Assessing inter-annual variability in nitrogen sourcing and retention through hybrid Bayesian watershed modeling

Jonathan W. Miller, Kimia Karimi, A. Sankarasubramanian, and Daniel R. Obenour

Department of Civil, Construction and Environmental Engineering (Miller, Sankarasubramanian, Obenour) and Department of Geospatial Analytics (Karimi), North Carolina State University

SUPPORTING INFORMATION

Figure S1- TN yearly loadings from major WWTPs.....Page 2

Figure S2- Box and whisker plots of yearly precipitation .....Page 3

Figure S3- Power relationship quantifying uncertainty of TN loadings. .....Page 4

Figure S4- WRTDS loads for additional LMSs.....Page 5

Figure S5- Watershed-level random effects for each incremental watershed.....Page 6

Figure S6- Major geologic regions in JL and FL region.....Page 7

Figure S7- Model residuals plotted by year .....Page 8

Figure S8- Predicted vs. Observed plots with and without random effects.....Page 9

Table S1- Yearly TN loads and discharge for major and minor WWTPs. .....Page 10

Table S2- LMS sites where WRTDS estimates were calculated using a break.....Page 12

Table S3- Prior and hierarchical distributions for watershed model parameters .....Page 13

Table S4- JL and FL loadings during normal, low, and high precipitation years.....Page 14

