

# Nutrient and Sediment Modeling in Watersheds across an Urban–Rural Gradient



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December 20, 2015

Hixon Fellowship Final Report

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# Introduction

## Ecosystem Services

Healthy ecosystems provide services that human populations rely on and often require, such as clean water, clean air, and plant pollination. The term “ecosystem services”, referring to these beneficial functions of an ecosystem, is a relatively new one, but the idea has been around for much longer. In 1897, the U.S. Forest Service created national forests to provide “favorable conditions of water supply” and a “continuous supply of timber”, both important ecosystem services (Forest Service Organic Administration Act 1897). Beginning in the late 1990’s, environmentalists began to argue that ecosystem services can be valued like any other service in the economy (Costanza et al. 1997), and that environmental degradation has economic consequences (Daily 1997). The Millennium Ecosystem Assessment popularized the term in 2005 (Thompson 2012) and now a growing number of studies and programs, such as the Natural Capital Project, seek to measure and assign a monetary value to ecosystem services.

Intact watersheds provide several ecosystem services, including water purification (Ernst et al. 2004), groundwater and surface flow regulation, erosion control, and streambank stabilization (Brauman et al. 2007). Erosion control and streambank stabilization prevent the deposition of large amounts of sediment into drinking water reservoirs, while water purification prevents large amounts of nutrients or pathogens from collecting in the reservoirs (Brauman et al. 2007).

However, the ability of a watershed to provide ecosystem services declines as it becomes more developed and degraded (Bernhardt et al. 2005; Palmer et al. 2009). For this reason, many cities across the U.S. have moved to protect some of the land in their municipal watersheds to retain ecosystem service and to prevent conversion of the watershed to development or cropland. In almost all cases, it is not feasible for the city to protect all land within the boundary of its water supply watershed, as full protection requires the purchase of land or the creation of an easement. Instead, city planners must focus their land protection activities on the parcels of land within the watershed that have the greatest impact on the functioning of the watershed. These parcels would include riparian areas, areas of high slope, areas likely to be developed, and current agricultural or industrial areas that negatively affect water quality (Cretaz and Barten 2007; Alcott et al. 2013).

## The Passumpsic and Farmington Watersheds

The Passumpsic River watershed is the more forested watershed in the study with 77% forest cover and only 6% developed cover, represents the rural end of the urban-rural gradient. The Farmington River watershed, by comparison, is relatively developed with 67% forested cover and 16% developed cover, and represents the urban end of the rural-urban gradient. The Farmington watershed also contains the Barkhamstead and Nepaug Reservoirs, the municipal water supply for the city of Hartford, a city of 125,000 and the capital of Connecticut.

## Sediment and Nutrient Retention Models

The Integrated Valuation of Environmental Services and Tradeoffs (InVEST) model is a tool, created by the Natural Capital Project and The Nature Conservancy, that provides users with a map of areas of particular importance to sediment or nutrient retention, as well as an estimate of annual yield for the outlet of the watershed. A related model, Resource Investment Optimization System (RIOS), is a tool that uses sediment or nutrient retention information from InVEST to calculate the value of this retention provided by the modeled watershed. Though these tools are widely used, there has only been one published paper on the use of these models together, and their accuracy was not rigorously evaluated (Ruckelshaus et al. 2014). The InVEST model predicts sediment retention based off of the Universal Soil Loss Equation, which has several shortcomings, including the fact that it "...is not event responsive, providing only an annual estimate of soil loss. It ignores the processes of rainfall-runoff, and how these processes affect erosion, as well as the heterogeneities in inputs such as vegetation cover and soil types"(Merritt et al. 2003).

The USLE is spatially and temporally lumped, which means that the model assumes the process of sediment movement occurs uniformly across space and time in the watershed. However, it is possible to create a physics-based, distributed flow and sediment model, which requires more information about precipitation and sediment concentration, but is generally more accurate (Beven and Kirkby 1979; Conroy et al. 2006).

