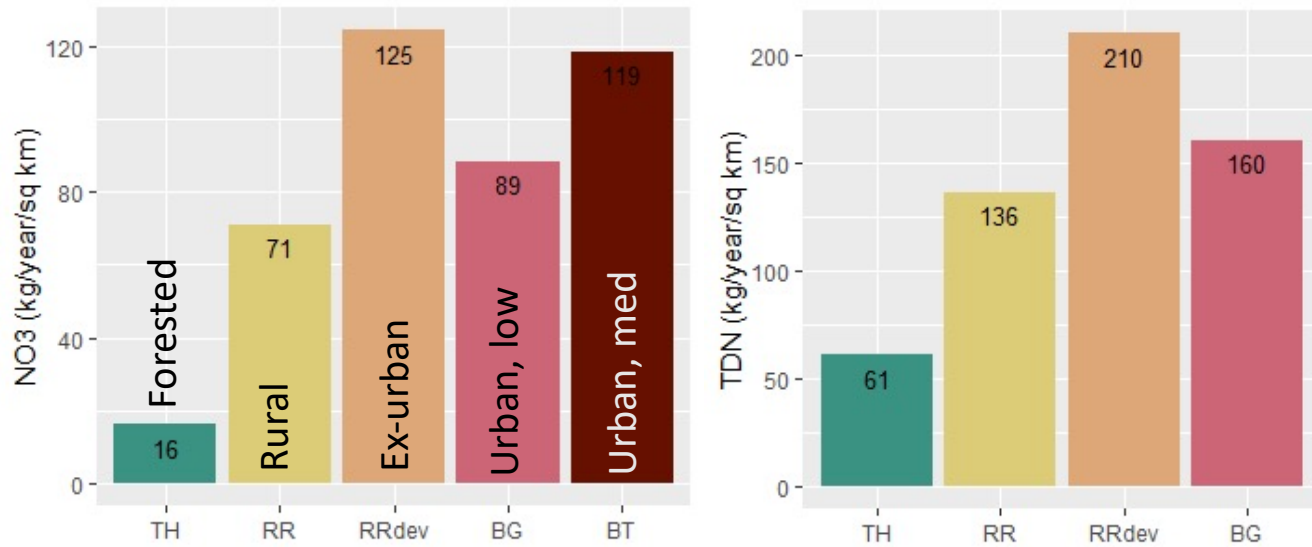


Nitrate concentration and loading timeseries





Total runoff and nitrogen loading

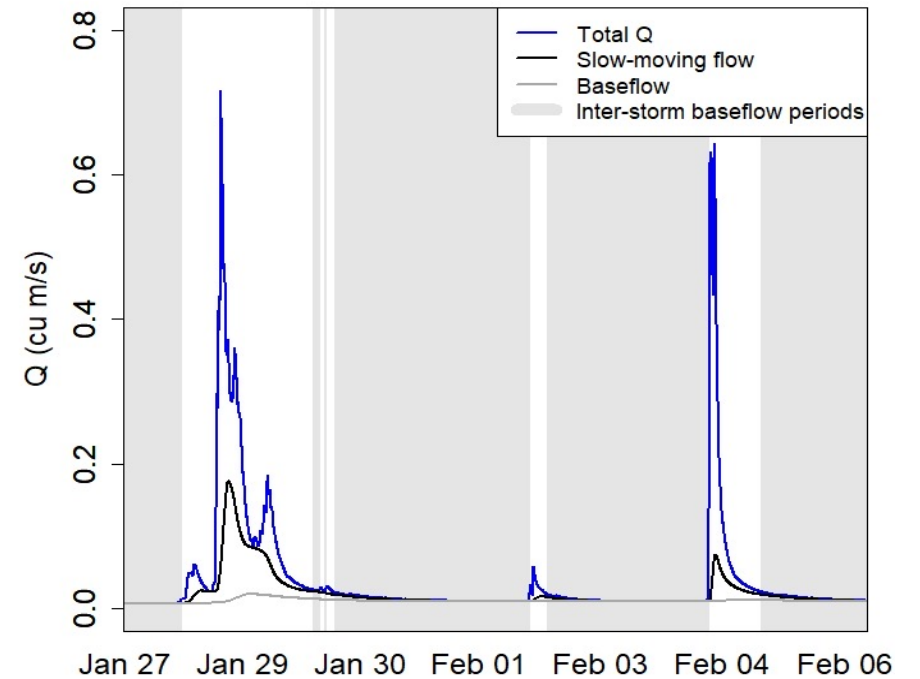


- Nitrogen loading was highest for the septic served ex-urban catchment, but otherwise increased with development intensity
- Total TDN loads are consistent with the Baltimore region (Shields et al., 2008)

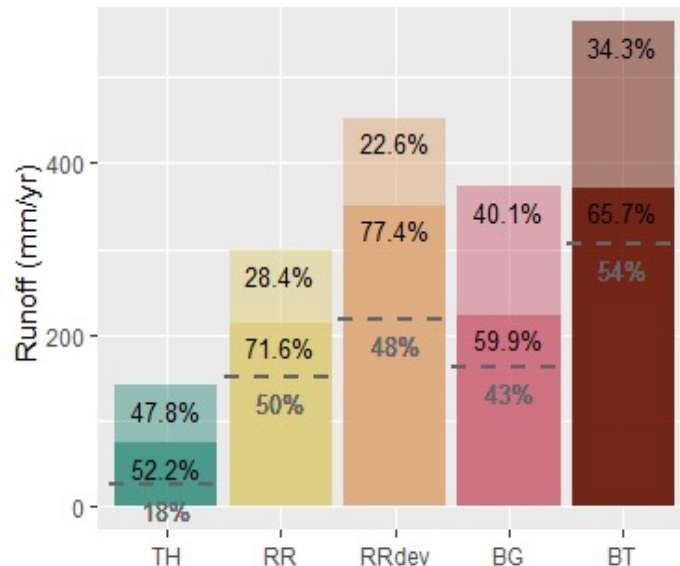
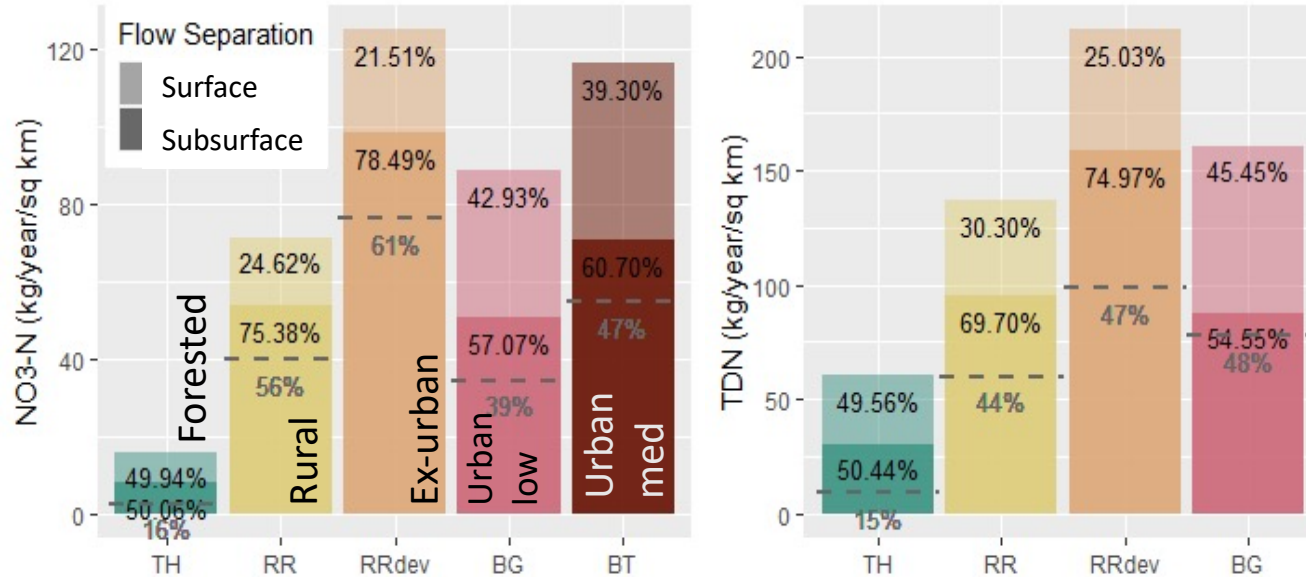
A note on hydrograph separation

- The goal is to differentiate surface from subsurface flow
- Two graphical flow separation estimates
 - An estimate of baseflow and subsurface stormflow
 - A conservative baseflow estimate with little event scale variation

Example hydrograph separation



Total runoff and nitrogen loading split by estimated flow path

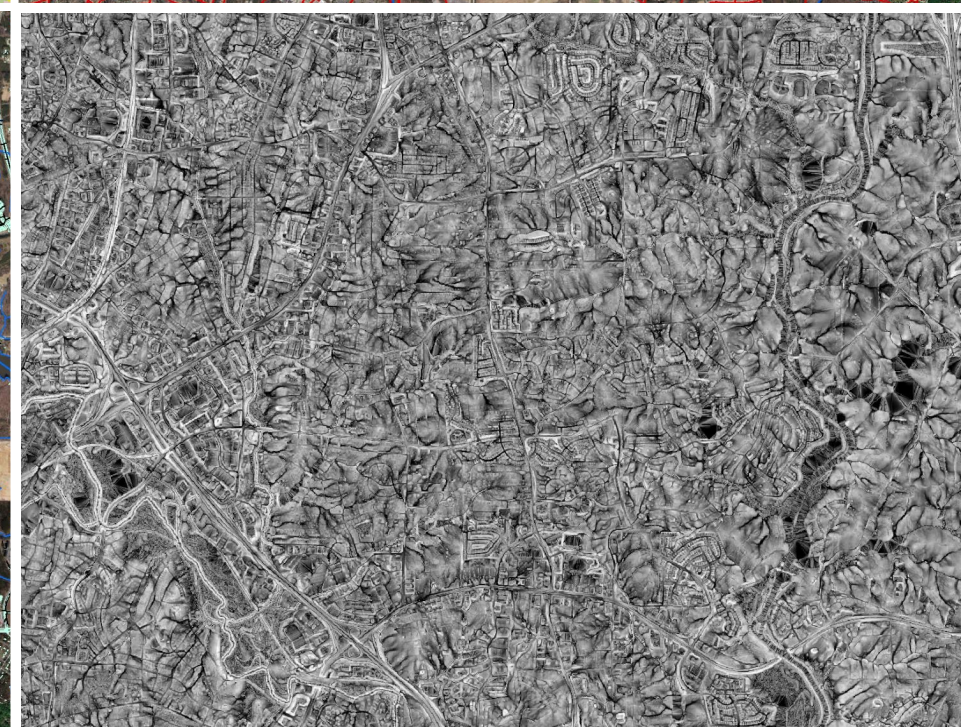
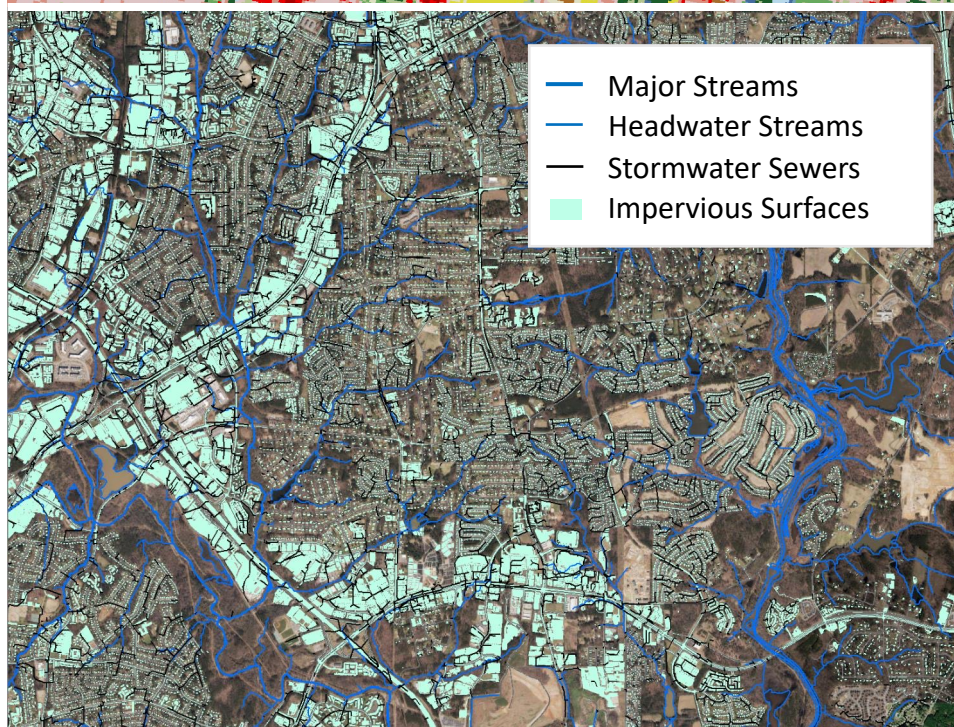
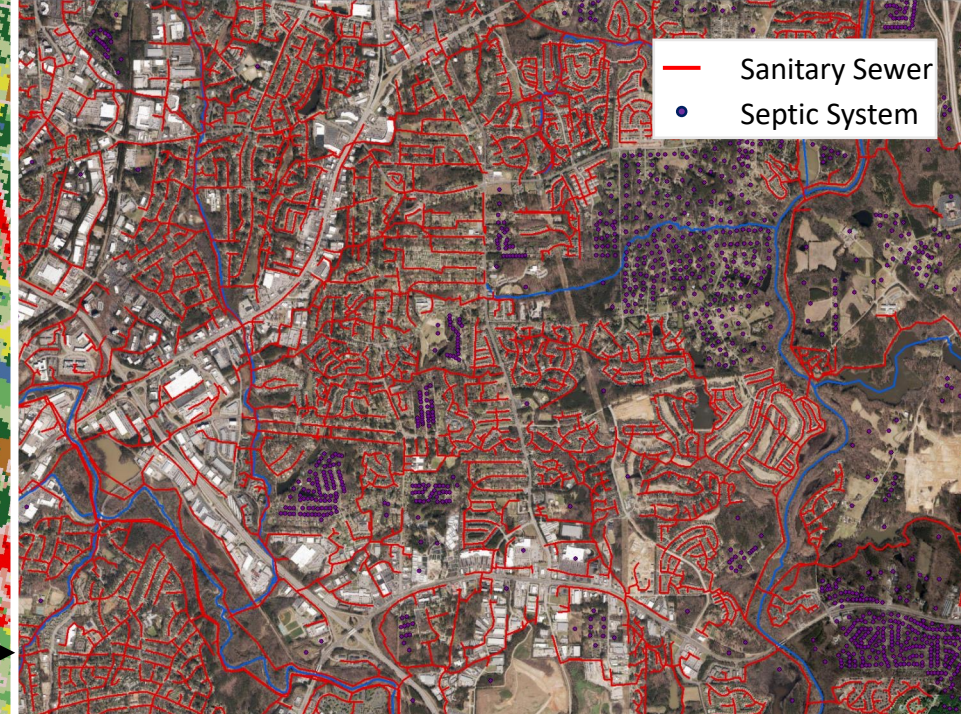
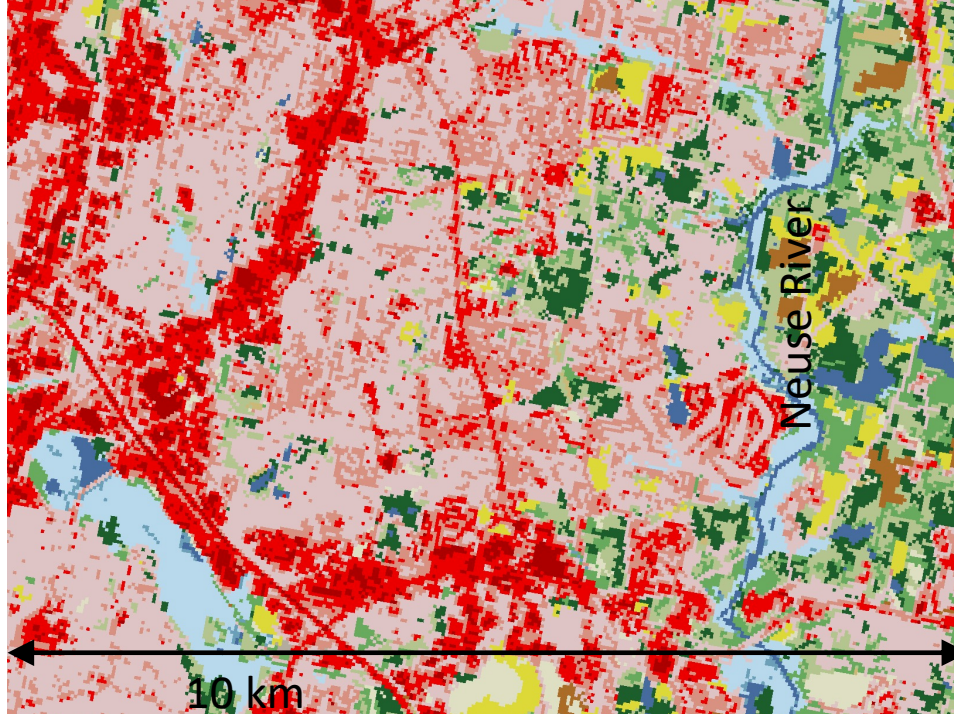


- Subsurface flow made up a large proportion of the total nitrogen loading, even for the most developed study catchment
- This is true using even the conservative estimate of baseflow