FIGURES

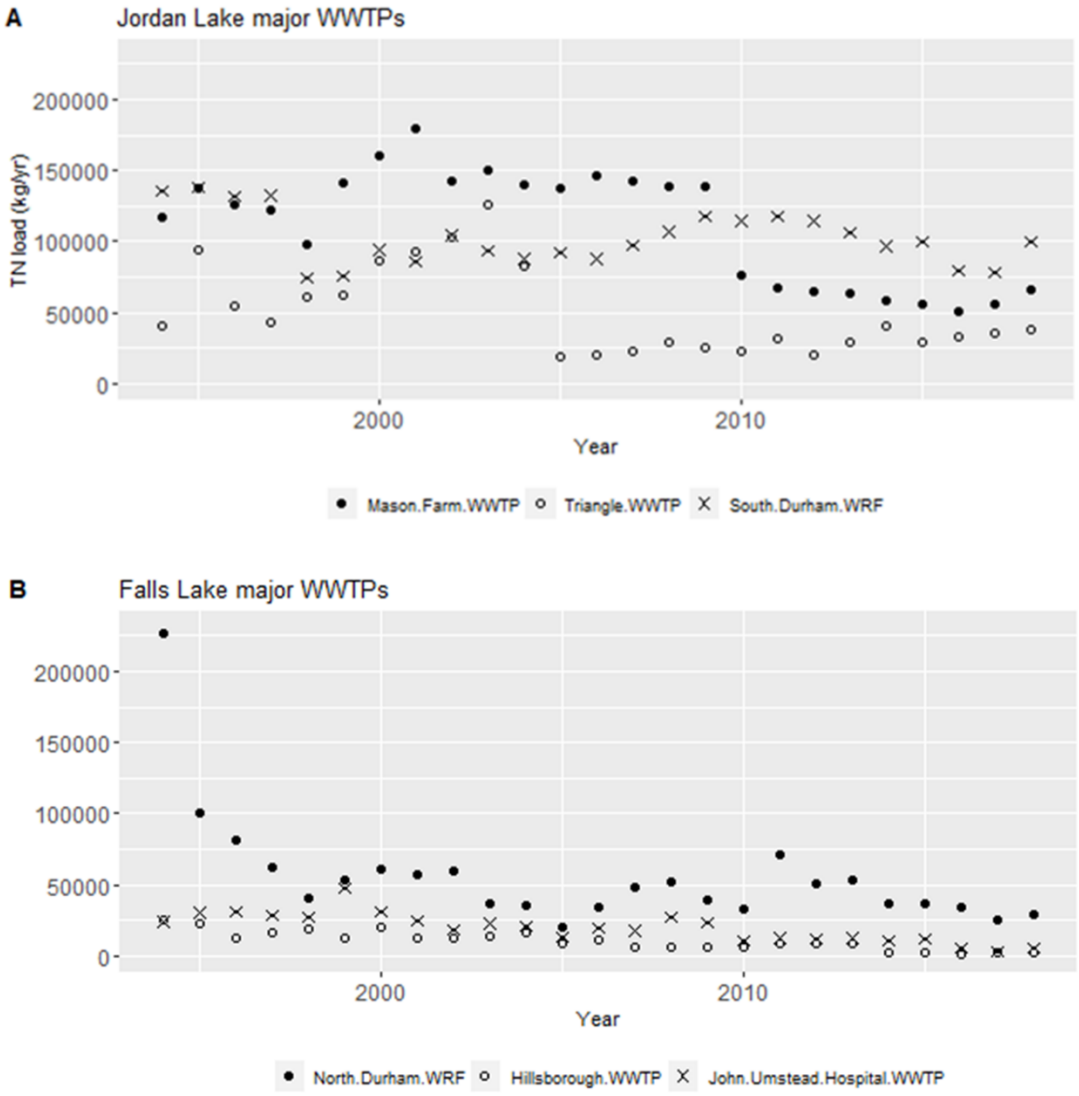

Figure S1: Yearly TN loadings from major WWTPs located closest to Jordan and Falls Lake.

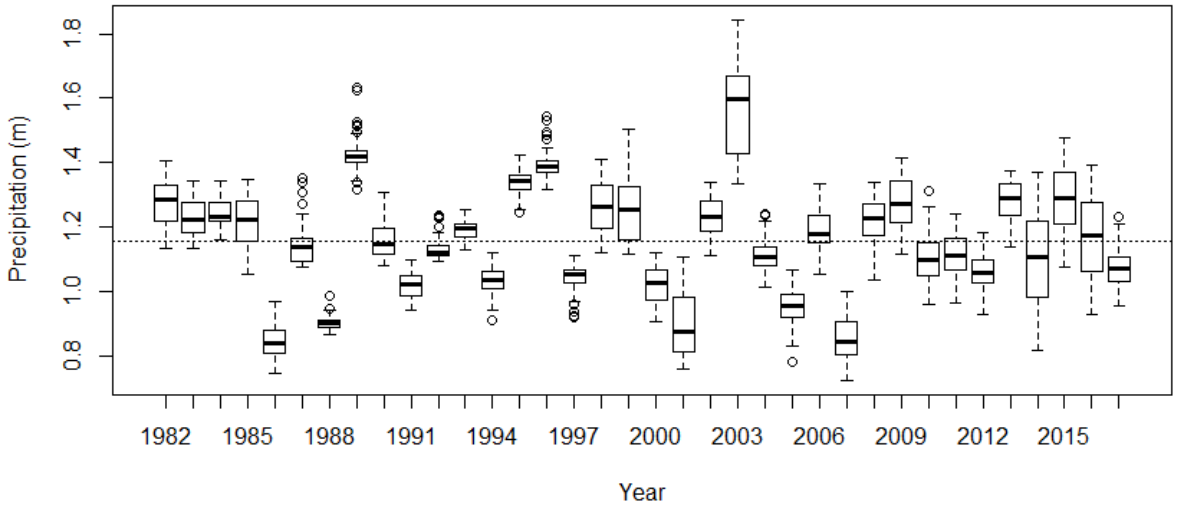

Figure S2: Box and whisker plots of yearly precipitation. The dashed line represents mean yearly precipitation for the JL and FL watersheds.