In contrast, the SWAT model is more established and incorporates many more variables into its estimates of nutrient and sediment loading. From Wikipedia:

"SWAT (Soil & Water Assessment Tool) is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds. ...It is a hydrology model with the following components: weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, and water transfer. .... This model is used worldwide and is continuously under development. As of July 2012, more than 1000 peer-reviewed articles have been published that document its various applications."

# Study Objectives and Hypothesis

## *Study Objectives:*

- To assess the accuracy of existing models (InVEST and ArcSWAT) within the Passumpsic and Farmington watersheds and to compare InVEST and SWAT to an alternative physics-based, distributed model of flow and sediment movement, using observed streamflow and sediment data (built into SWAT) if time allows.
- To use the more accurate model within RIOS to evaluate the best land acquisition strategy for reducing sedimentation and nutrient loading in Hartford's reservoirs.

## *Hypotheses:*

- The InVEST model will provide annual sediment value within our expected range (given our in-stream measurements), but this will not give us much information about the source of sediment loading within the watersheds or the seasonal variability of sediment deposition.
- The default SWAT model and its physically-based submodel will provide more information about each of the subwatersheds, leading to a more accurate prediction of the value of various management practices (determined by RIOS).

# Methods

## Study Area

The Passumpsic watershed has an area of 1125 km<sup>2</sup> and ranges from 137-1048 meters above sea level. The Farmington watershed has an area of 1571 km<sup>2</sup> and ranges 0.2-675 meters above sea level.

These watersheds have several advantages as study sites. Validating model predictions in the Passumpsic is aided by the presence of 8 active USGS gauges that measure instantaneous discharge in ft<sup>3</sup>/sec, which are located on third, fourth, fifth, and sixth order streams within the watershed, providing spatial and temporal information about the movement of water within the river system. Similarly, the Farmington watershed contains 22 USGS gages, and these gages are similarly nested among stream orders.

This spatial and temporal data is very important for validating spatially explicit, physically-based models, and also provides accurate information for InVEST and SWAT, though within InVEST this information is averaged into one annual number (SWAT has a daily time-step option). Water quality data, including total suspended solids (TSS), has been collected at these USGS gauges for several decades, but the data collection is infrequent (less than once per year on average), and needs to be supplemented by other information. For this reason, grab samples have been taken before, during, and after storm events during

the summer and fall of 2015. These grab samples were taken near the locations of the USGS stream gauges, so that both TSS and discharge data would be available at each of these sites. These samples were filtered for sediment, and the filter was dried and weighed to give TSS in mg/L. Separately, ion chromatography and a flow analyzer was used to calculate the concentration of N and P species in the grab samples.

Additionally, there are NOAA weather stations located near or within both watersheds, which can be interpolated to create a grid of rainfall and temperature data. These provide information about the intensity of precipitation by measuring mm of rainfall per hour. This can be converted into megajoules and used to estimate the amount of sediment eroded by rainfall, a component of any sediment retention model. Figure 1 illustrates the location of protected areas within the two watersheds.