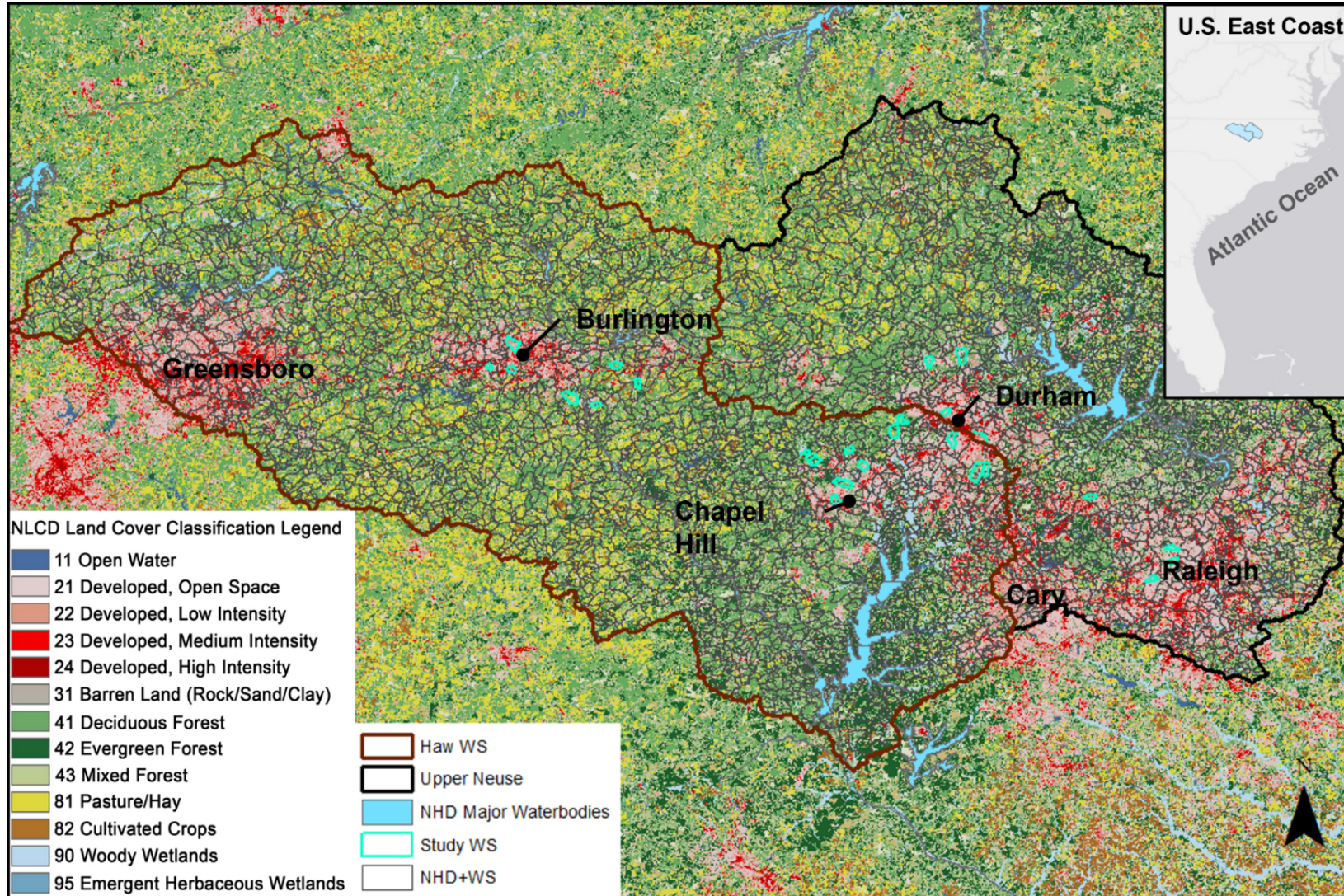
Baseflow nitrogen loading:

What are the primary sources of nonpoint source nitrogen loading to streams along the exurban-urban gradient?

What landscape features control nitrogen loading in developed watersheds? **Where is nitrogen coming from?**



To investigate nonpoint source baseflow nitrogen loading:

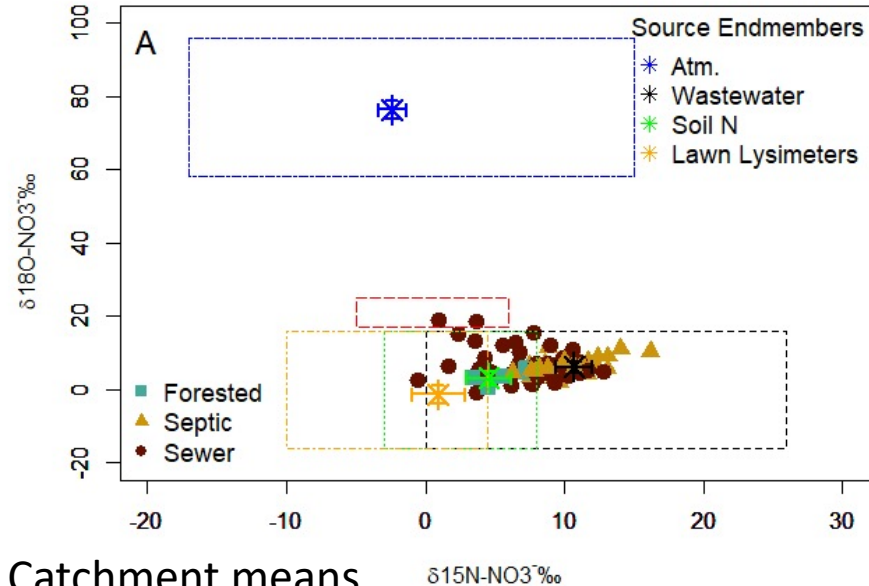


- Selected 27 NHD+ scale catchments which represent the regional distribution of metrics of landcover, infrastructure, and population
- 13 catchments were sampled for isotopic nitrate analysis, 1 primarily forested, 6 septic served, and 6 sewer served
- Catchments were sampled at baseflow every other week with between 1 and 5 years of data

Delesantro, J. M., Duncan, J. M., Riveros-Iregui, D., Blaszcak, J. R., Bernhardt, E. S., Urban, D. L., & Band, L. E. (2022). The Nonpoint Sources and Transport of Baseflow Nitrogen Loading Across a Developed Rural-Urban Gradient. *Water Resources Research*, 58(7), 1–25.
<https://doi.org/10.1029/2021WR031533>

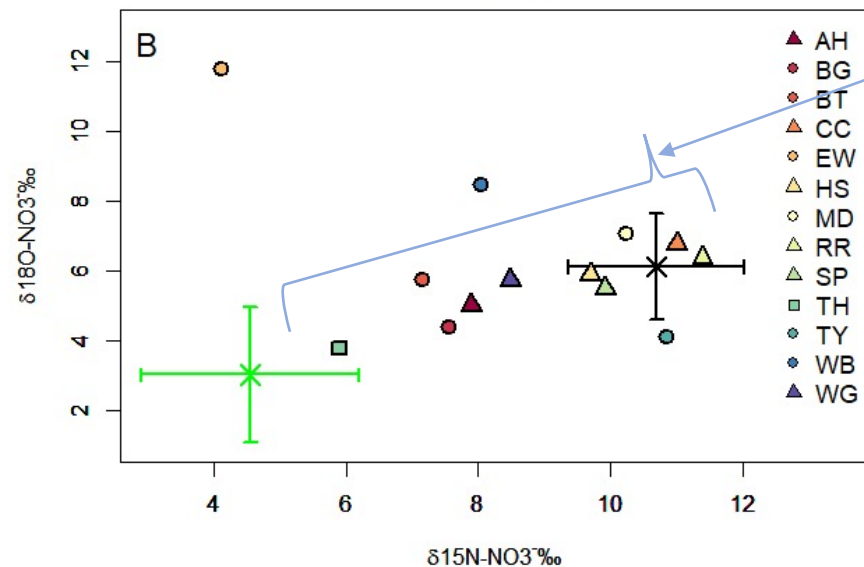
What are the primary baseflow sources?

All sampling



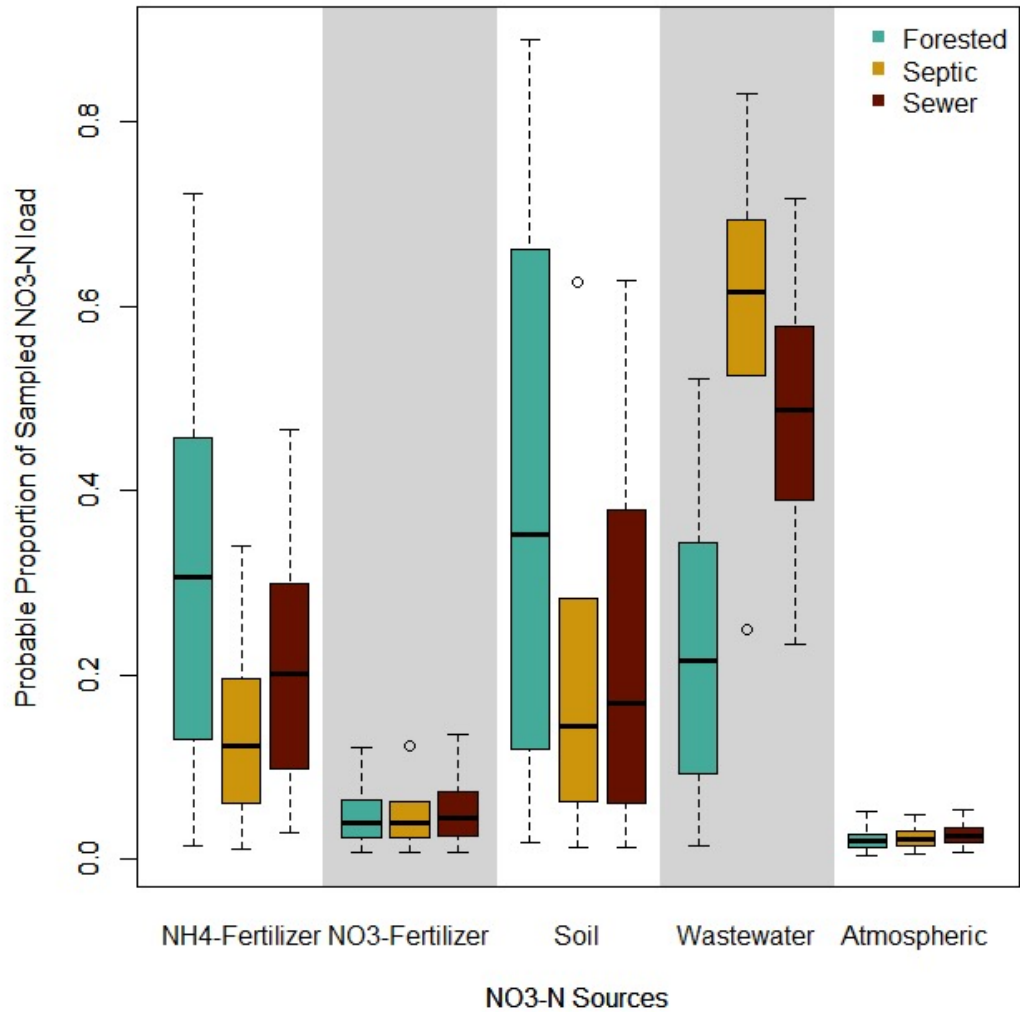
- Nitrate made up 73% of total dissolved nitrogen
- Most of the sampled isotopic nitrate values were within the literature range for wastewater and clustered around our wastewater endmember sampling
- Mean catchment values generally clustered around the wastewater endmember or along the wastewater-soil N mixing line

Catchment means



The source regions (A) are from: Kendall, C., Elliott, E. M., & Wankel, S. D. (2008). Tracing Anthropogenic Inputs of Nitrogen to Ecosystems. *Stable Isotopes in Ecology and Environmental Science: Second Edition*, 375–449.

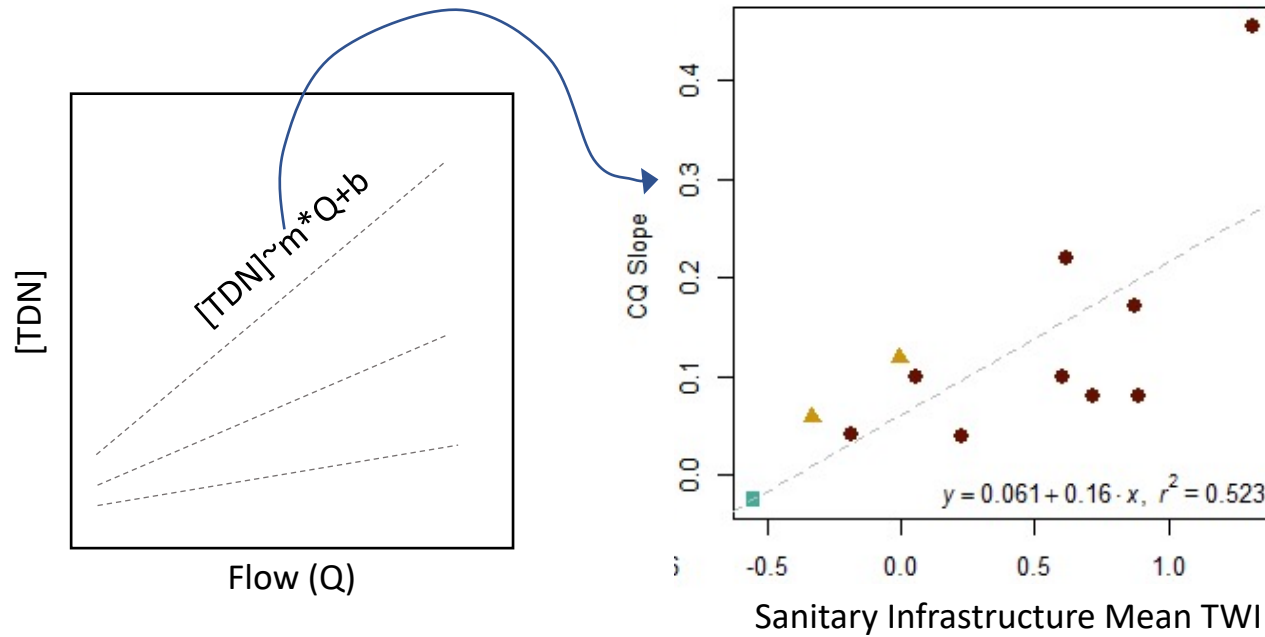
What are the primary sources?



Probability distribution estimates of NO₃⁻ sources proportions by mass

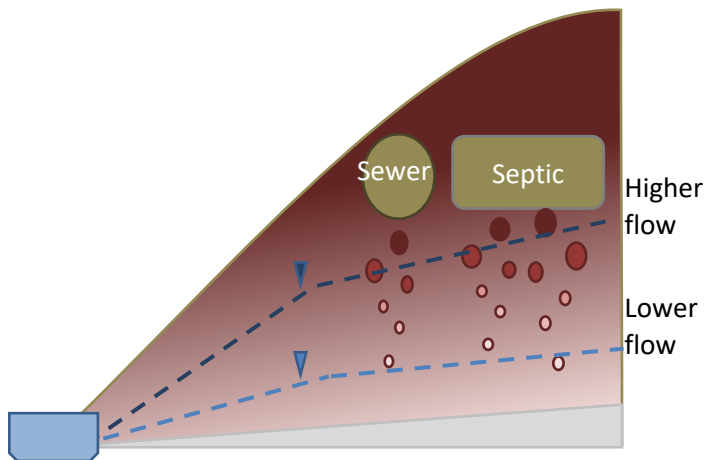
- Uses a Bayesian approach to solve mixing equations and reflect uncertainty
- Wastewater was the probable primary source for both septic and sanitary sewer served catchments

How is baseflow nitrogen transported?