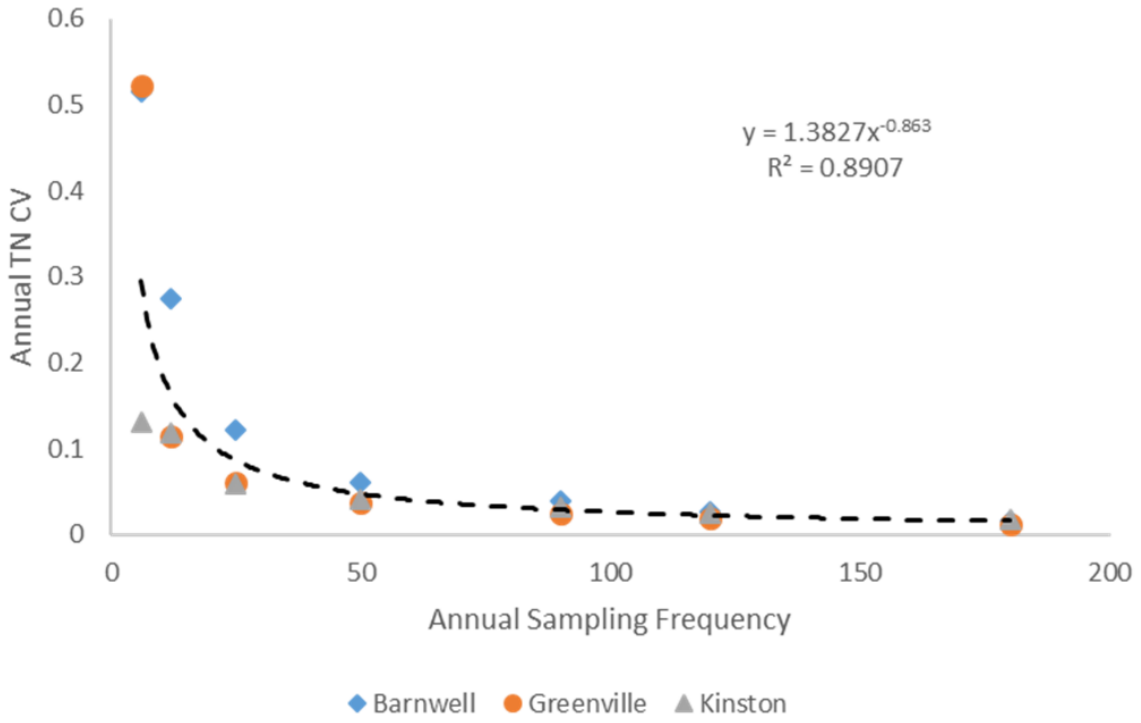

Figure S3: Power relationship quantifying the uncertainty (i.e., coefficient of variation (CV)) of TN yearly (Weighted Regression on Time Discharge and Season) loadings based on the number of water quality samples available.

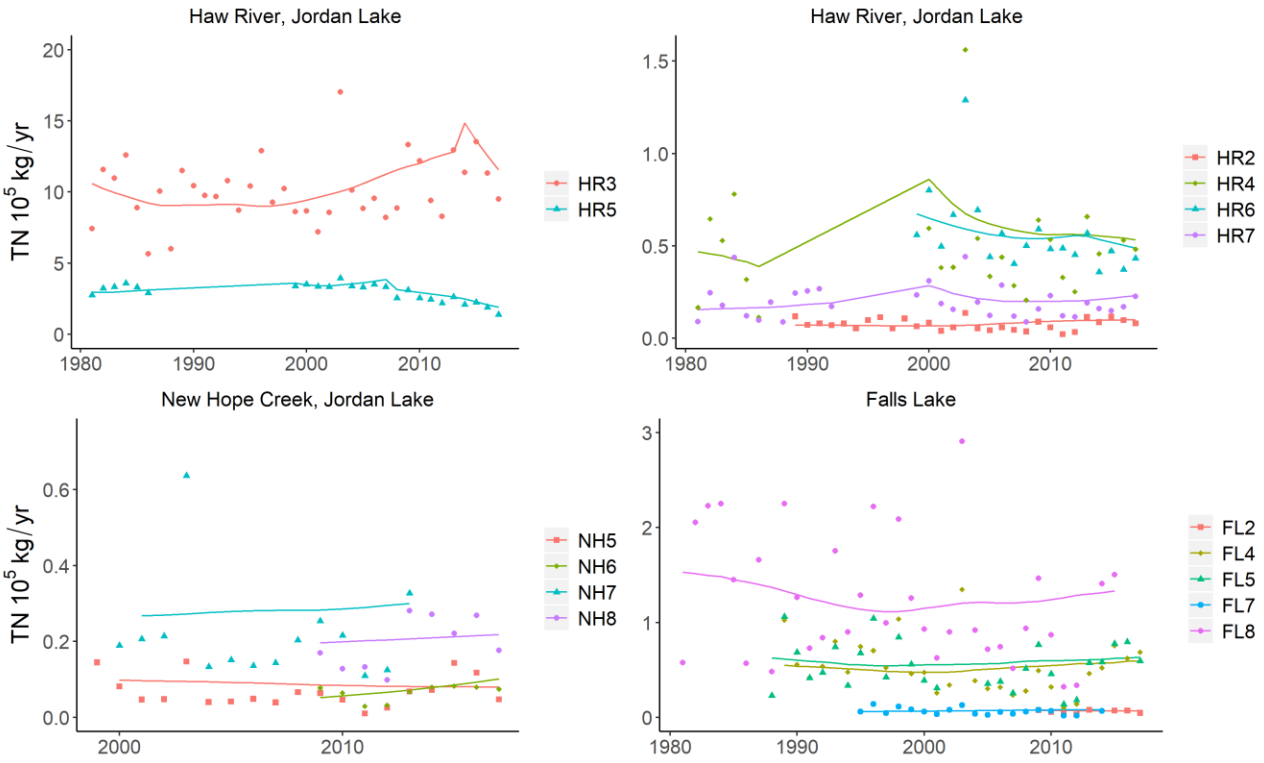

Figure S4: WRTDS loads for additional LMSs that are located upstream of LMSs that drain directly into Jordan and Falls Lake (Fig. 3).