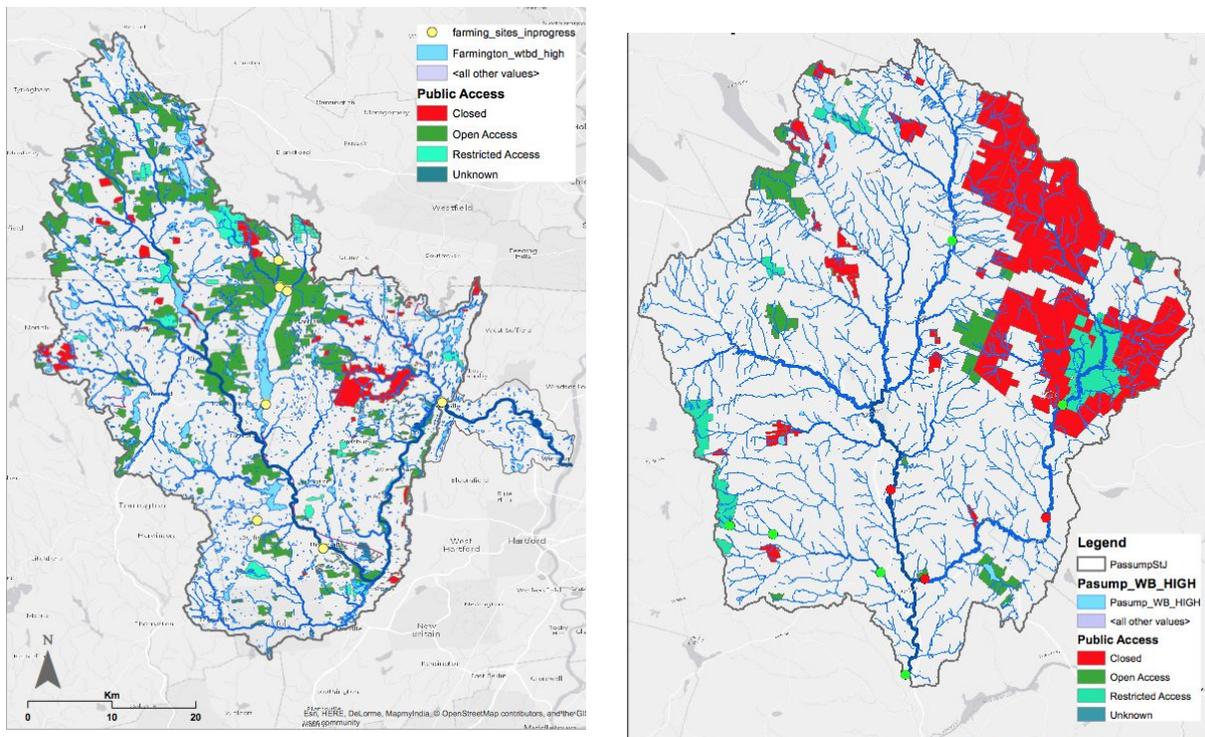


Figure 1. Protected areas within the Farmington and Passumpsic watersheds.

## Modeling Effort

Several tools were used in the preprocessing of the spatial data used in these models. First, in order to aid in the selection of sampling sites, the Farmington River stream network was attributed with stream orders. The NHD High Resolution stream network does not come with stream orders as an attribute of the shapefile, so QGIS and a series of scripts from

Matthew Schultz were used to determine a stream's order. Oxbows and braided channels needed to be manually attributed.

Next the USDA's Soil Data Viewer was used to process spatial soil data from the gSSURGO dataset. Often, SSURGO has multiple records for a single point, because information about multiple soil horizons is included in the database. The Soil Data Viewer is an add-on to ArcMap, and its interface allows the user to select a soil attribute (e.g. K Factor, Rock Free) and a aggregation method (e.g. Weighted Average). A shapefile is produced with no more than one value per point (though data may be missing for large areas, depending on the soil attribute). These shapefiles were converted to rasters and used in the InVEST models.

Researchers at the University of Texas created a MODIS Toolbox, which imports MOD16 ET data into ArcMap and re-projects it from its native sinusoidal projection. Additionally, I created a script that would fill in any missing ET data by taking an average of the surrounding 8 cells.

Raster data was re-projected into either the NAD 1983 HARN StatePlane Vermont FIPS 4400 (Meters) Coordinate System or the NAD 1983 HARN StatePlane Connecticut FIPS 0600 (Meters) Coordinate System. Categorical data were re-projected using the Nearest resampling algorithm, while continuous data were re-projected using the Bilinear resampling algorithm.

Finally, I created subwatersheds from a Python script that used the locations of the USGS gages and flow direction and accumulation rasters obtained from the DEM.

## InVEST

<b>InVEST Data Requirement</b>	<b>Source</b>
DEM	USGS National Elevation Dataset at 1/3 Arc-Second Resolution
Root restricting layer	Natural Resources Conservation Service gSSURGO Database
Precipitation	PRISM Climate Group Annual Gridded Precipitation
Plant Available Water Content	Natural Resources Conservation Service gSSURGO Database
Average Annual Reference Evapotranspiration	MODIS Global Evapotranspiration Project (MOD16) ET
Land Use/Land Cover	National Land Cover Database 2011
Subwatersheds	Self-created from gage locations and DEM
Biophysical Table	Modified from table included with InVEST software
Seasonality Parameter	Floating point value on the order of 1 to 30 corresponding to the seasonal distribution of precipitation, user defined