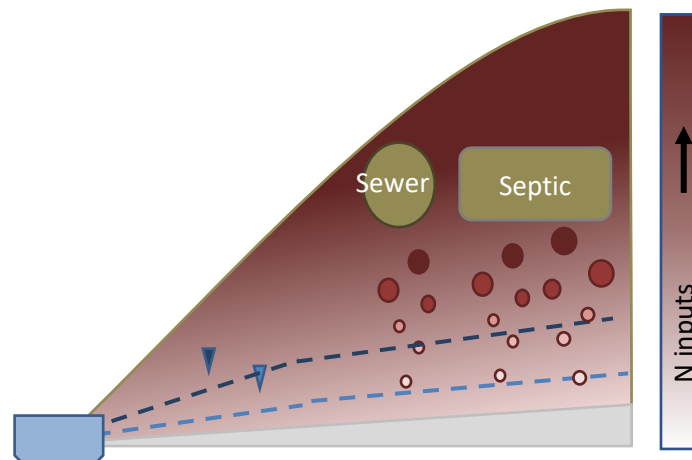


- All significant linear concentration-discharge (CQ) relationships were positive for developed catchments
- The catchment CQ slope was well predicted by the hydrogeomorphic position of sanitary infrastructure
- This suggests that nitrogen from sanitary infrastructure in wet locations, was more readily transported by increases in water tables, than nitrogen from sanitary infrastructure in dry locations

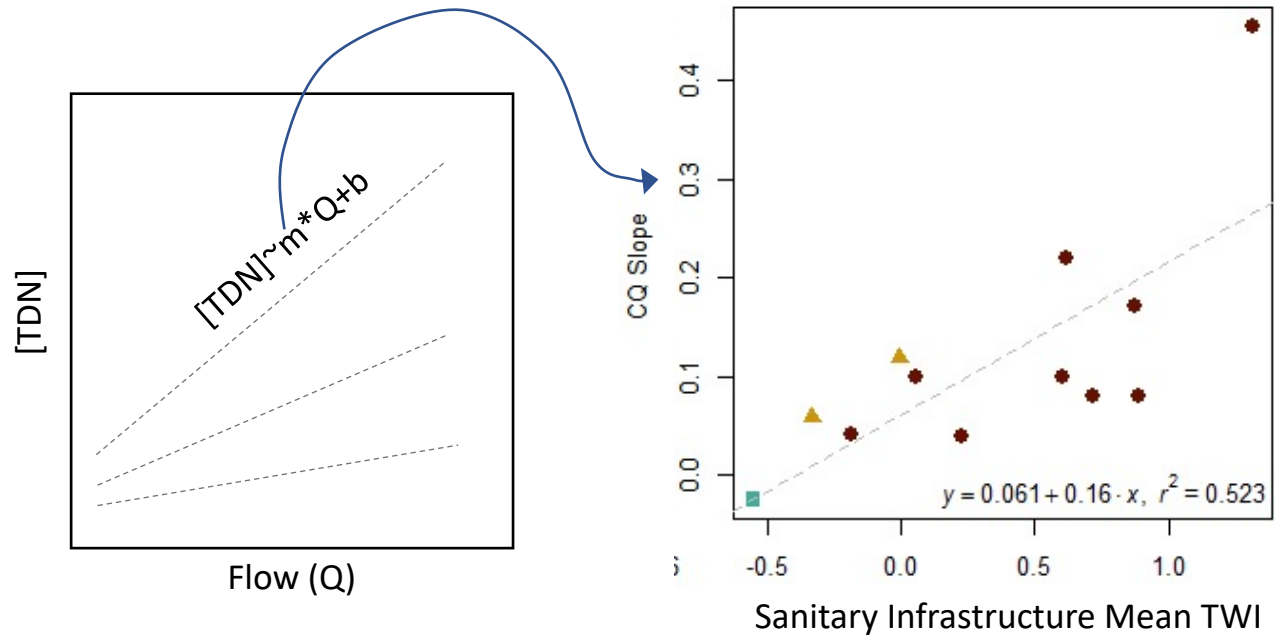
Wet Hydrogeomorphic Position



Dry Hydrogeomorphic Position

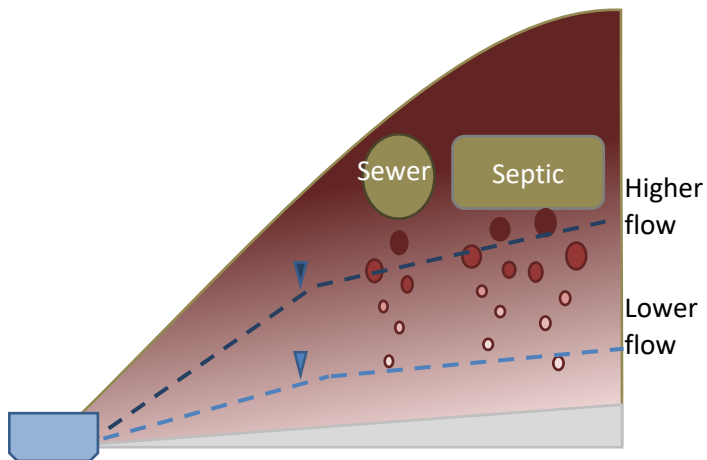


How is baseflow nitrogen transported?

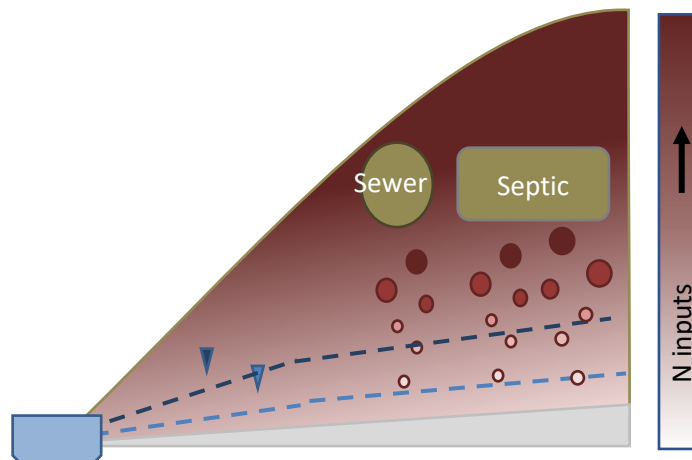


- Wastewater was the primary source of baseflow nitrogen across developed catchments
- Subsurface N was abundant, and export was transport limited
- The position of sanitary infrastructure within the terrestrial flow field largely governed loading

Wet Hydrogeomorphic Position

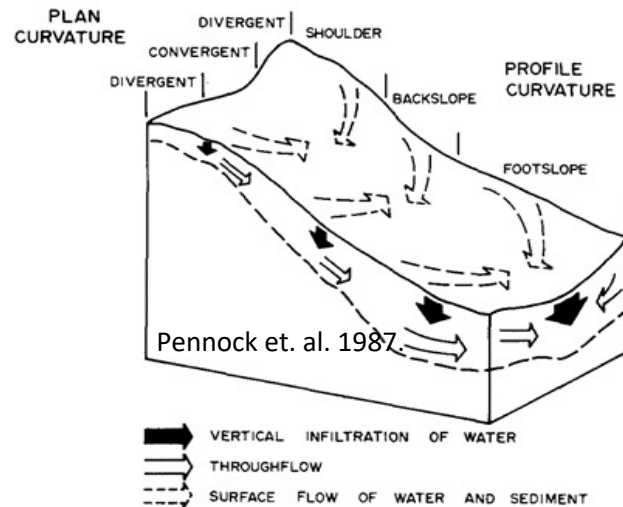


Dry Hydrogeomorphic Position



What landscape features control nitrogen loading?

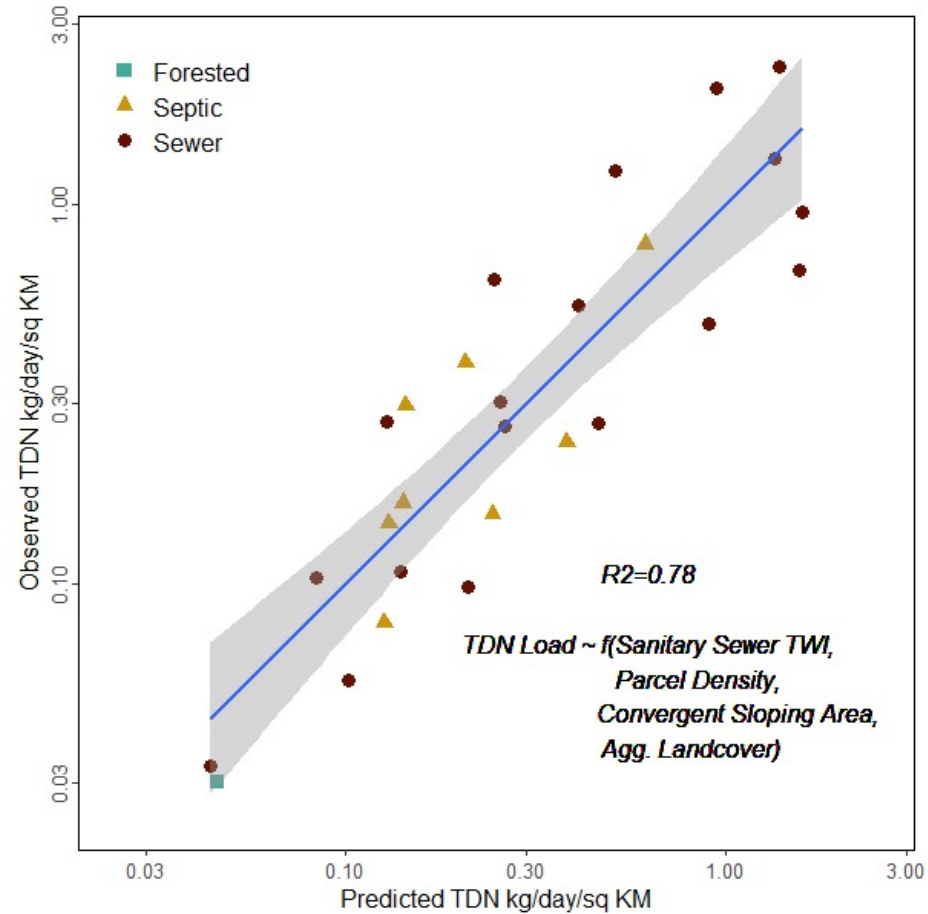
Best landscape predictors of baseflow TDN loading		
	TDN (kg/sq km)	
	R ²	effect
Hydrogeomorphic position		
Sewer TWI (median)		0.41+
Sanitary TWI		0.39+
Topography		
Convergent area		0.27+
Footslope area		0.26+
Population		
Parcel Density		0.25+



- Wastewater was the primary source of baseflow nitrogen across developed catchments
- Subsurface N was abundant, and export was transport limited
- The position of sanitary infrastructure within the terrestrial flow field largely governed loading
- The topographic wetness of the location of sanitary infrastructure was the best predictor of baseflow nitrogen loading

**N loading ~ f(Population (supply),
 Hydrogeomorphic position of N pools,
 Geologic and topographic properties)**

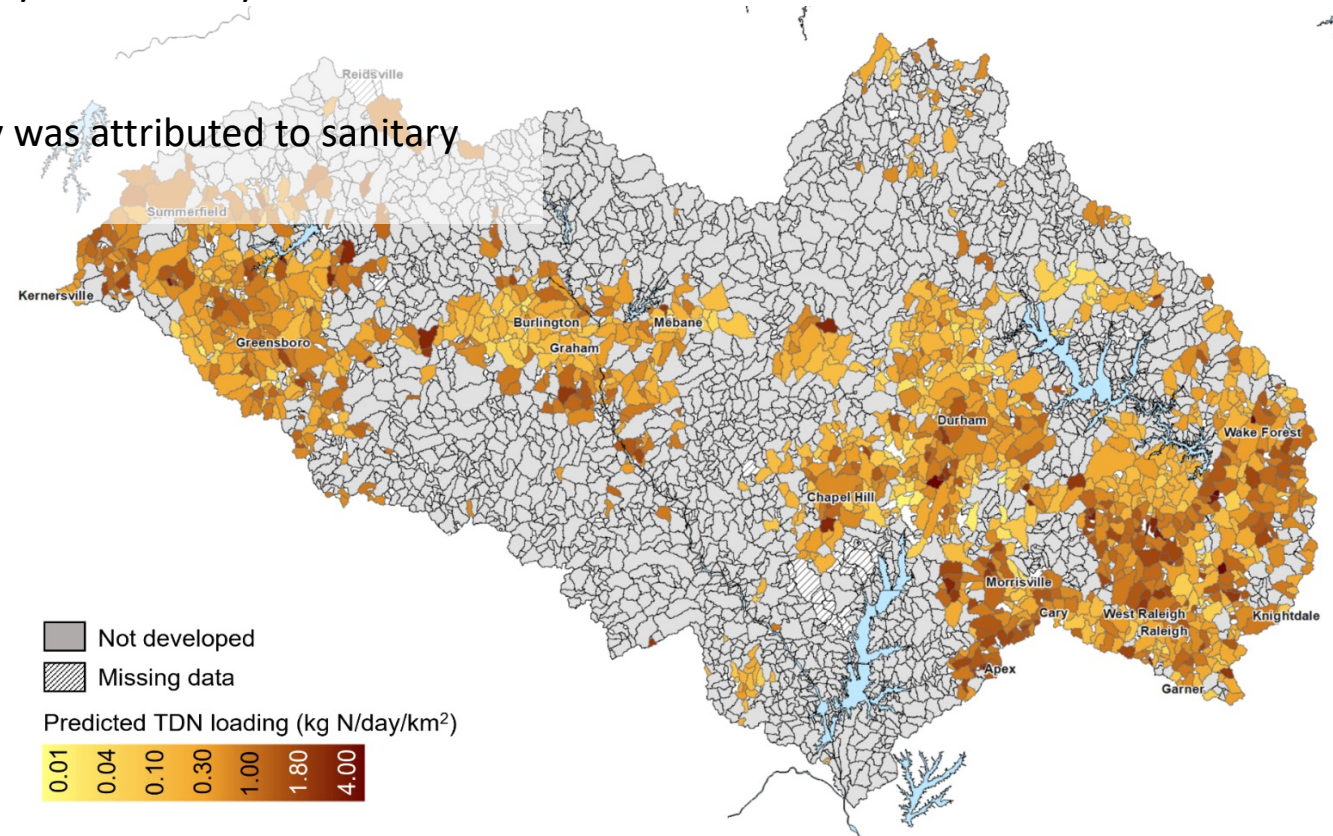
Conceptually informed, parsimonious empirical model




Parameter	Estimate	Std Error	p
Convergent landform	0.0772	0.0179	0.0002
Parcel Dens	0.0029	0.0006	0.0001
Sewer TWI	1.0353	0.3316	0.0049
NLCD Agg	0.0816	0.0197	0.0004
Intercept	-5.137	0.5511	4.27E-09

- Wastewater was the primary source of baseflow nitrogen across developed catchments
- Subsurface N was abundant, and export was transport limited
- The position of sanitary infrastructure within the terrestrial flow field largely governed loading
- The topographic wetness of the location of sanitary infrastructure was the best predictor of baseflow N loading
- We generate an empirical model which describes 78% of baseflow N loading

- In and around the lowest population density cities agricultural land-use and convergent sloping land area were large drivers of spatial variation in baseflow loading
- While across most sub catchments, population density and sanitary infrastructure placement drove spatial variation
- We estimate that 39% of baseflow loading regionally was attributed to sanitary infrastructure in wet areas of the landscape



Delesantro, J. M., Duncan, J. M., Riveros-Iregui, D., Blaszcak, J. R., Bernhardt, E. S., Urban, D. L., & Band, L. E. (2022). The Nonpoint Sources and Transport of Baseflow Nitrogen Loading Across a Developed Rural-Urban Gradient. *Water Resources Research*, 58(7), 1–25. <https://doi.org/10.1029/2021WR031533>



How is nitrogen transported to streams in developed watersheds?

- Baseflow and subsurface flows contributes most N loading across the most common low and moderate development intensity landscapes.
- Subsurface N, originating from wastewater, is abundant and the position of sanitary infrastructure within the terrestrial flow field largely governs loading.

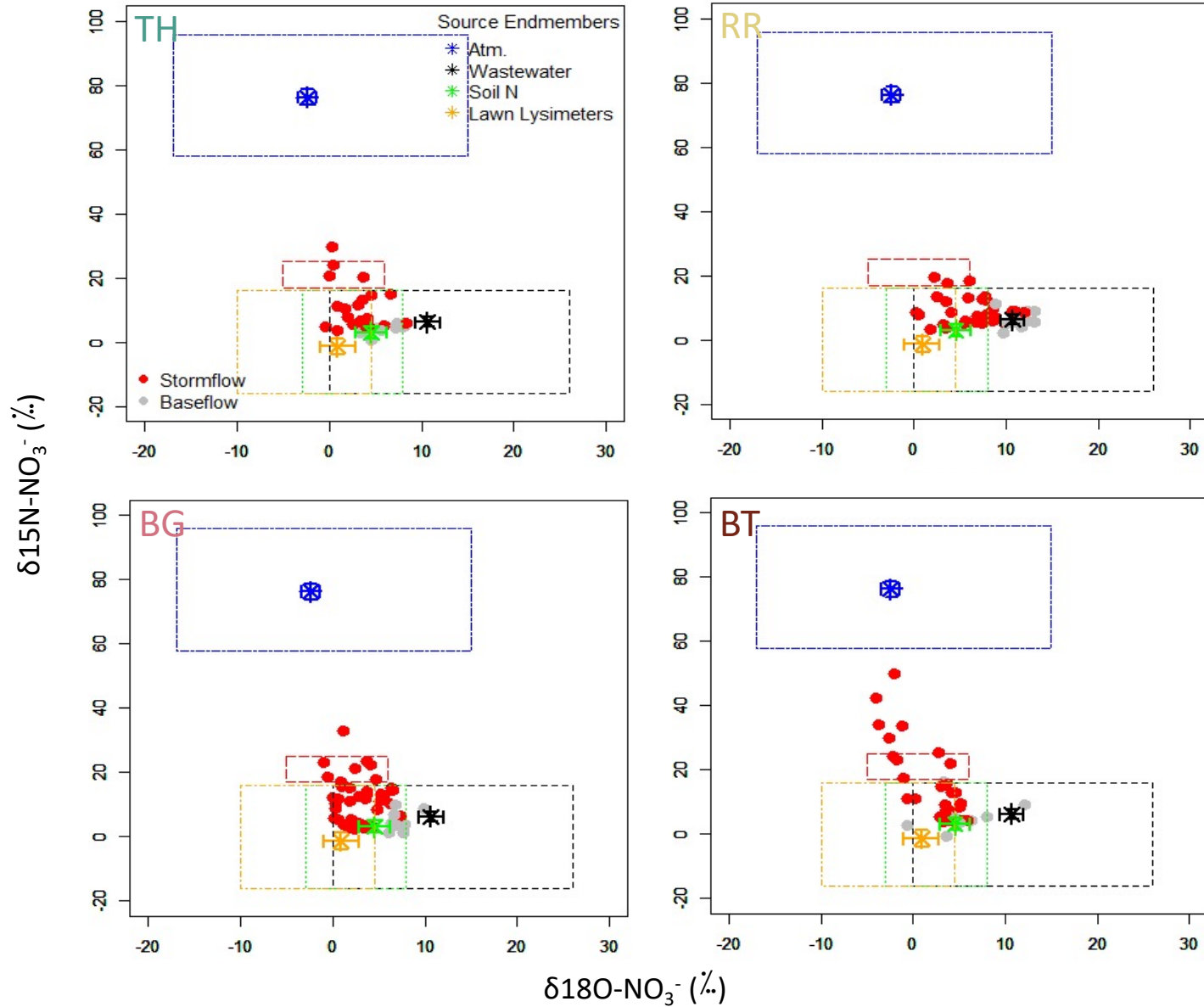
Management implications

- The current paradigm of focusing urban watershed management on surface sources and surface flow paths may only be valid for the most heavily developed catchments.
- To manage the most common exurban, low, and moderate development intensity catchments we will need to focus on subsurface sources by considering the hydrogeomorphology of development and sanitary infrastructure.
- And we can make better use of the longer residence times of subsurface and baseflow transport. This provides strong support for restoration, but we'll to curb peak flows to support restoration and reduce erosion and entrenchment.