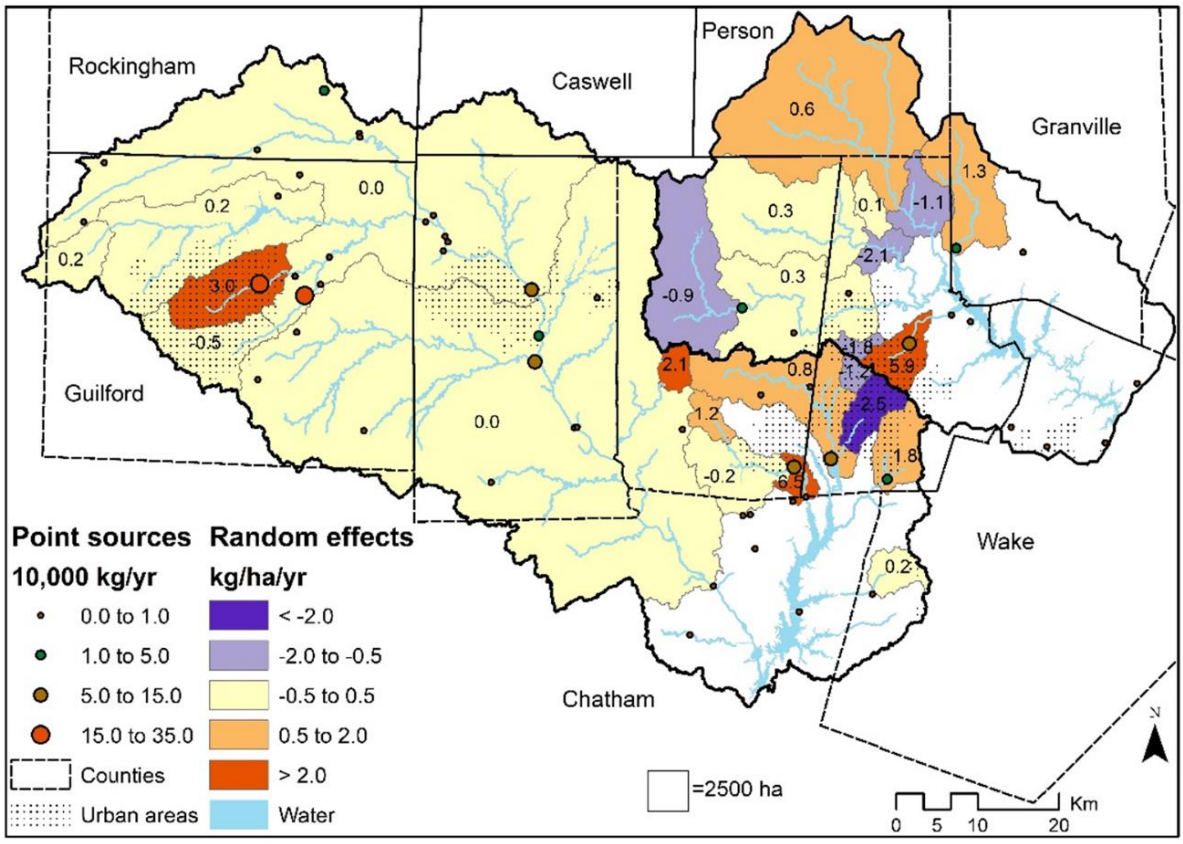

Figure S5: Area-normalized watershed-level random effects for each incremental watershed (i.e., load monitoring site watershed)