Threshold flow accumulation value	Integer value defining the number of upstream cells that must flow into a cell before it's considered part of a stream, user defined
Water Purification threshold table	A .csv table containing annual nutrient load threshold information for each of the points of interest in kg/yr, user defined
Rainfall erosivity index (R)	A variable capturing the duration and intensity of annual rainfall, with units of $\text{MJ} \cdot \text{mm} \cdot (\text{ha} \cdot \text{h} \cdot \text{yr})^{-1}$ , calculated from the PRISM dataset
Soil erodibility (K)	A variable capturing the erodibility of the soil, with units of $\text{ton} \cdot \text{ha} \cdot \text{h} \cdot (\text{ha} \cdot \text{MJ} \cdot \text{mm})^{-1}$ , from the gSSURGO database

## Water Yield

This is the general equation used in the water yield model:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \cdot P(x)$$

For vegetated pixels, the following equations are used to calculate  $AET(x)/P(x)$ :

$$\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + \left(\frac{PET(x)}{P(x)}\right)^\omega\right]^{1/\omega}$$

$$PET(x) = K_c(\ell_x) \cdot ET_0(x)$$

$$\omega(x) = Z \frac{AWC(x)}{P(x)} + 1.25$$

For non-vegetated (e.g. urban) pixels, this equation is used to calculate  $AET(x)$ :

$$AET(x) = \text{Min}(K_c(\ell_x) \cdot ET_0(x), P(x))$$

## SDR

The Sediment Delivery Ratio model uses the USLE equation:

$$usle_i = R_i \cdot K_i \cdot LS_i \cdot C_i \cdot P_i$$

$$LS_i = S_i \frac{(A_{i-in} + D^2)^{m+1} - A_{i-in}^{m+1}}{D^{m+2} \cdot x_i^m \cdot (22.13)^m}$$

where

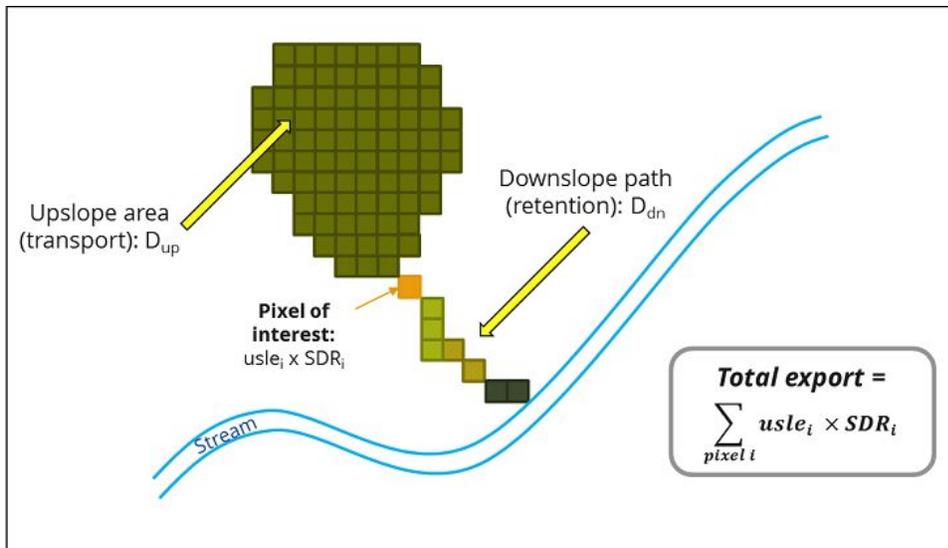
- $S_i$  the slope factor for grid cell calculated as function of slope radians  $\theta$ 
  - $S = 10.8 \cdot \sin(\theta) + 0.03$  where  $\theta < 9\%$
  - $S = 16.8 \cdot \sin(\theta) - 0.50$ , where  $\theta \geq 9\%$