I would like to thank Aleah Walsh, and Brooke Hassett for their work in the field, lab, and office and all the dedicated and curious undergraduates who have assisted: Natalie Gauger, Rhyan Stone, Will Hamilton, Lauren Whitenack, Helen Drotor, Tianzhen Nie, Maribel Herrera, Grace Allen, and Meredith Emery.

Questions?

Extra Content



While baseflow NO_3^- is driven by wastewater sources, storm flows mobilized and mixed all potential sources

Among developed catchments, variation and mixing of sources increased with development intensity

There are event scale patterns in source variation which we are currently investigating

Source region data:

Kendall, C., Elliott, E. M., & Wankel, S. D. (2008). Tracing Anthropogenic Inputs of Nitrogen to Ecosystems. *Stable Isotopes in Ecology and Environmental Science: Second Edition*, 375–449.

Lawn lysimeter endmember data:

Kaushal, S. S., Groffman, P. M., Band, L. E., Elliott, E. M., Shields, C. A., & Kendall, C. (2011). Tracking nonpoint source nitrogen pollution in human-impacted watersheds. *Environmental Science and Technology*, 45(19), 8225–8232.

Compositional and Structural Attributes

Features

- Landcover
- Roads
- Stormwater sewers
- Sanitary sewers
- Septic systems
- Population and parcel density
- Geologic basin
- Slope and landforms
- Topographic wetness index
- Streams

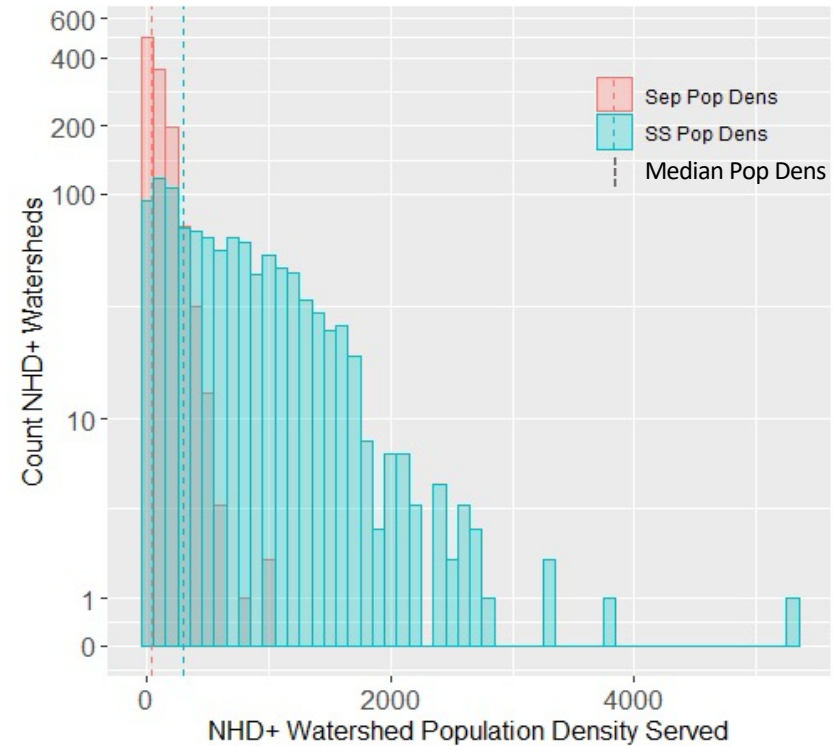
Metrics

- Abundance or coverage
- Density
- Position relative to streams outlets and topographic wetness

Development is largely low density and sanitary infrastructure is a major development consideration

Across the 6975 km² study area:

- 36% of the total area is covered by developed catchments.
- 90% percent of regional population lives in developed catchments
- Median population density was 390 per/km²
- And there is a large overlap in the use of septic and sewers systems encompassing the median population density.
- 68.0% of primarily septic served catchments had septic system densities greater than 50/km² and 18.1% had densities greater than 100/km²



Sanitary sewer are preferentially located near streams

- 40.2% of all sanitary sewer lines were within 200 ft of streams
- 91.1% of the sanitary sewer volume was within 200ft of a stream
- The density of sanitary sewers within the 50ft stream buffer was double that of the catchment density
- Septic systems are slightly preferentially placed on uplands

-
- Sanitary Sewer
 - Septic System

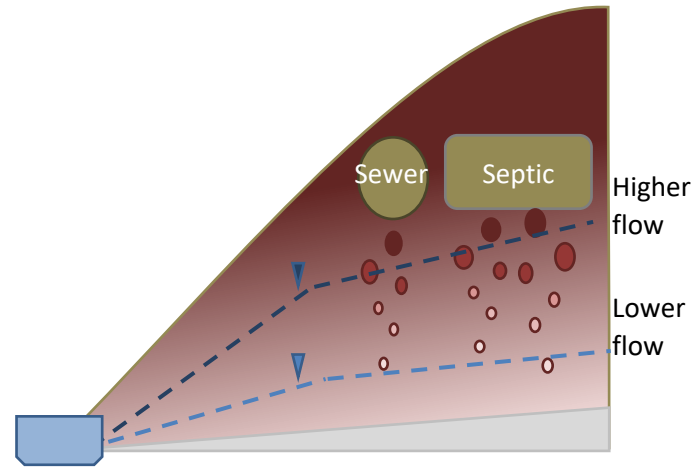
10 km

What landscape features control nitrogen loading?

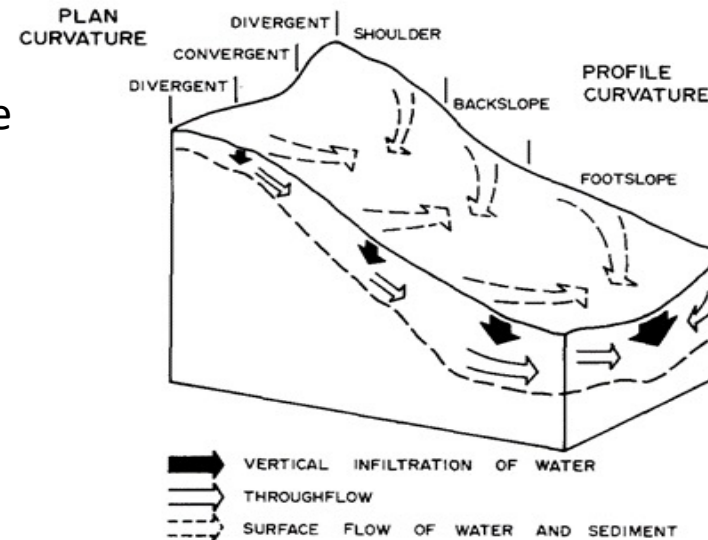
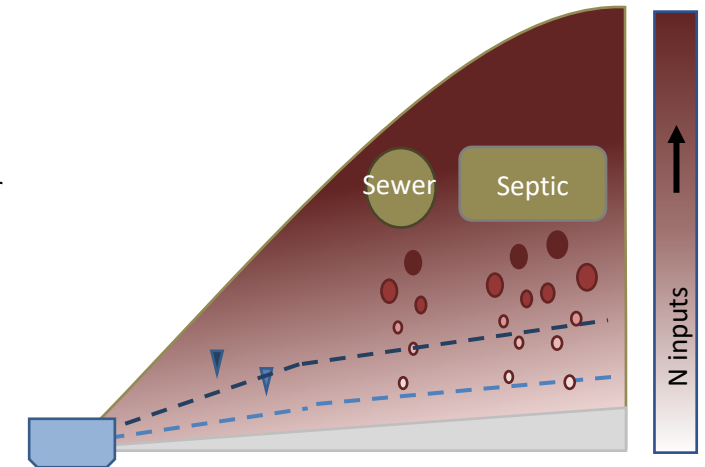
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Topography		
Convergent area	0.27+	
Footslope area	0.26+	
Population		
Parcel Density	0.25+	

- Household density, representing N wastewater source
- Sanitary infrastructure hydrogeomorphic position, representing hydrologic connectivity of the primary source
- Convergent sloping topographic area, representing areas of greater saturation and potentially baseflow generation

Wet Hydrogeomorphic Position



Dry Hydrogeomorphic Position

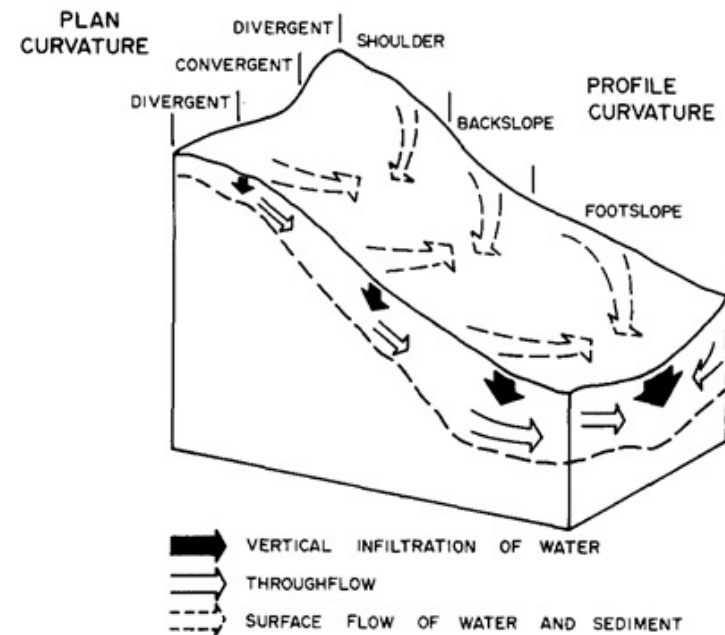
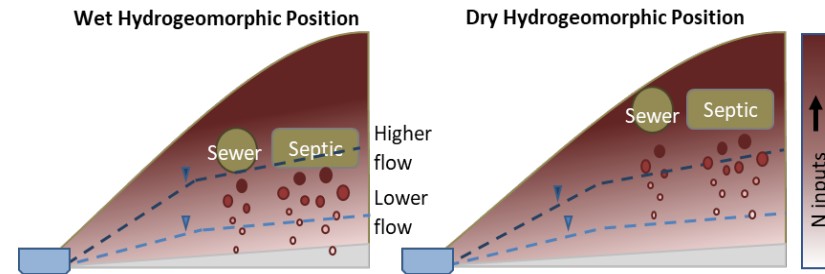


Pennock, D. J., Zebarth, B. J., & De Jong, E. (1987). Landform classification and soil distribution in hummocky terrain, Saskatchewan, Canada. *Geoderma*, 40(3-4), 297-315. [https://doi.org/10.1016/0016-7061\(87\)90040-1](https://doi.org/10.1016/0016-7061(87)90040-1)

Conceptually informed, parsimonious empirical model

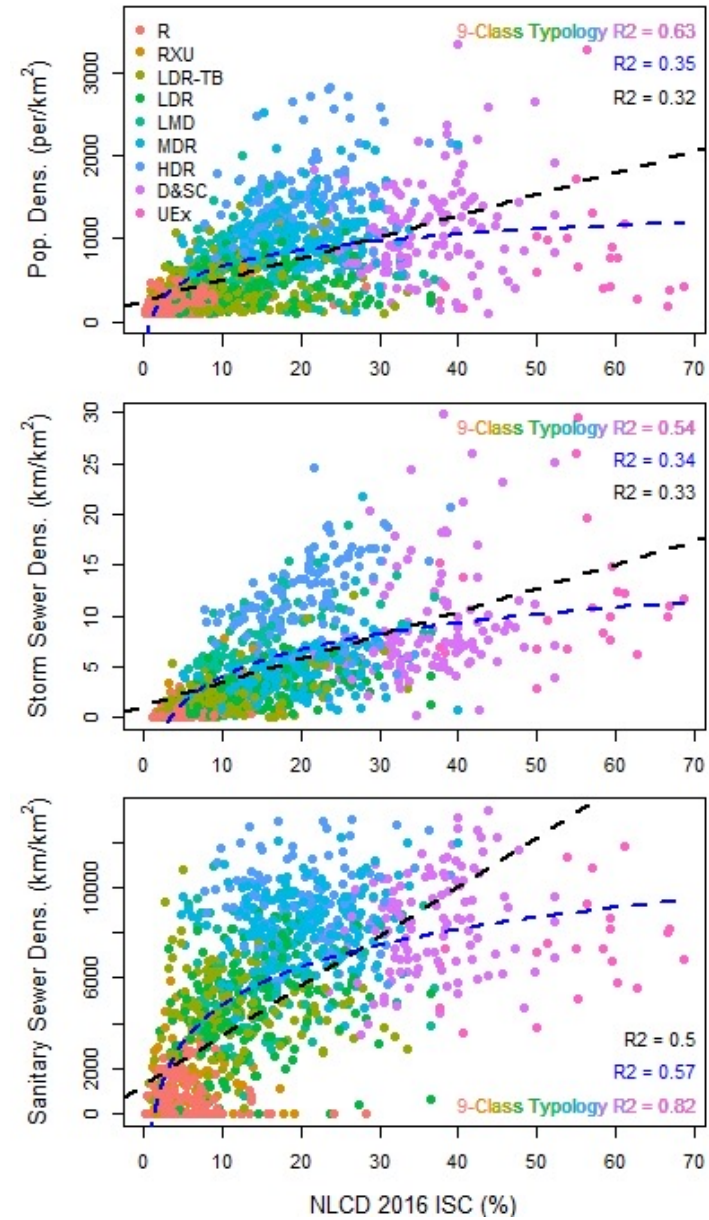
N load ~ f(Population (supply),
Hydrogeomorphic position of N pools,
Geologic and topographic properties)

Landscape predictors of log normalized baseflow TDN loading	
	TDN (kg/sq km)
	R ² effect
Hydrogeomorphic position	
Sewer TWI (median)	0.41+
Sanitary TWI	0.39+
Sanitary Flow Distance to Stream	0.21-
Topography	
Covergent area	0.27+
Footslope area	0.26+
Level area	0.21-
Shoulder area	0.21+
Median TWI	0.24-
Median Slope	0.17+
Buf200_Slope_Avg	0.17+
Population	
Parcel Density	0.25+
Buf50Parcel_Dens	0.22+
Pop. Density	0.15+
Developed Landscape Features	
SW Pipe Density	0.26+
SS Density	0.16+
SS pop Dens	0.16+
Road Density	0.16+
Road Density Buffer, 50ft	0.21+
Non-engineered Landscape Features	
Stream Density	0.22+



Pennock et. al. 1987.

Landcover and ISC poorly predicts other important urban landscape features important to runoff and water quality relative to our 9-class typology



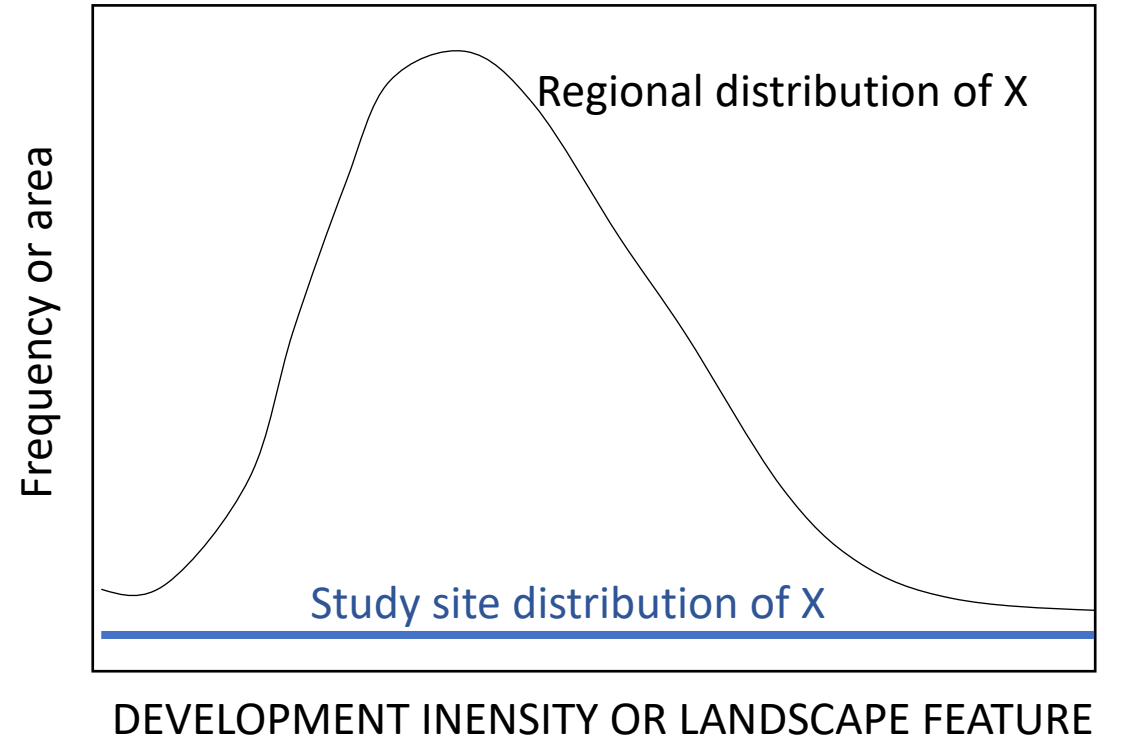
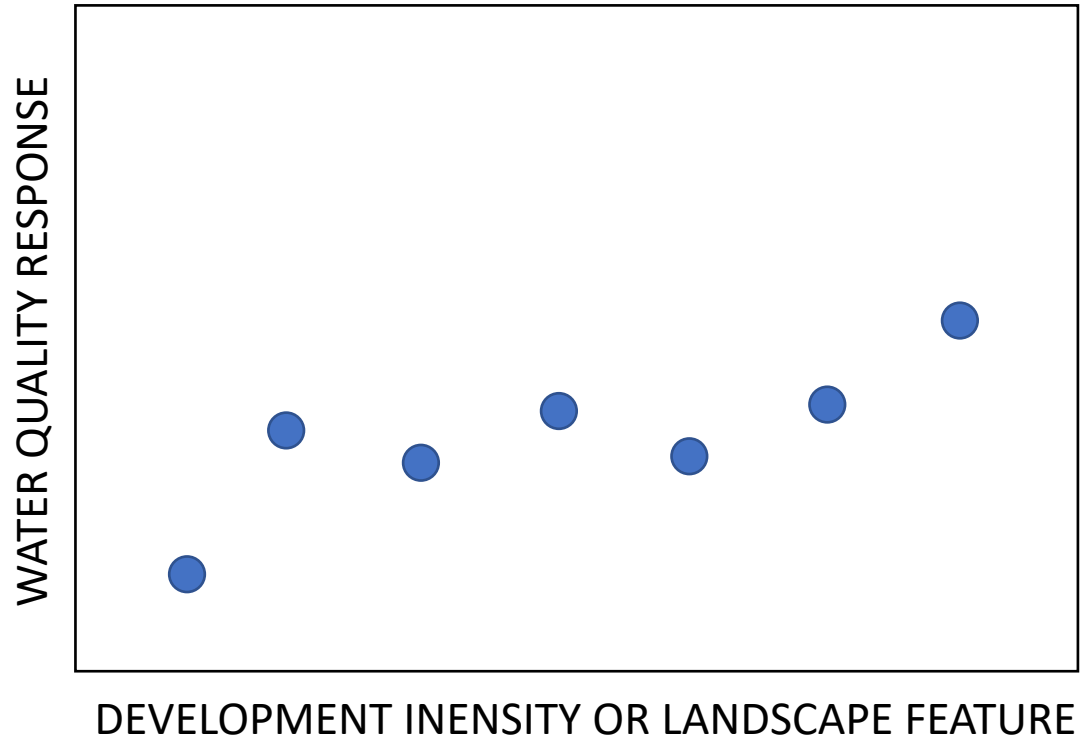
How does monitoring methodology effect estimates of total loading?

