Assessing the Impacts of Land Use on Downstream Water Quality Using a Hydrologically Sensitive Area Concept

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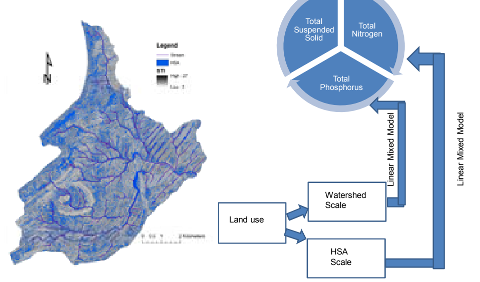
Graphical Abstract



Introduction

- Between 1986 to 2012, approximately 29 percent increase in urban lands was observed in New Jersey, accompanied by 26.7 percent decrease in agricultural lands, 6.7 percent decrease in forest, and 5.4 percent loss in wetlands (Lathrop et al., 2016).
- Urbanization increases impervious surface and alters magnitude, volume, frequency, and timing of high streamflow events which directly or indirectly changes hydrological, biological, and chemical processes of an aquatic ecosystems.

Landscape changes in New Jersey (source: Lathrop et al., 2016)

- Water quality degradation has prompted an increasing interest in better understanding how land uses in a landscape affect downstream water quality.

Rationale

- Areas having higher propensity to generate runoff in a watershed primarily generate and transport pollutants to streams and influence stream hydrograph. Consequently, the high intensity land uses such as agricultural and urban lands located within these areas in the watershed contribute more to water quality degradation.

Hypothesis

- Even though higher potential runoff generating areas (hydrologically sensitive areas) represent a small fraction of a watershed, the land uses within these areas have similar impacts on downstream water quality as the land uses in the whole watershed.
- Validation of this hypothesis is a critical step to the development of efficient water management strategies for water quality improvement

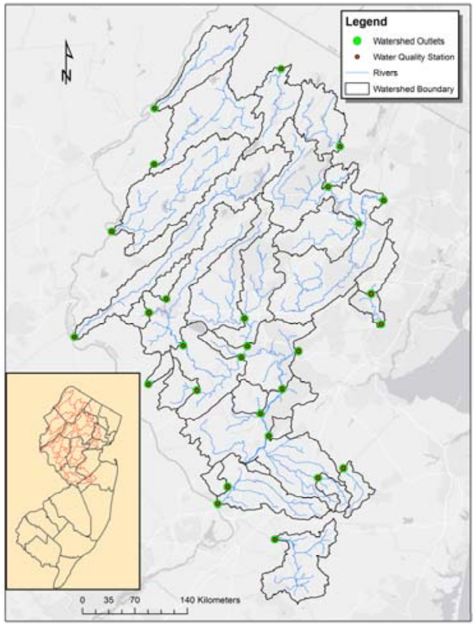
Objectives

- To assess the impact of land uses at both hydrologically sensitive areas and watershed scale on water quality using a linear mixed model.

Materials and Methods

Study Area

- This study was conducted in 28 watersheds located in the north-central New Jersey including parts of Essex, Hunterdon, Mercer, Middlesex, Monmouth, Morris, Somerset, Sussex, Union, Passaic, Burlington, and Ocean Counties.
- All 28 watersheds are located in three physiographic regions including Valley and Ridge, Highlands, and Piedmonts where variable source hydrology is the dominant runoff process.



Location of 28 watersheds in the study area.

Soil Topographic Index

- Soil topographic index(STI) is an indicator of hydrological sensitivity of a landscape and is calculated using following equation:

$$TI = ln\left(\frac{\alpha}{T\tan(\beta)}\right) \quad (1)$$

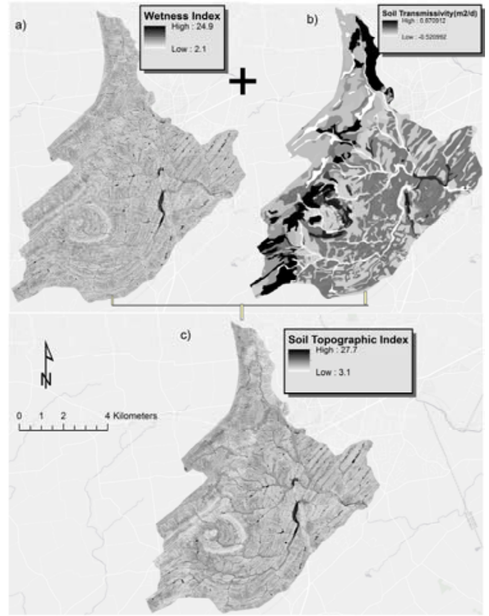
- Where α is the upslope contributing area per unit contour length(m), β is the local surface slope (mm[-1]), T is a soil transmissivity(m^2/day) computed as a product of the saturated hydraulic conductivity (m/day) and the depth to a restrictive layer (m).
- STI indicates the likelihood of a point in a watershed to generate runoff and is used to identify spatial distribution of runoff contributing areas in watershed

Soil Transmissivity

- Soil transmissivity was based on soil saturated hydraulic conductivity and soil depth of topsoil layers in the Soil Survey Geographic(SSURGO) database downloaded from U.S. Department of Agriculture
- The saturated hydraulic conductivity is the geometric mean of the saturated hydraulic conductivity of all soil layers above a restrictive layer

Wetness Index

- The wetness index was based on the light detection and ranging (LiDAR) digital elevation model (DEM) at a 3-meter resolution.
- The wetness index was generated for each watershed using the SAGA geographic information system in R.
- The soil transmissivity was then combined with wetness index to create STI for each of the 28 watersheds.