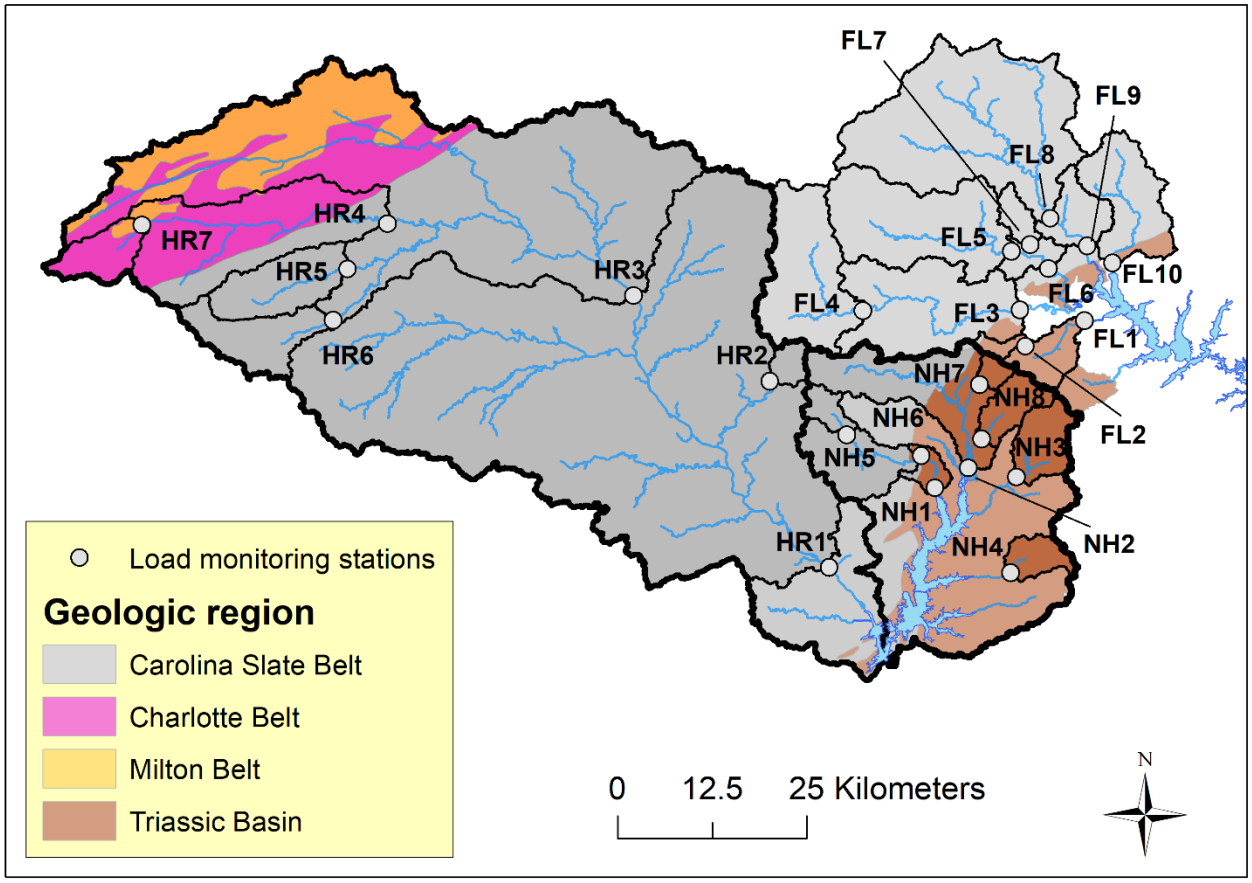

Figure S6: Major geologic regions in JL and FL region.