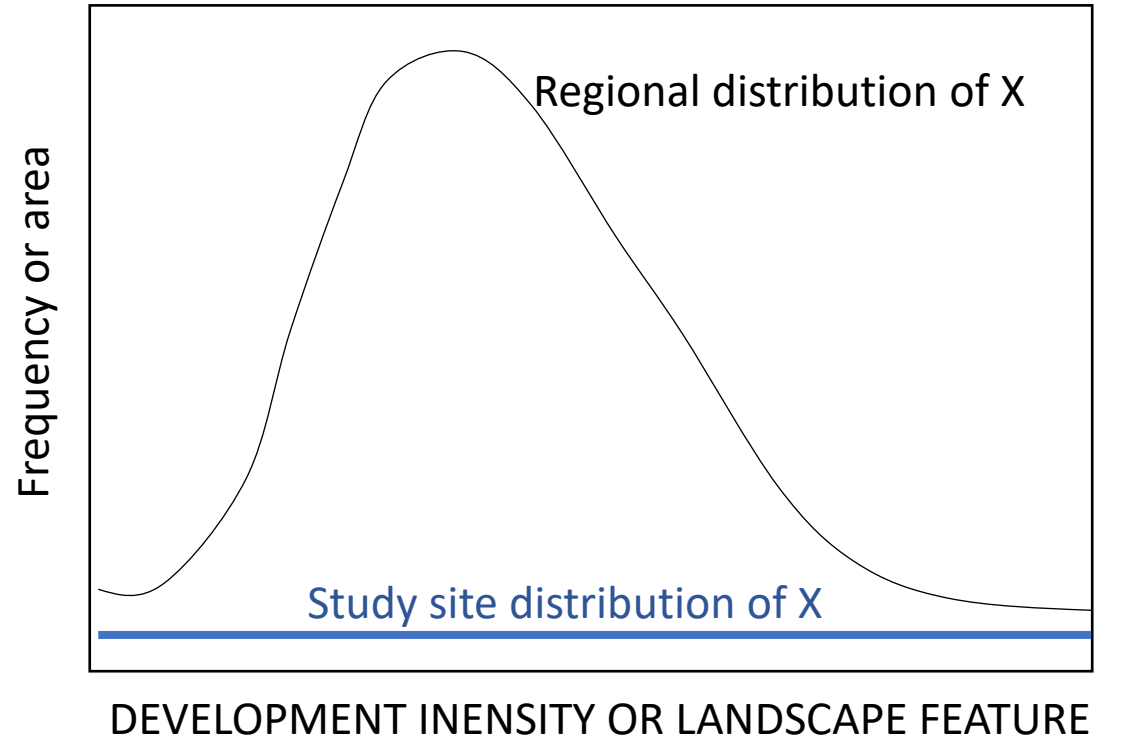
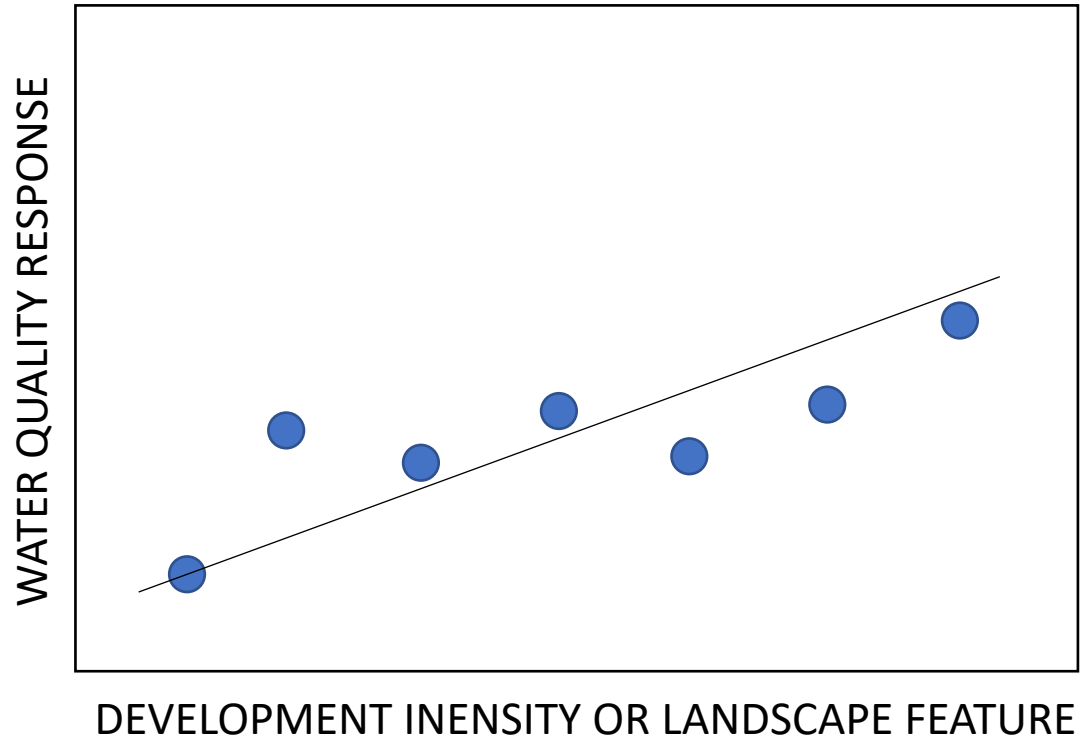
Sensor estimated concentration explained greater than 84% of the variation in N concentration across catchments.

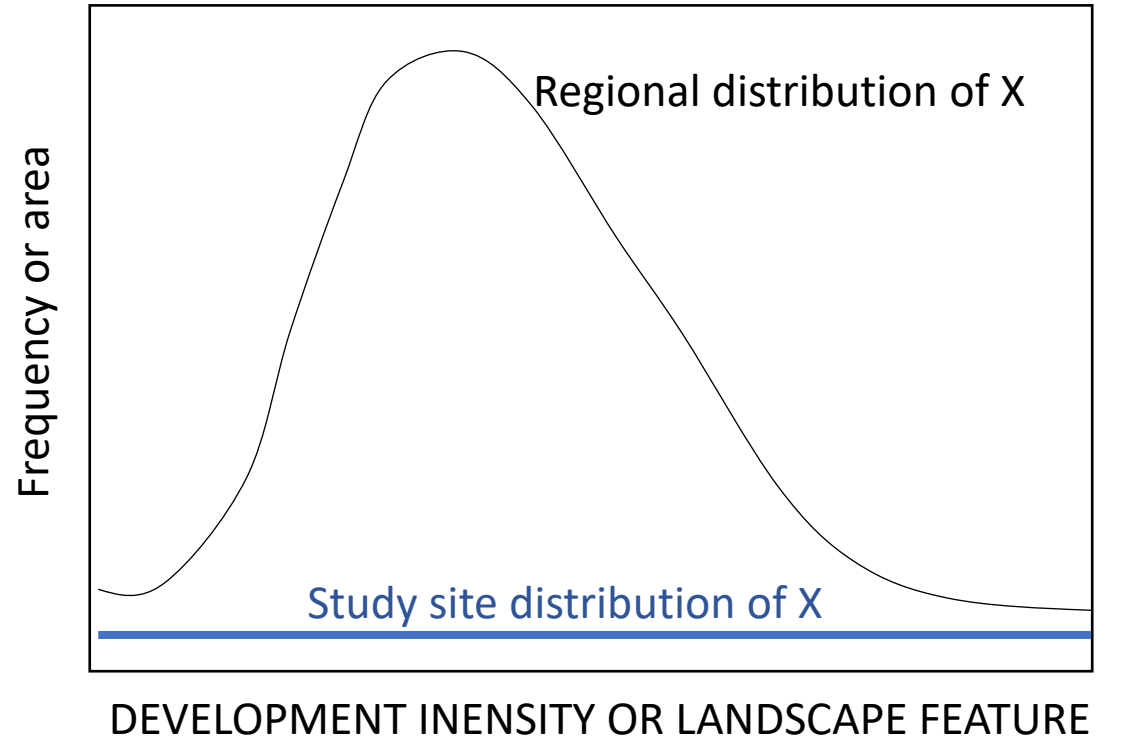
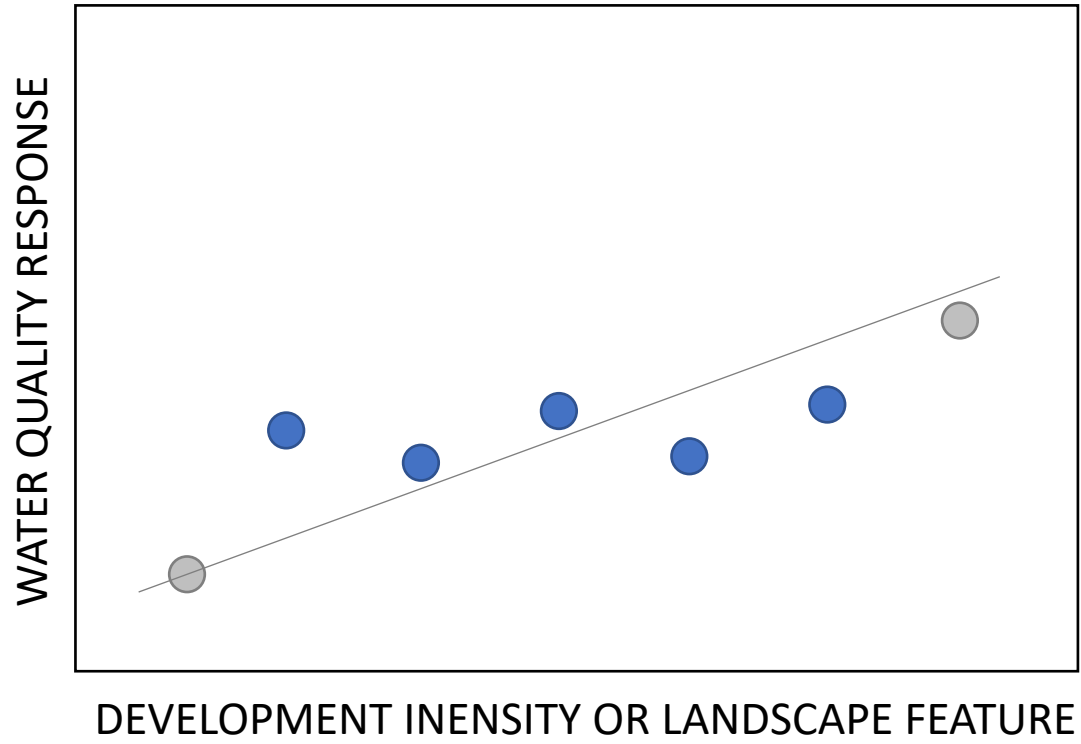
Seasonal concentration-discharge relationship based on discrete stream samples explained less than 37.7% of variation in concentration across study catchments and solutes.

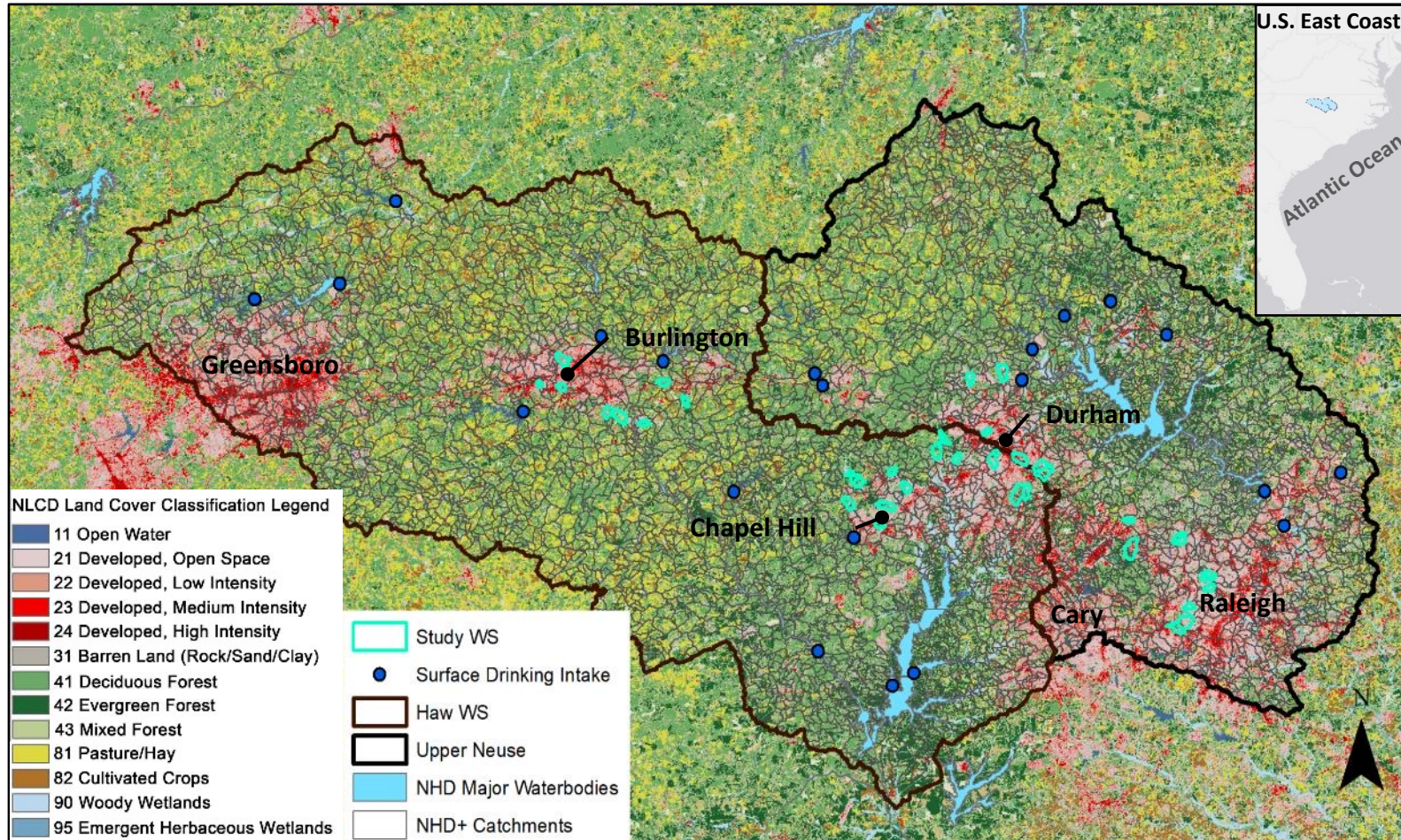
Annual loading estimates based on seasonal discharge-concentration relationships varied widely from estimates obtained from high frequency monitoring (-19.16% to 33.41%) for all catchments except RR.

Our sampling resulted in 227-383 samples per catchment, but most studies rely on far fewer samples to build concentration-discharge relationships. We randomly down sampled our dataset to 150 and 100 samples per catchment, consistent with previous studies. Seasonal concentration-discharge regression-based estimates of total loading again varied widely from the high frequency measurements across catchments, -16.92% to 46.18% for 150 samples and -39.4% to 99.7% for 100 samples. Seasonal concentration-discharge relationships were also not statistically significant for the moderate development BT catchment using only 100 samples.









Our monitoring...