Spatial distribution of (a) wetness index, (b) soil transmissivity, and (c) soil topographic in for a selected watershed.

Hydrologically Sensitive Areas(HSAs)

- Areas having higher potential to generate runoff
- We delineated HSAs by using STI values grater than equal to 10
- HSAs area made up of approximately 27 percent of the watersheds

Land Use Matrix and Water Quality Data

- 2007-land use data from NJDEP was used for watersheds and their HSAs
- Total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) for each watershed was obtained from National Water Quality Monitoring Council
- Water quality data were used from 2006 to 2008 for each station

Statistical Analysis

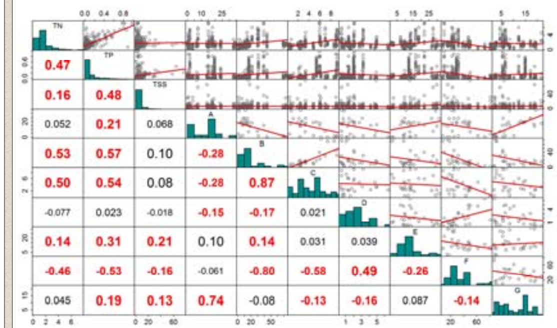
- To understand the relationship between land use matrix and water quality data of watershed and their HSAs following linear missed model was used in R platform: $Y_{ij} = \boldsymbol{\beta X_i} + u_i + \varepsilon_{ij}$
- Where i was the index for watershed and j was the index for the number of measurements on water quality varying by watershed, Y_{ij} was the observed water quality for watershed I, $\boldsymbol{X_i}$ was a land use matrix, $\boldsymbol{\beta}$ represented the fixed effects of these predictors, u_i represents the random effect due to the unique characteristics of watershed i, and ε_{ij} is the residual
- A backward stepwise elimination of predictors was performed using Akaike information criterion (AIC)

Results and Discussion

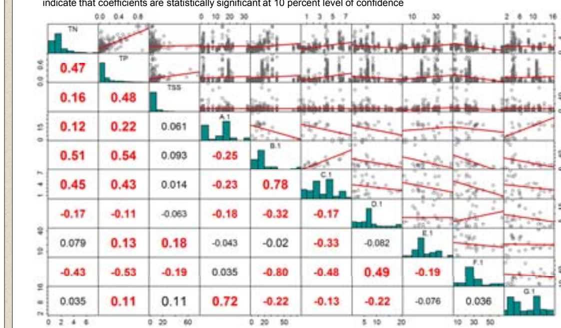
Descriptive Statistics of Explanatory Variables

		In Watershed			In HSAs		
Land use (%)	Total N	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Agricultural land	28	13.43	0.06	34.10	12.98	0.11	33.07
Forest	28	36.11	8.19	80.94	30.36	7.37	64.62
High medium density urban land	28	20.26	1.23	72.63	17.30	1.28	73.15
Low density urban land	28	3.91	0.46	9.07	2.77	0.41	6.57
Rural residential	28	9.72	1.96	21.66	7.14	1.63	15.94
Water	28	2.08	0.35	6.43	7.24	0.80	19.73
Wetlands	28	14.49	1.66	31.45	22.19	3.38	42.88

Visualization of Data and Correlation:



Spearman Correlation Matrix for water quality indicators and land uses. A for agricultural land, B high medium density urban land, C low density urban land, D water, E wetlands, F forest, and G rural residential; Bold numbers indicate that coefficients are statistically significant at 10 percent level of confidence



Spearman's Correlation Matrix for water quality indicators and land uses in HSAs: A.1 for agricultural land, B.1 high medium density urban land, C.1 low density urban land, D.1 water, E.1 wetlands, F.1 forest, and G.1 rural residential; Bold numbers indicate that coefficients are statistically significant at 10 percent level of confidence

Relationship Between TN and Land Use Matrix:

	Watershed Scale Model		HSA Scale Model	
Predictors	β-value	p-value	β-value	p-value
Intercept	0.308***	0.000	0.304***	0.000
Agricultural land	0.263**	0.017	0.205*	0.085
Low density urban land	0.424***	0.006	0.336**	0.026
High medium density urban land	0.033	0.811		
Wetlands	0.053	0.536	0.090	0.375
Forest			-0.108	0.391
Model Evaluation Statistic				
AIC	349.37		351.01	
BIC	375.21		376.84	
Loglik	-167.68		-168.50	

Relationship Between TP and Land Use Matrix:

	Watershed Scale Model		HSA Scale Model	
Predictors	β-value	p-value	β-value	p-value
Intercept	-2.821***	0.000	-2.859***	0.000
Agricultural land	0.301*	0.066	0.143	0.434
Low density urban land	0.683***	0.000	0.401*	0.085
Wetlands	0.275**	0.039	0.293*	0.077
Forest			-0.272	0.181
Model Evaluation Statistic				
AIC	729.73		734.65	
BIC	753		761.8	
Loglik	-358.86		-360.32	

*** significant with at least 1 percent level of confidence; ** 5 percent level of confidence; and * 10 percent level of confidence

Conclusions

- Low density urban land significantly contributed to elevated TN and TP concentration in streams at both watershed and HSA scales.
- Agricultural land and wetlands increased while forest reduced TN, TP or TSS concentration in streams with varying levels of statistical significance.
- The HSA scale model emphasized the positive impacts of forest in water quality improvement.
- This study supports the hypothesis that land uses HSAs have similar or comparable significant impacts on in-stream water quality as the land uses in entire watersheds do.

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