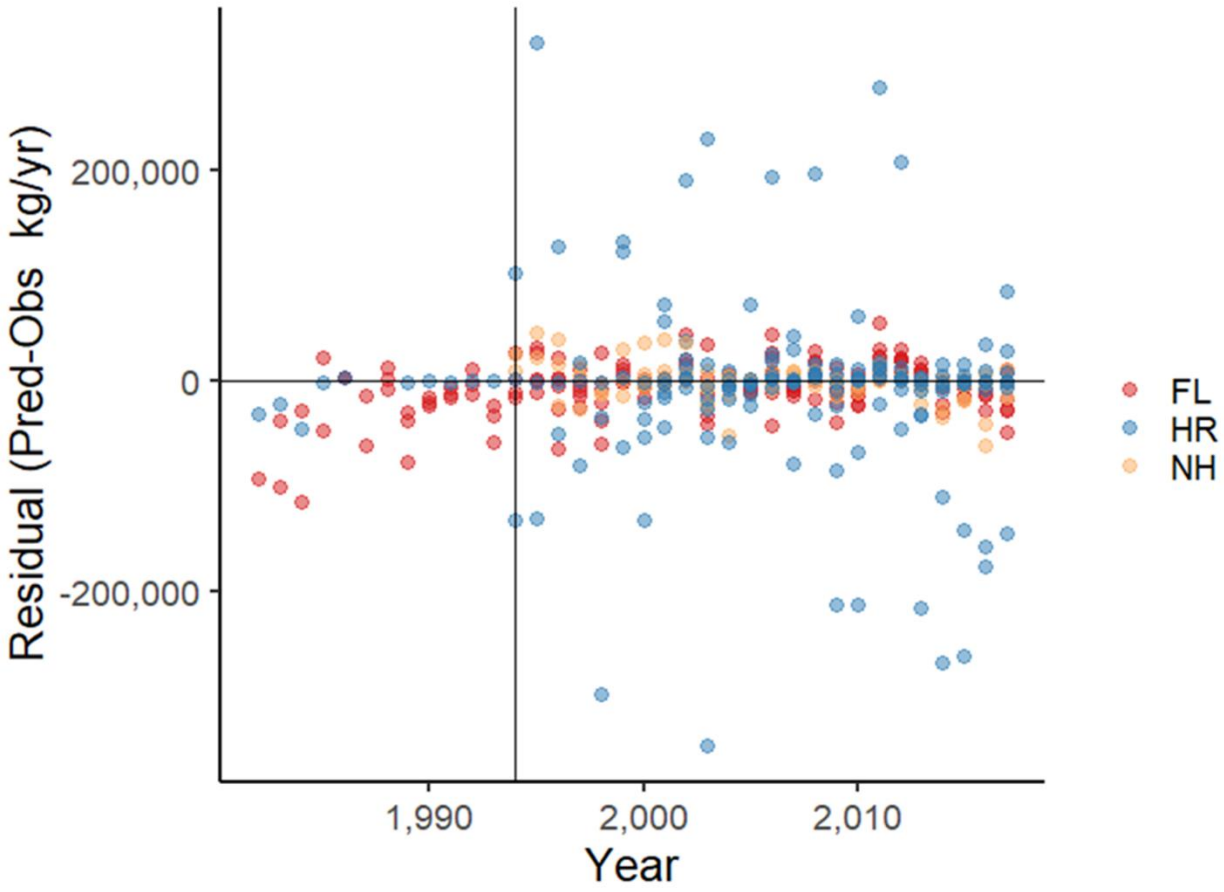

Figure S7: Model residuals plotted by year. Load monitoring sites with major point source dischargers were not included before 1994 (solid vertical line).