- Captures both the range and median of potential drivers
- Approximates the distribution such that our study catchments represent regional development
- And as a result, focus on generally low to moderate development intensity catchments

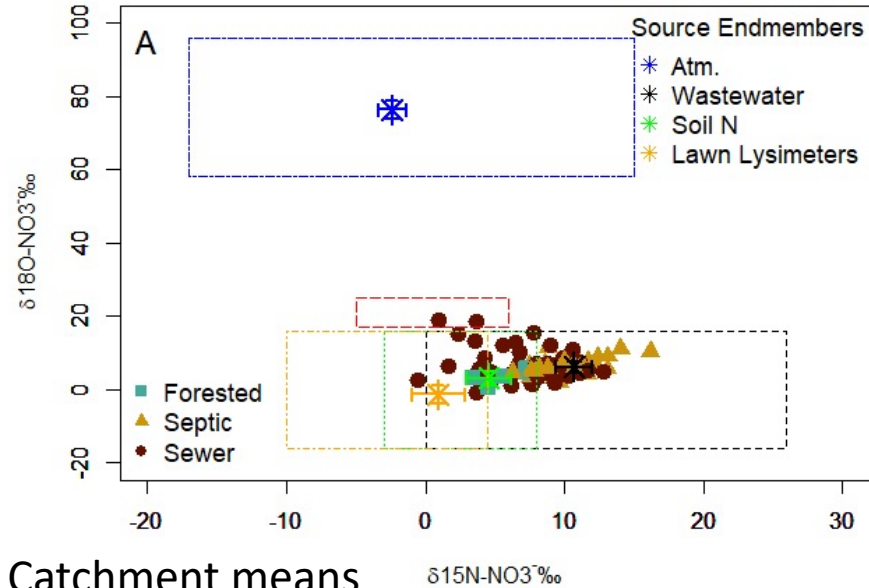
These developments are most common in the US and Europe and are also the fastest growing developments by area*

*Richards, L. (2006). Water and the density debate. *Planning*, 72(6), 30–35.

*Dijkstra, L., & Poelman, H. (2014). A harmonized definition of cities and rural areas: The new degree of urbanization. *Regional and Urban Policy*.

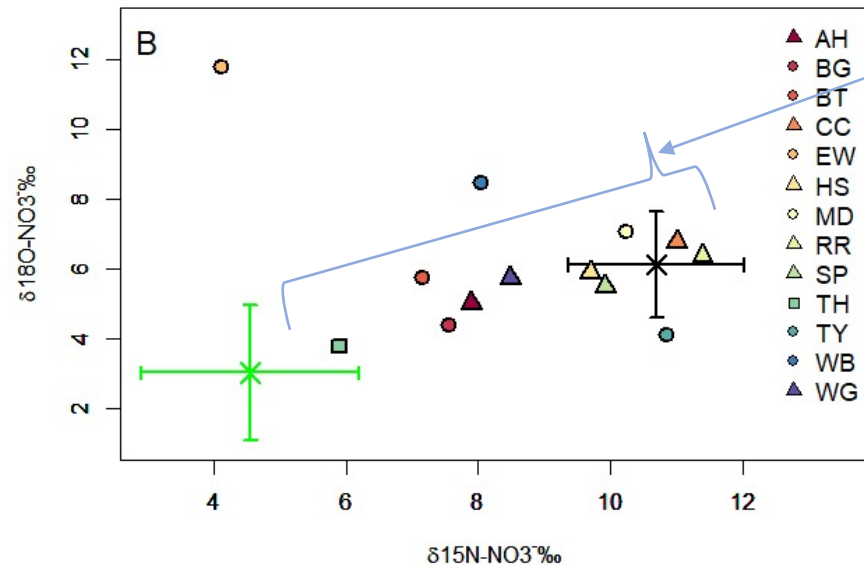
What are the primary baseflow sources?

All sampling



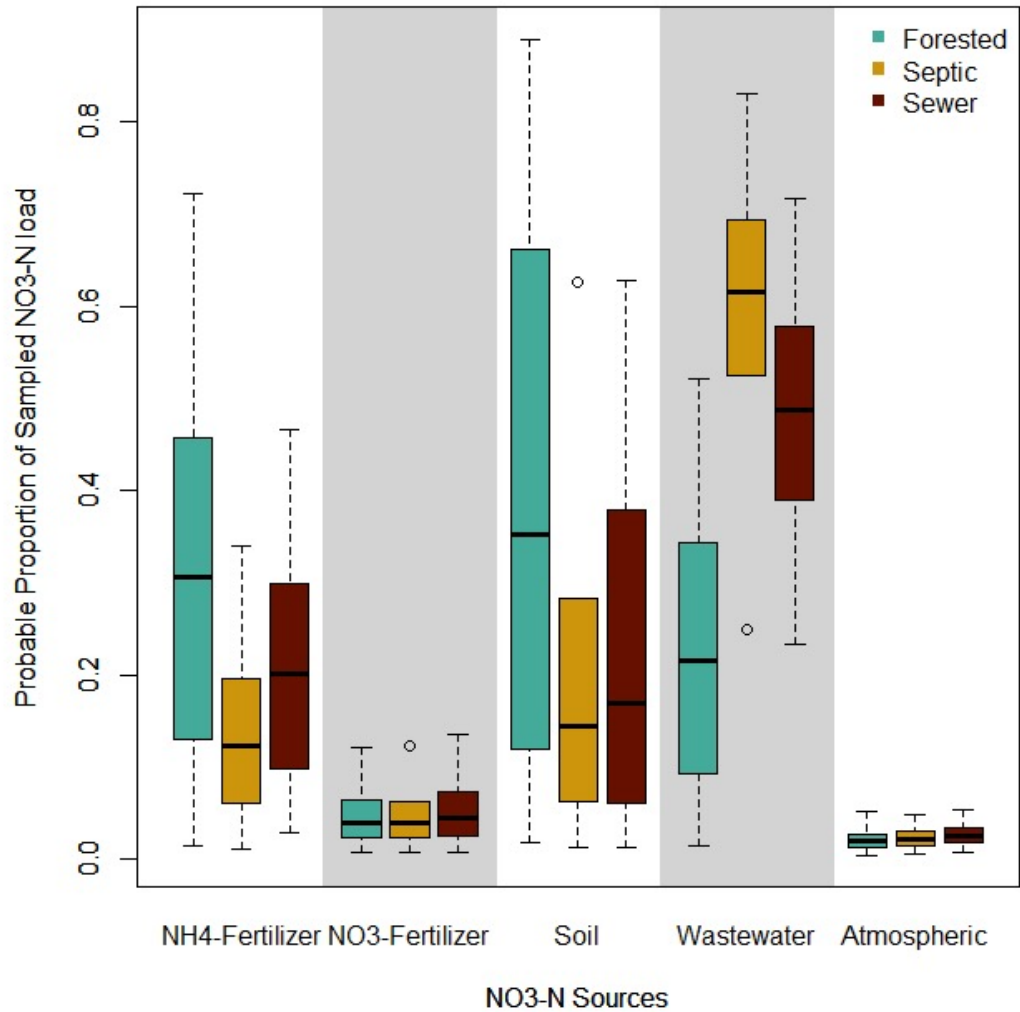
- Nitrate made up 73% of total dissolved nitrogen
- Most of the sampled isotopic nitrate values were within the literature range for wastewater and clustered around our wastewater endmember sampling
- Mean catchment values generally clustered around the wastewater endmembers or between wastewater and soil nitrogen endmembers

Catchment means



The source regions (A) are from: Kendall, C., Elliott, E. M., & Wankel, S. D. (2008). Tracing Anthropogenic Inputs of Nitrogen to Ecosystems. *Stable Isotopes in Ecology and Environmental Science: Second Edition*, 375–449.

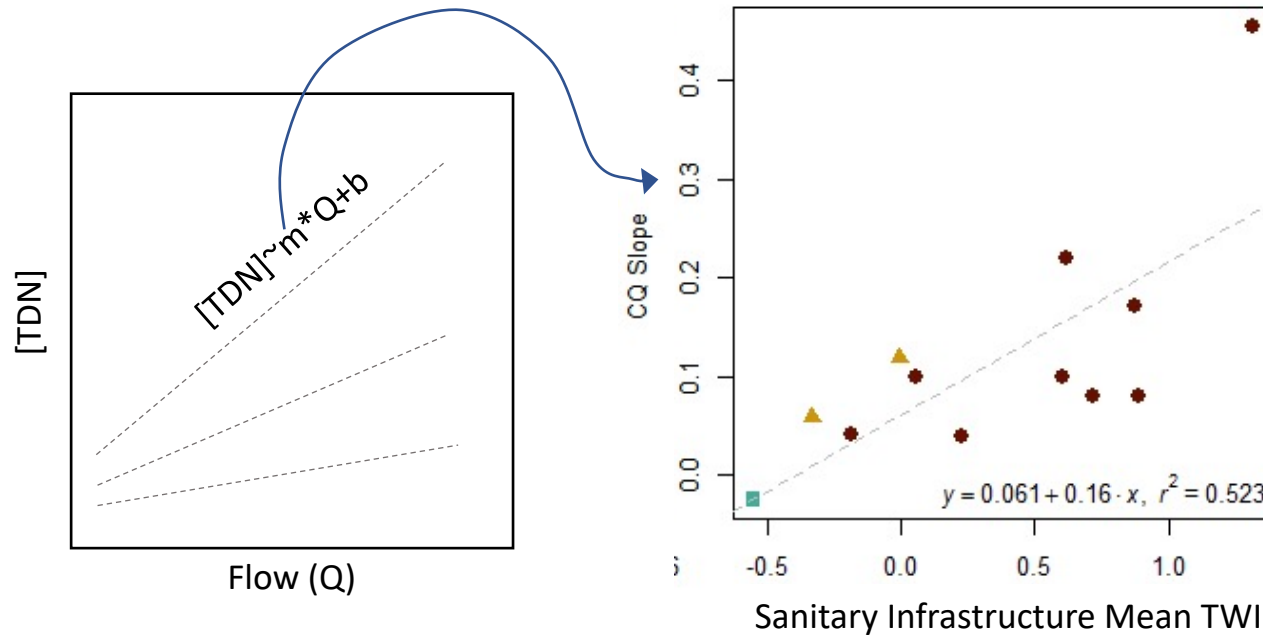
What are the primary sources?



Probability distribution estimates of NO₃⁻ sources proportions by mass

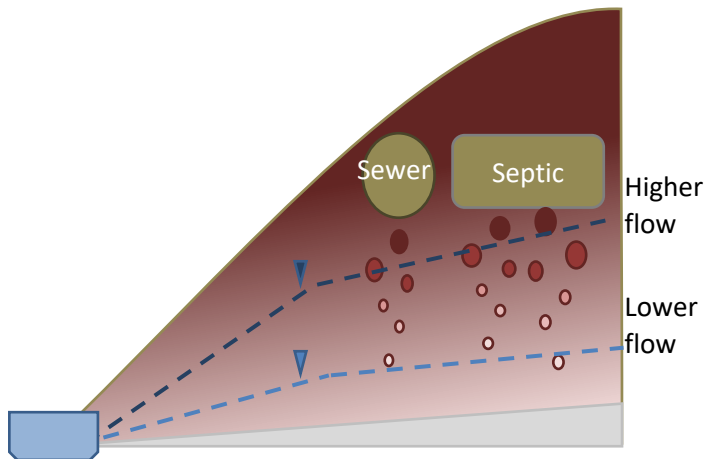
- Uses a Bayesian approach to solve mixing equations and reflect uncertainty
- Wastewater was the probable primary source for both septic and sanitary sewer served catchments
- Soil N was the most probable primary source for the primarily forested catchment

How is baseflow nitrogen transported?

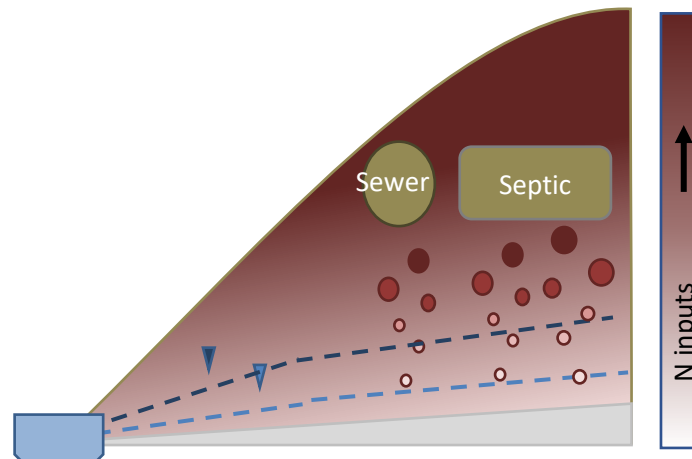


- All significant linear concentration-discharge (CQ) relationships were positive for developed catchments
- The catchment CQ slope was well predicted by the hydrogeomorphic position of sanitary infrastructure
- This suggests that nitrogen from sanitary infrastructure in wet locations, was more readily transported by increases in water tables, than nitrogen from sanitary infrastructure in dry locations

Wet Hydrogeomorphic Position



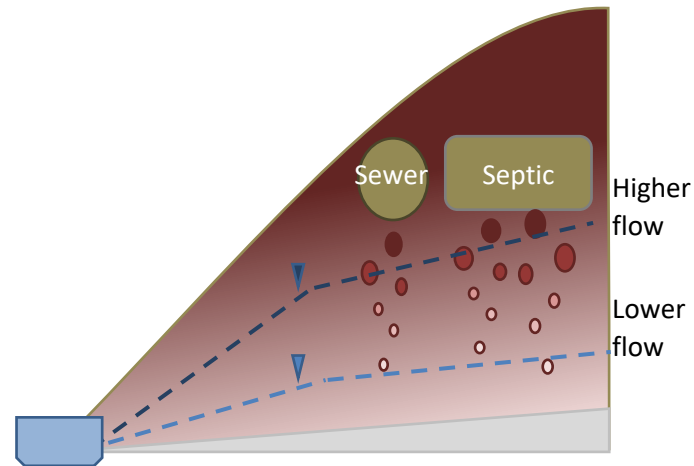
Dry Hydrogeomorphic Position



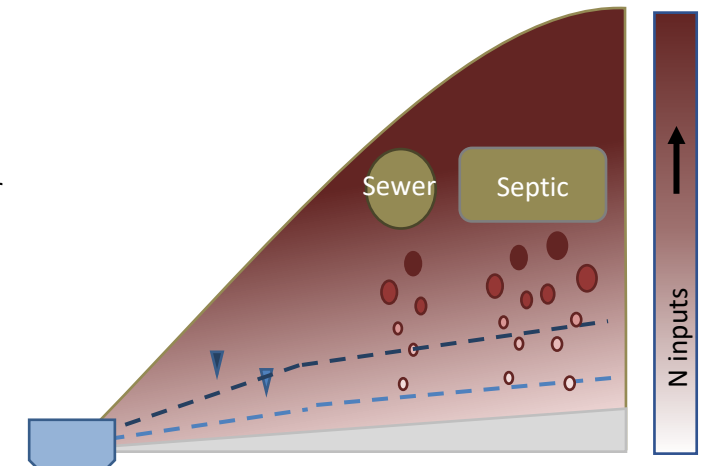
What landscape features control nitrogen loading?

Best landscape predictors of baseflow TDN loading		
	TDN (kg/sq km)	
	R ²	effect
Hydrogeomorphic position		
Sewer TWI (median)	0.41+	
Sanitary TWI	0.39+	
Topography		
Convergent area	0.27+	
Footslope area	0.26+	
Population		
Parcel Density	0.25+	

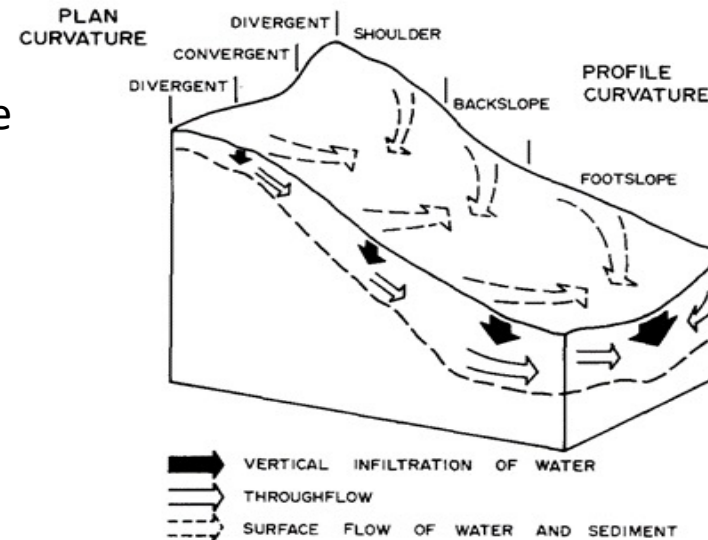
Wet Hydrogeomorphic Position



Dry Hydrogeomorphic Position



- Household density, representing N wastewater source
- Sanitary infrastructure hydrogeomorphic position, representing hydrologic connectivity of the primary source
- Convergent sloping topographic area, representing areas of greater saturation and potentially baseflow generation



Pennock, D. J., Zebarth, B. J., & De Jong, E. (1987). Landform classification and soil distribution in hummocky terrain, Saskatchewan, Canada. *Geoderma*, 40(3-4), 297-315. [https://doi.org/10.1016/0016-7061\(87\)90040-1](https://doi.org/10.1016/0016-7061(87)90040-1)

What are the primary sources of baseflow non-point source nitrogen loading to streams along the rural-urban gradient?