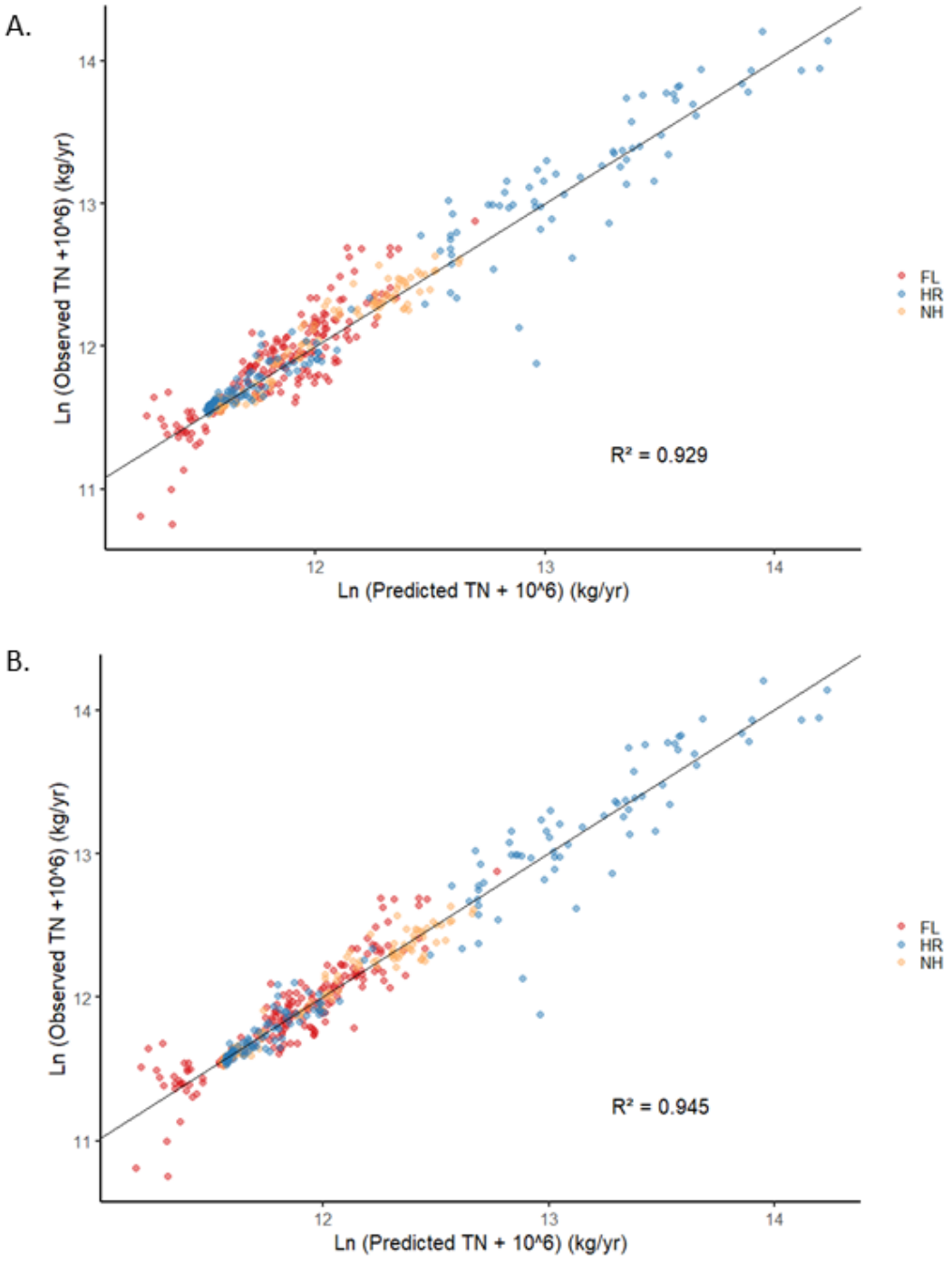

Figure S8: Predicted vs. Observed plots without (A) and with (B) watershed-level random effects

TABLES

Table S1: Point source TN loads, flows, and residence time to downstream loading monitoring sites for major and minor point source dischargers.

NC DEQ ID#	Name	TN load (kg) (2017)	Discharge (MGD) (2017)	Downstream LMS	Mean RT (days) to LS	Mean HL (m/yr) to LS
NC0026824	John Umstead Hospital WWTP	3396	1.610	FL10	0.05	
NC0023841	North Durham WRF	25,765	8.280	FL1	0.24	
NC0026433	Hillsborough WWTP	2016	0.919	FL3	1.10	
NC0037869	Arbor Hills Mobile Home Park	18	0.001	FL3	0.55	312.0
NC0056731	Grande Oak Subdivision WWTP	41	0.002	FL3	0.20	107.4
NC0023876	Southside WWTP	43,342	5.872	HR1	1.26	
NC0021211	Graham WWTP	0	0.000	HR1	1.30	
NC0021474	Mebane WWTP	6,177	1.269	HR1	1.76	96.0
NC0035866	Bynum WWTP	122	0.006	HR1	0.02	
NC0042285	Trails WWTP	485	0.020	HR1	1.19	
NC0022675	Birmingham Place	0	0.000	HR1	2.94	
NC0022098	Cedar Valley WWTP	126	0.006	HR1	3.29	
NC0038164	Nathanael Greene Elem. School WWTP	0	0.000	HR1	2.64	
NC0045128	Sylvan Elementary School	172	0.001	HR1	1.78	
NC0045152	Jordan Elementary School	130	0.002	HR1	1.08	
NC0042528	B Everett Jordan 1927 LLC	123	0.008	HR1	1.04	
NC0025241	Mason Farm WWTP	55,655	5.878	NH1	0.20	
NC0056413	Carolina Meadows WWTP	2115	0.148	NH1	0.01	
NC0047597	South Durham WRF	78,164	8.023	NH2	0.55	
NC0042803	Birchwood Mobile Home Park	102	0.007	NH2	1.20	
NC0074446	Hilltop Mobile Home Park	335	0.010	NH2	1.54	
NC0026051	Triangle WWTP	35,557	4.502	NH3	0.14	

NC0023868	Eastside WWTP	55,515	3.883	HR3	0.04
NC0024881	Reidsville WWTP	48,902	2.280	HR3	1.50
NC0066966	Quarterstone Farm WWTP	1,438	0.038	HR3	1.28
NC0046019	The Summit WWTP	0	0.000	HR3	1.76
NC0046809	Pentecostal Holiness Church	19	0.000	HR3	1.59
NC0060259	Willow Oak Mobile Home Park	164	0.008	HR3	1.14
NC0077968	Horners Mobile Home Park	127	0.003	HR3	0.52
NC0045161	Altamahaw/Ossipee Elementary School	283	0.003	HR3	0.50
NC0045144	Western Alamance High School	478	0.006	HR3	0.40
NC0031607	Western Alamance Middle School	0	0.000	HR3	0.45
NC0055271	Shields Mobile Home Park	0	0.000	HR3	0.41
NC0065412	Pleasant Ridge WWTP	40	0.008	HR3	1.14
NC0073571	Countryside Manor WWTP	300	0.008	HR3	2.78
NC0046043	Oak Ridge Military Academy	255	0.004	HR3	2.74
NC0022691	Autumn Forest Manuf. Home Community	160	0.018	HR4	0.44
NC0047384	T.Z. Osborne WWTP	582,529	27.680	HR3	1.55
NC0038172	McLeansville Middle School WWTP	0	0.000	HR3	1.55
NC0029726	Guilford Correctional Center WWTP	0	0.000	HR3	1.53
NC0024325	North Buffalo Creek WWTP	161,171	6.619	HR5	0.29

Table S2: LMS sites where WRTDS estimates were calculated using a break (i.e. wall) in their record due to a large sustained change (> 25% up or down) in an upstream point source load.