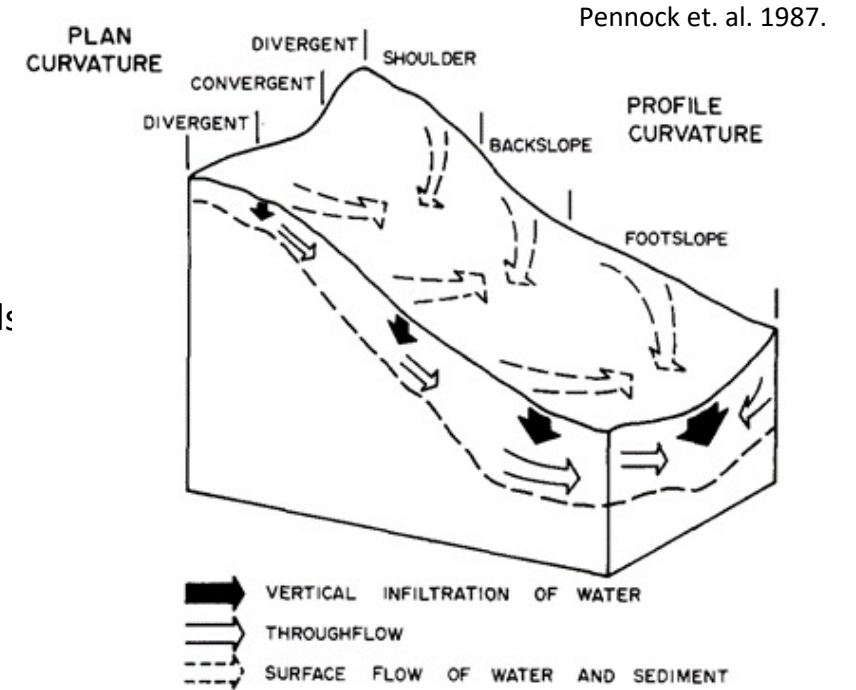
- Wastewater

How is nitrogen transported to streams at baseflow in developed watersheds?

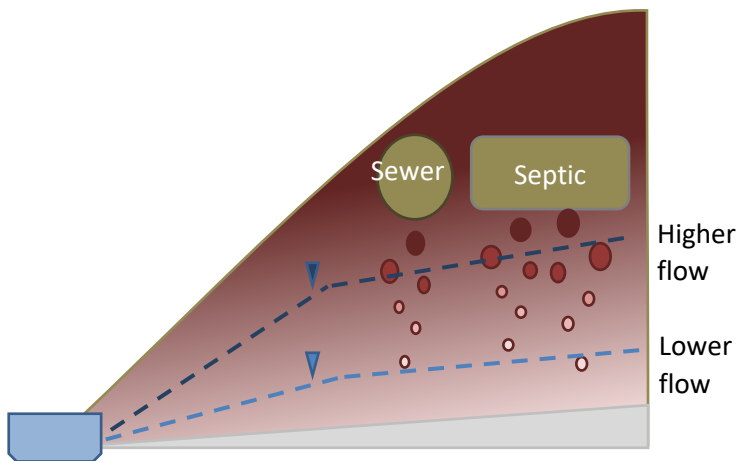
- Subsurface N was abundant, and export was transport limited

What landscape features control nitrogen loading at baseflow in developed watershed:

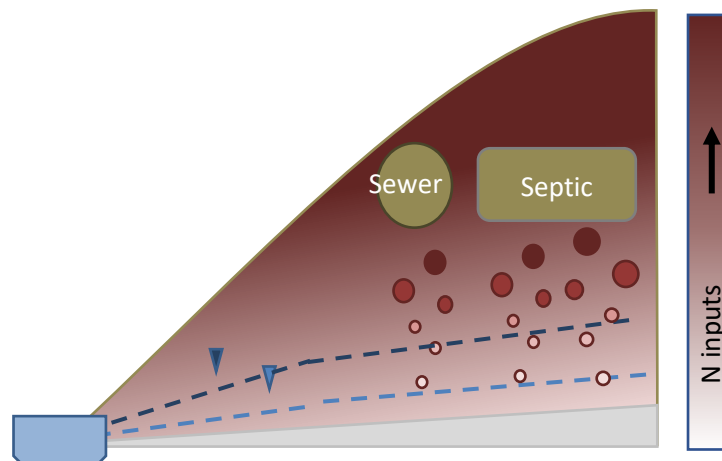
- Hydrogeomorphic position of sanitary infrastructure
- Topographic features which promote saturation
- Household and population density

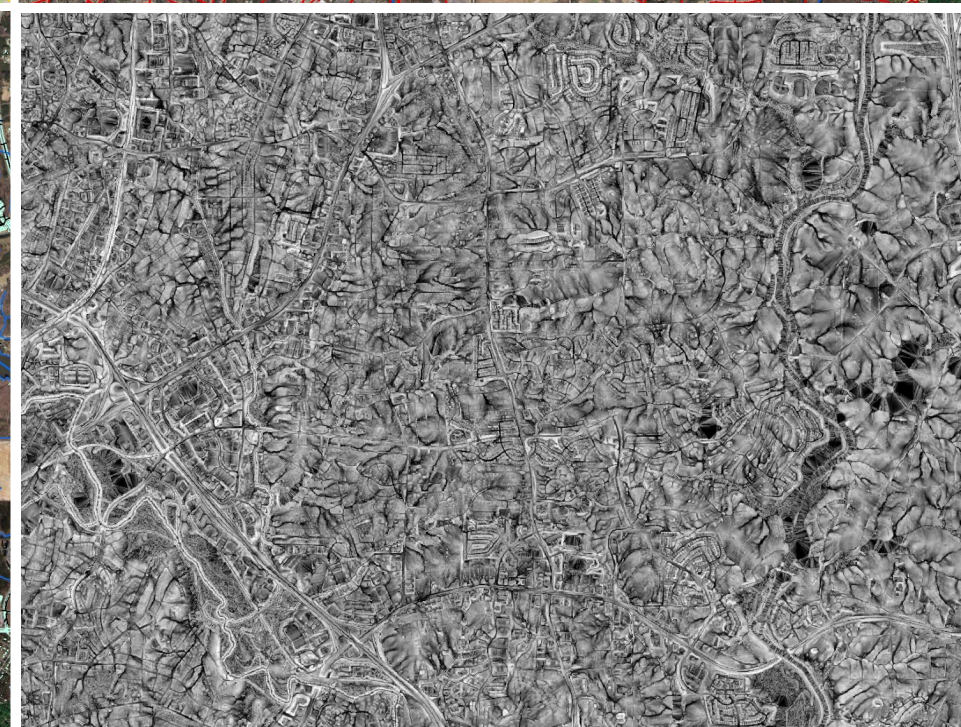
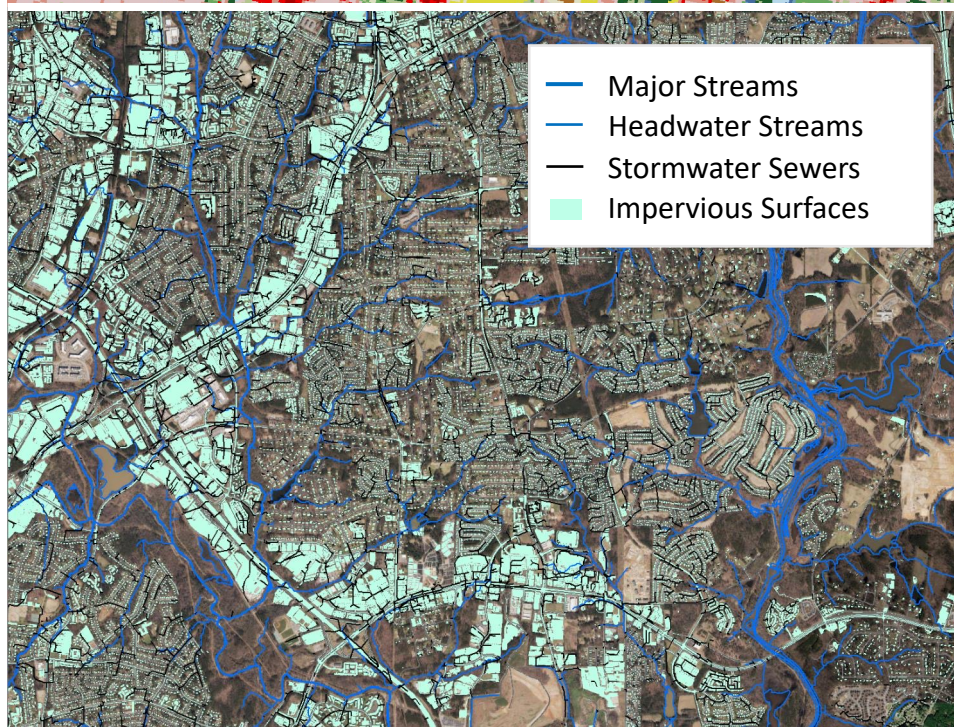
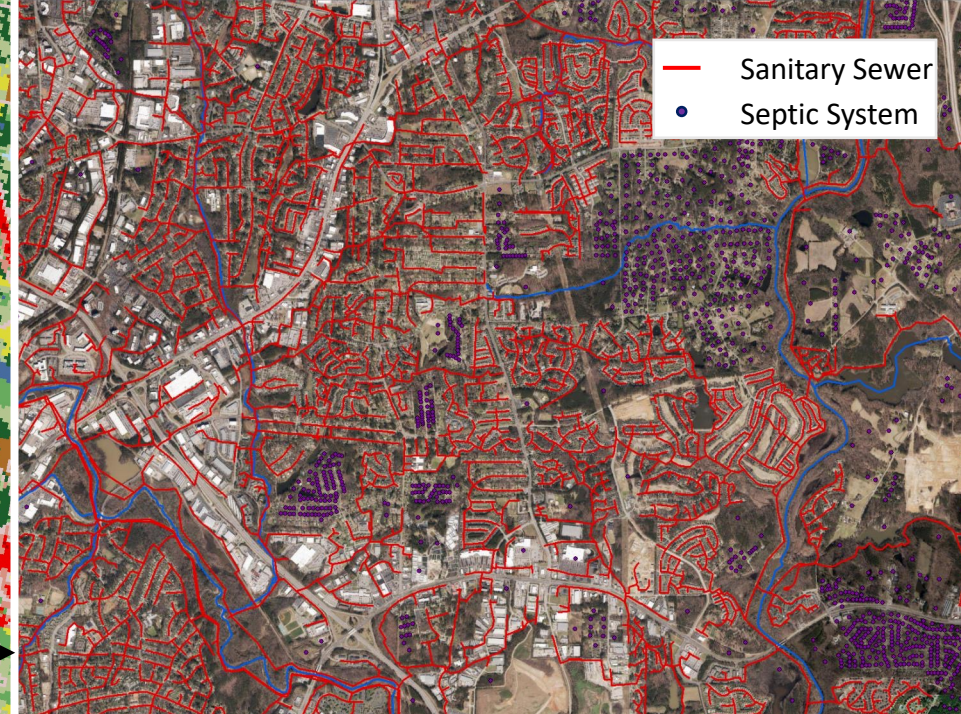
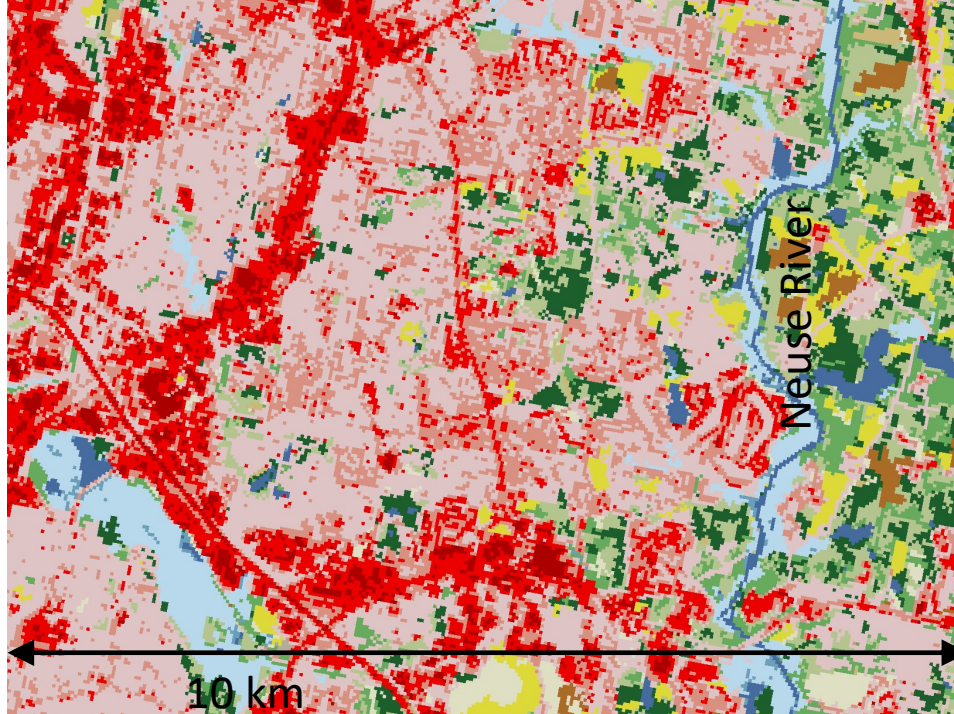


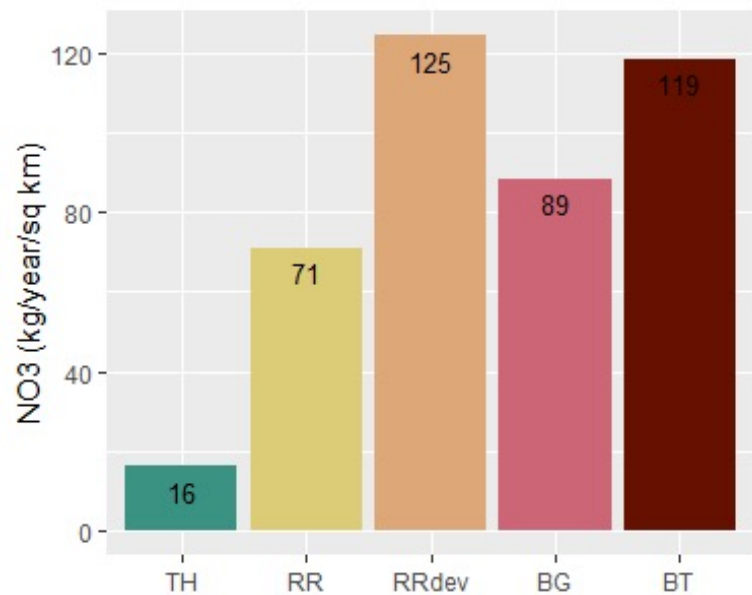
Wet Hydrogeomorphic Position



Dry Hydrogeomorphic Position

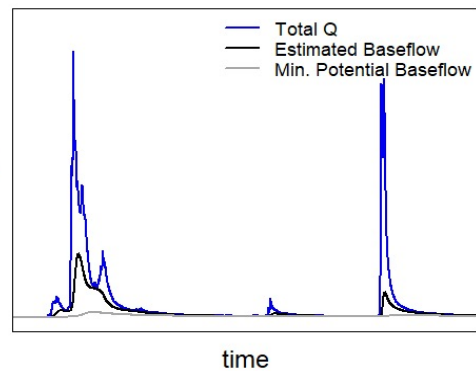




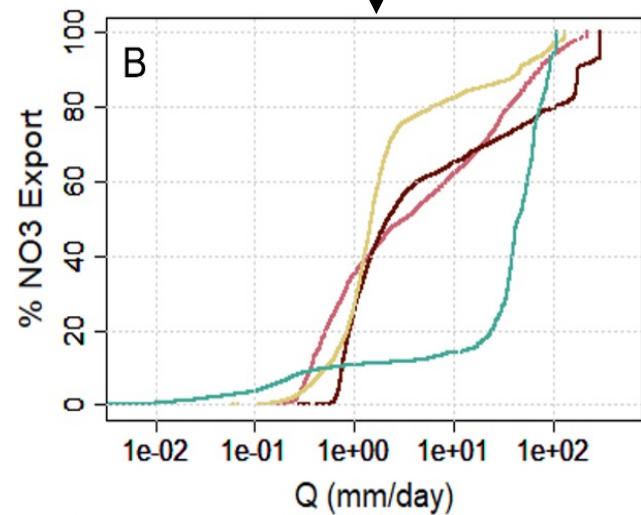
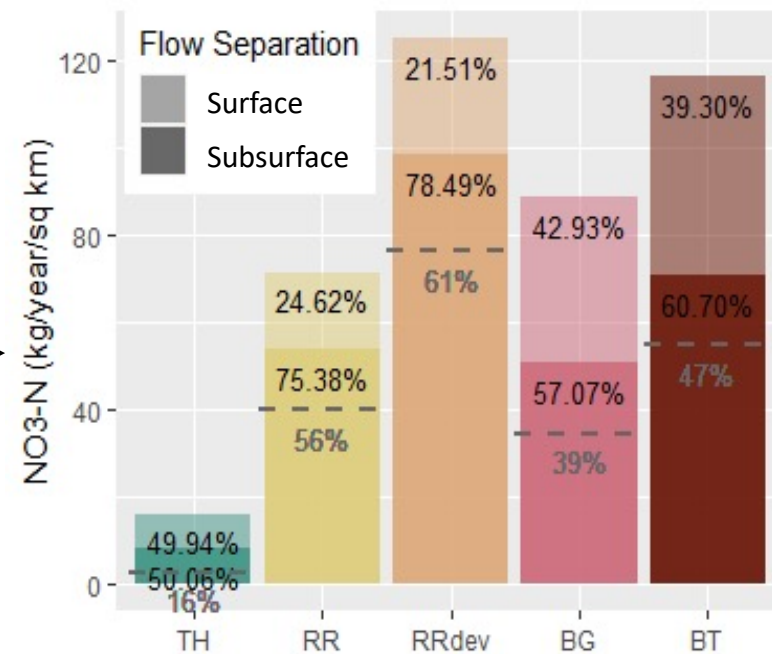


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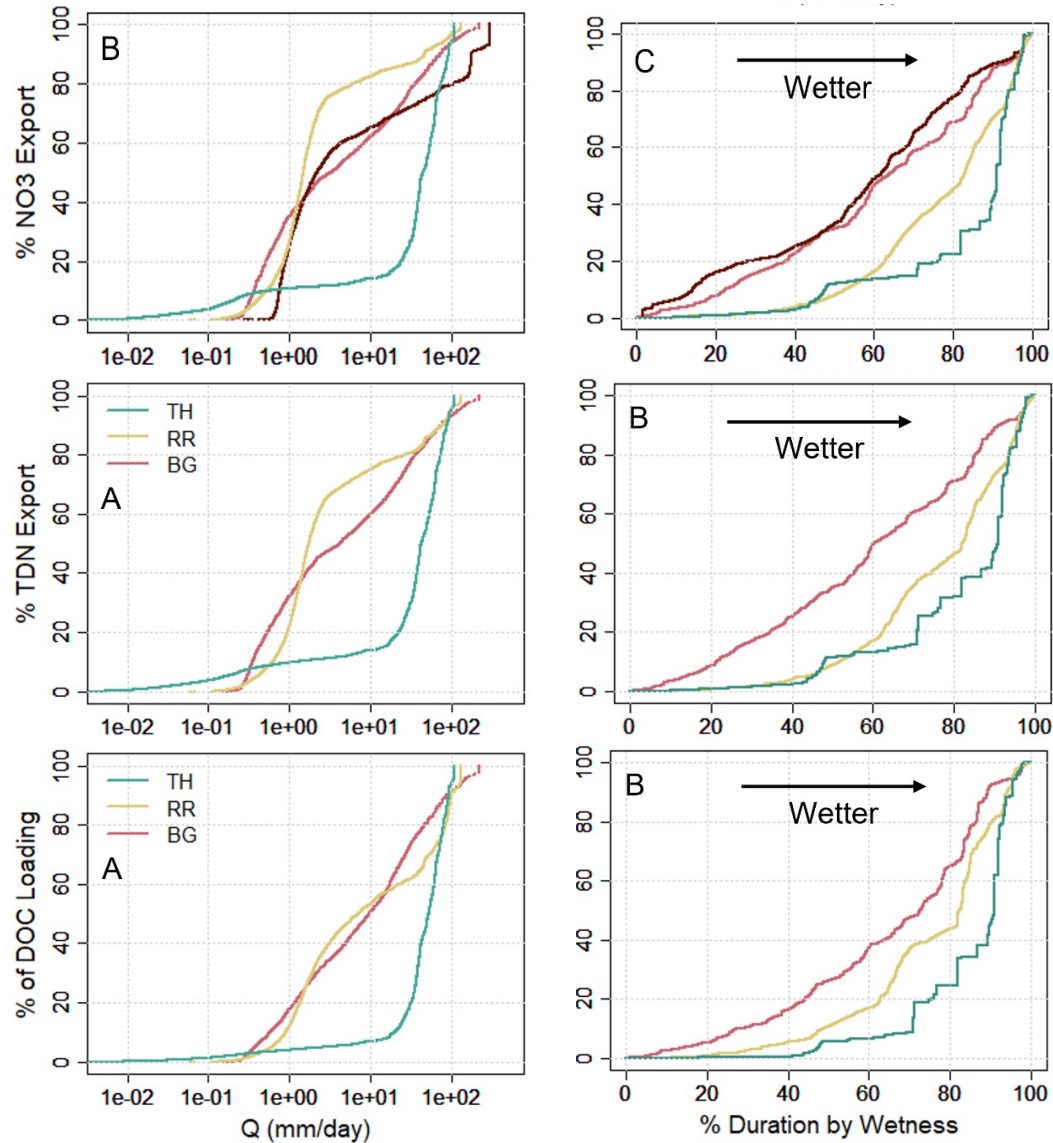
Q



→

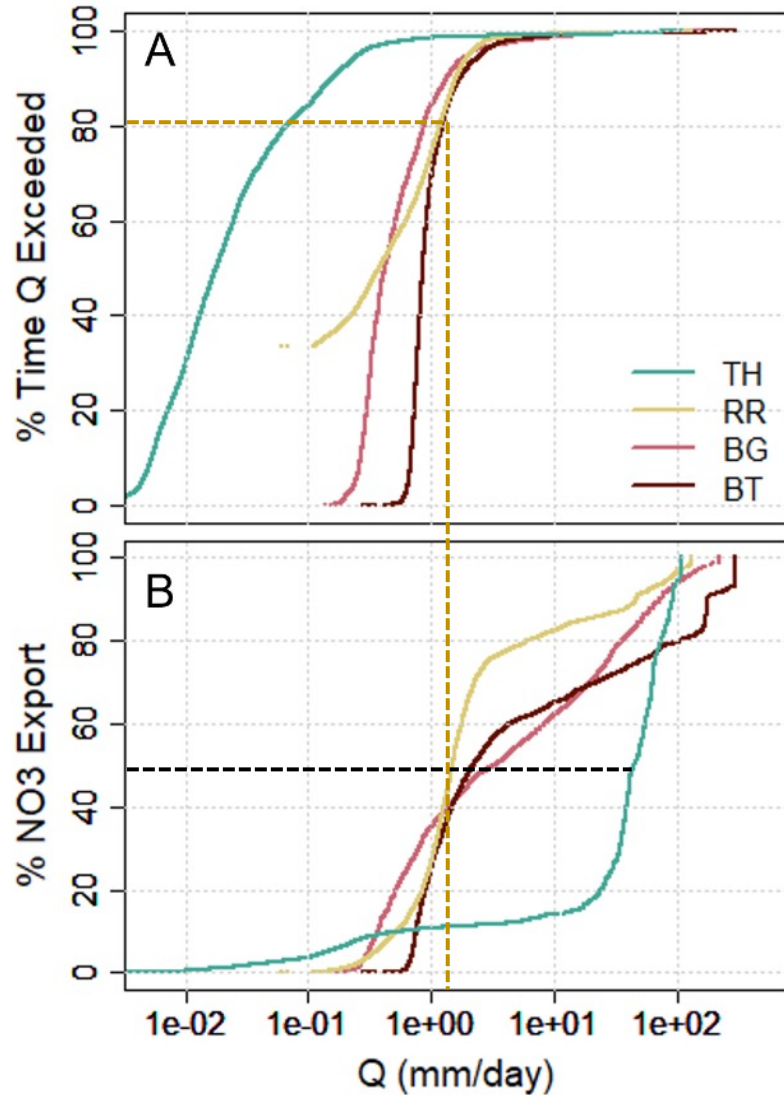


Flow duration and cumulative percent loading



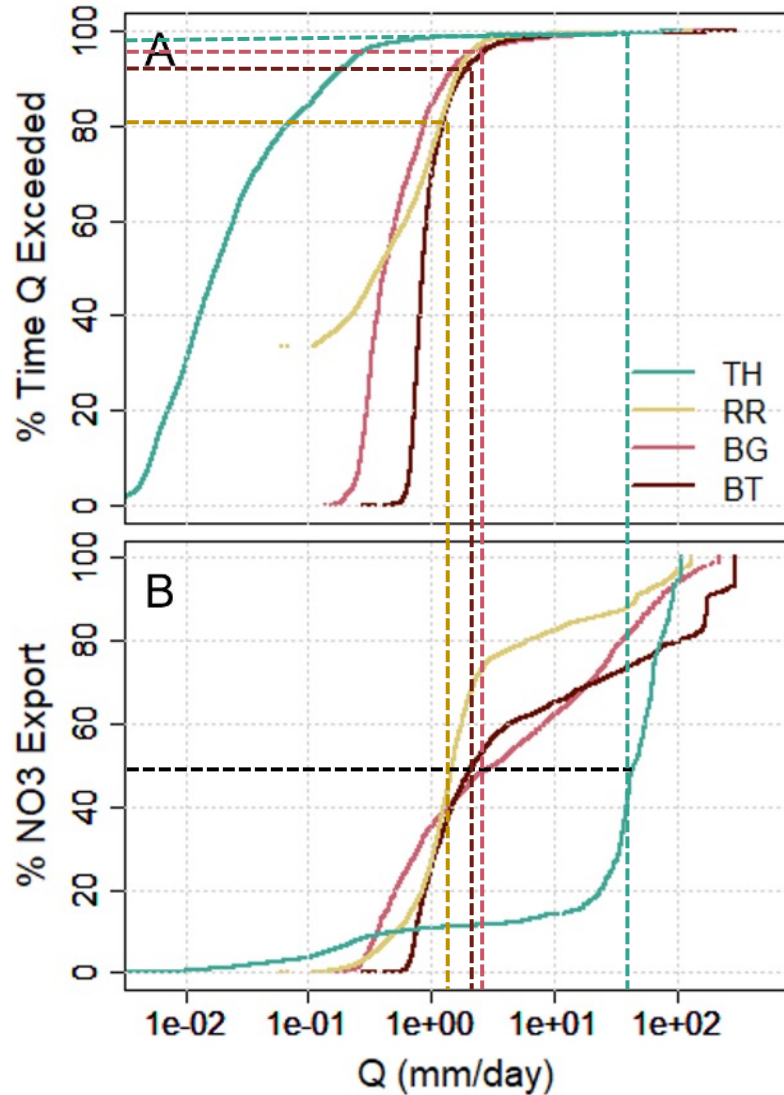
- Nitrate is mobilized at lower flows and drier periods than TDN and DOC
- Indicates a potential shift to mobilizing soil N during wet periods
- Suggests that increasing frequency of large events and wet periods could mobilize stored organic carbon and nitrogen

Flow duration and cumulative percent loading



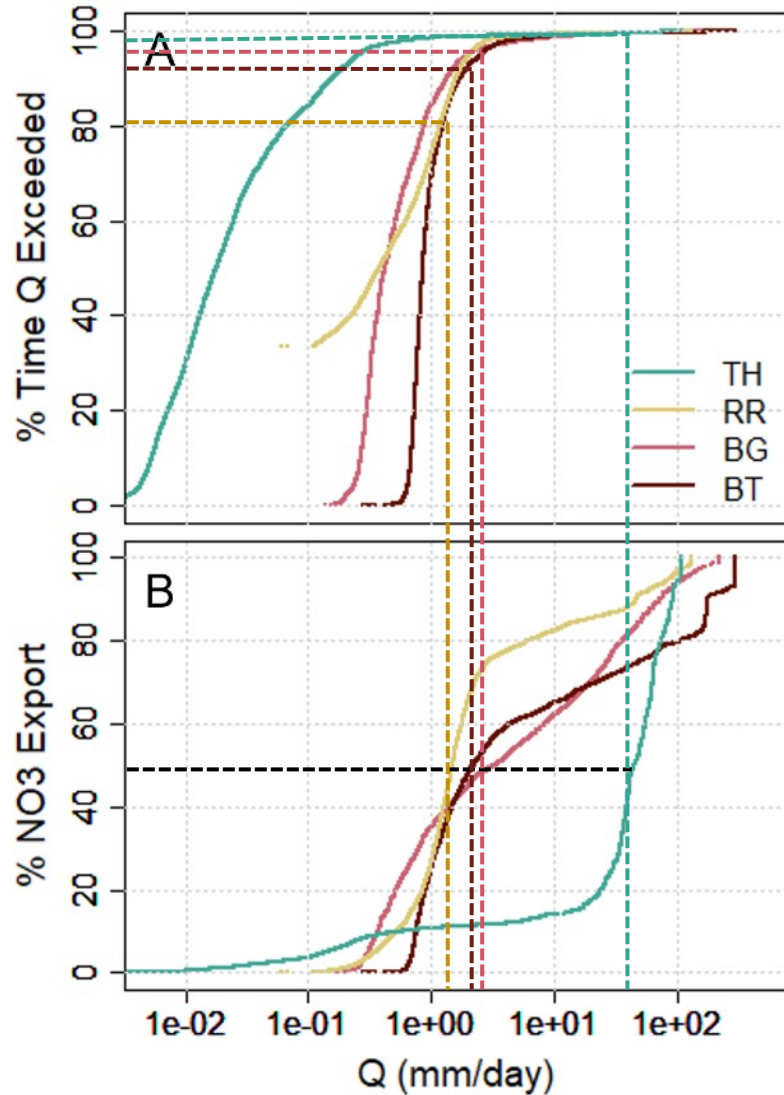
- More nitrate is delivered by lower and more common flows for the septic served catchment relative to the urban catchments.
 - Suggests that septic systems enrich and supplement baseflow
- High flows are required to mobilize nitrate for the primarily forested catchment
 - Suggests high retention at low flows relative to other catchments

Flow duration and cumulative percent loading

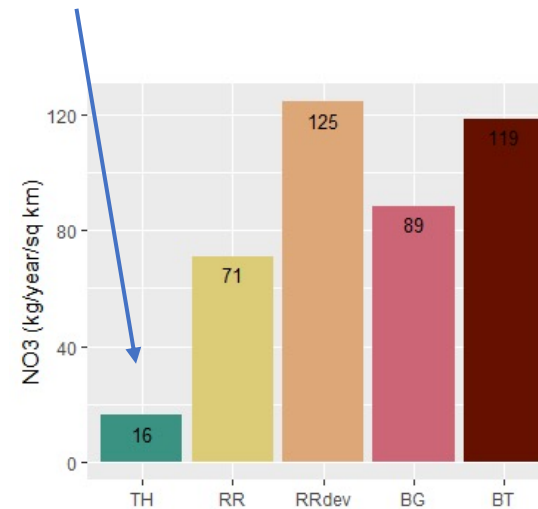


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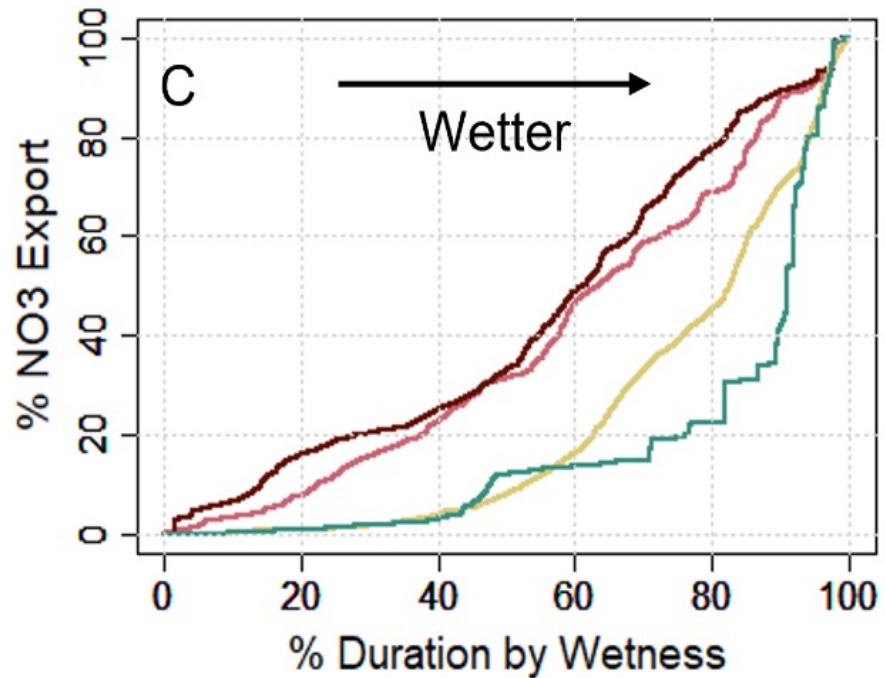
Flow duration and cumulative percent loading



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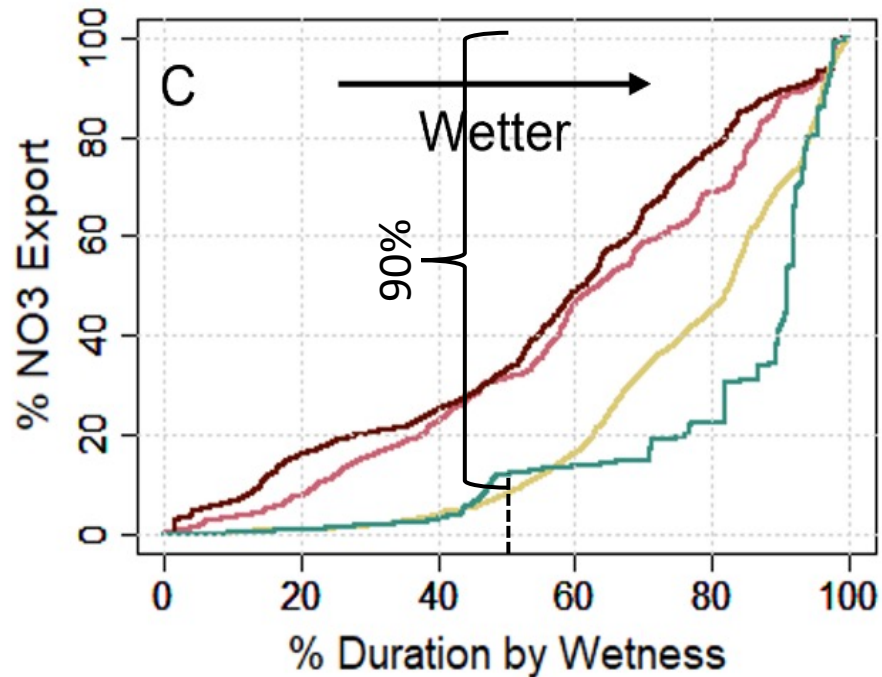


Flow duration and cumulative percent loading



- Antecedent wetness was represented by previous 30 day Q.
- Loading was higher during wet periods for all catchments, but the hydroclimatic variation in loading decreased with development intensity

Flow duration and cumulative percent loading



- Antecedent wetness was represented by previous 30 day Q.
- Loading was higher during wet periods for all catchments, but the hydroclimatic variation in loading decreased with development intensity
- Around 90% of catchment export occurred during the wettest half of the sampling period for the forested and rural catchment
- Suggesting higher potential retention from the forested and rural catchment during dry periods

Nitrate concentration and loading timeseries