		Years of record		# of samples		Point source	
LMS	Name	Pre	Post	Pre	Post	Permit	WWTP
NH1	Morgan Creek, JL	1994-2009	2010-2017	360	228	NC0025241	Mason Farm
NH3	Northeast Creek	1995-2004	2005-2017	108	322	NC0026051	Triangle
HR3	Haw River, Burlington	1994-2013	2014-2017	223	56	NC0047384	T.Z. Osborne
HR5	N. Buffalo Creek	1999-2007	2008-2017	148	241	NC0024325	North Buffalo Creek
FL3	Eno River, Durham	1994-2006	2007-2017	158	217	NC0026433	Hillsborough

Table S3: Prior distributions and hierarchical distributions for watershed model parameters. Note, EC is export coefficient, DC is delivery coefficient, PIC is precipitation impact coefficient, and SD is standard deviation. Priors are normal distributions (N) with mean and standard deviation or uniform distributions with upper and lower bounds.

Parameter	Description	Units	Prior	Source
β_{ag}	Agriculture EC	kg/ha/yr	N(9,7)	Dodd et al. 1992
β_{ur1}	Urban type 1 EC	kg/ha/yr	N(8,3)	Dodd et al. 1992
β_{ur2}	Urban type 2 EC	kg/ha/yr	N(8,3)	Dodd et al. 1992
β_{und}	Undeveloped EC	kg/ha/yr	N(2,2)	Dodd et al. 1992
β_{ch}	Chicken EC	kg/an/yr	N(0.001,0.0003)	Strickling and Obenour 2018
β_{h}	Hog EC	kg/an/yr	N(0.04,0.02)	Strickling and Obenour 2018
β_{cw}	Cow EC	kg/an/yr	U(0,5)	-
β_{ps}	Point source DC	-	N(1,0.10)	-
γ_{ag}	Agriculture PIC	-	N(μ_γ, σ_γ)	-
γ_{ur1}	Urban type 1 PIC	-	N(μ_γ, σ_γ)	-
γ_{ur2}	Urban type 2 PIC	-	N(μ_γ, σ_γ)	-
γ_{und}	Undeveloped PIC	-	N(μ_γ, σ_γ)	-
γ_{ch}	Chicken PIC	-	N(μ_γ, σ_γ)	-
γ_{h}	Hog PIC	-	N(μ_γ, σ_γ)	-
γ_{cw}	Cow PIC	-	N(μ_γ, σ_γ)	-
γ_{ret}	Retention rate PIC	-	N(0,1)	-
κ	Stream decay rate	d^{-1}	N(0.14,0.05)	Hoos and McHahon 2009, Garcia et al. 2011
ω	Reservoir loss rate	m/yr	N(11,2)	Hoos and McHahon 2009, Garcia et al. 2011
σ_ε	Model residual SD	kg/yr	U(0,1x10^6)	-
σ_{LMS}	LMS random effect SD	kg/yr	U(0,1x10^6)	-
μ_γ	PIC mean	-	N(1,1)	-
σ_γ	PIC SD	-	N(0,1)	-

Table S4: Percent of nutrient sources that contributes to downstream reservoirs for normal precipitation years (i.e., middle third of years based on precipitation). In parenthesis are nutrient sources during low (lower 33%) and high precipitation years (upper 67%), respectively. Haw River (HR) and New Hope (NH) watersheds of Jordan Lake and Falls Lake (FL).

	% TN		
Nutrient source	HR	NH	FL
Agriculture	17 (11,25)	1 (1,2)	30(21,37)
Urban, pre-1980	18 (18,17)	6 (6,5)	30 (34,25)
Urban, post-1980	2 (1,1)	2 (1,1)	5 (4,4)
Undeveloped	6 (5,7)	2 (2,2)	19 (16,19)
Livestock	2 (2,2)	0 (0,0)	1 (2,2)
Discharger	33 (40,28)	11 (15,10)	14 (24,13)