The USLE is multiplied by SDR using the following equations:

$$D_{up} = \bar{C} \bar{S} \sqrt{A} \quad D_{dn} = \sum_i \frac{d_i}{C_i S_i} \quad IC = \log_{10} \left( \frac{D_{up}}{D_{dn}} \right)$$

$$SDR_i = \frac{SDR_{max}}{1 + \exp \left( \frac{IC_0 - IC_i}{k} \right)}$$

Schematic of how export of each cell is calculated:



## Nutrient Retention

Nutrient retention and export are routed through cells using the following equations:

$$ALV_x = HSS_x \cdot pol_x \quad HSS_x = \frac{\lambda_x}{\lambda_W} \quad \lambda_a = \log \left( \sum_U Y_u \right)$$

Cell	Vegetation retention	ALV	Retained by Cell (retained)	Outflow quantity (OQ) from Cell (Gi=1-Ei)
1	E1	ALV1	0	ALV1
2	E2	ALV2	ALV1×E2	ALV1×G2+ALV2
3	E3	ALV3	((ALV1×G2+ALV2)×E3)	(ALV1×G2+ALV2)×G3+ALV3
4	E4	ALV4	ALV1×G2×G3×E4+ ALV2×G3×E4+ ALV3×E4	ALV1×G2×G3×G4+ ALV2×G3×G4+ ALV3×G4+ ALV4

## ArcSWAT

ArcSWAT Data Requirement	Source
DEM	USGS National Elevation Dataset at 1/3 Arc-Second Resolution
Land Use/Land Cover	National Land Cover Database 2011
Soil Database	Natural Resources Conservation Service SSURGO database or STATSGO database
Optional ArcSWAT Data	Source
Subbasin outlet location table	USGS stream gaging stations
Precipitation gage location table	NOAA GHCN-Daily and CoCoRaHS weather stations
Temperature gage location table	NOAA GHCN-Daily and CoCoRaHS weather stations

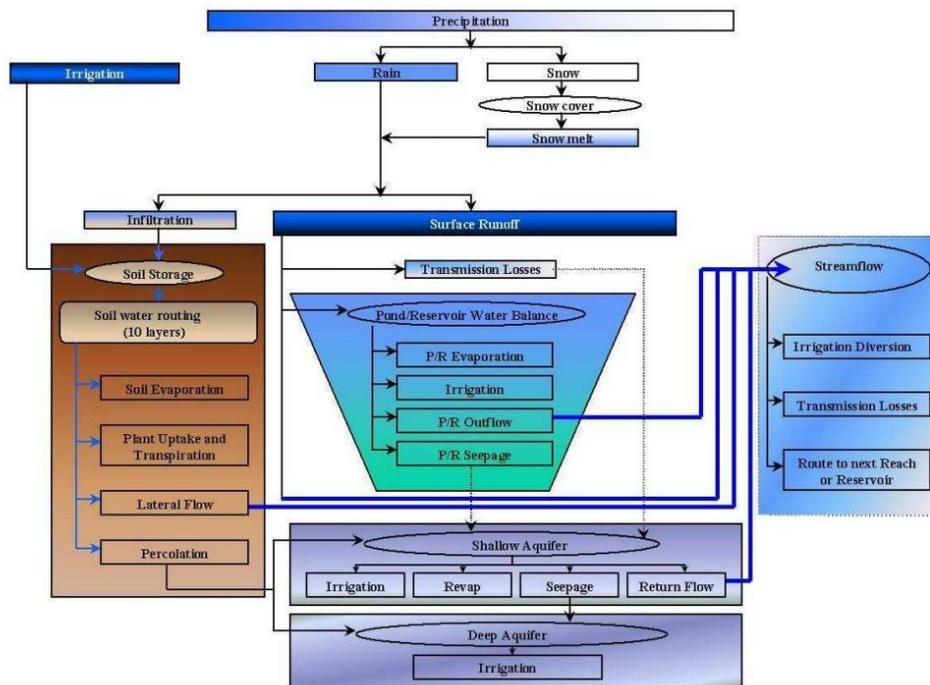


Figure 1.5: Schematic of pathways available for water movement in SWAT

Figure 2. ArcSWAT models many more hydrologic processes than does the InVEST Water Yield model.

## PHOSPHORUS

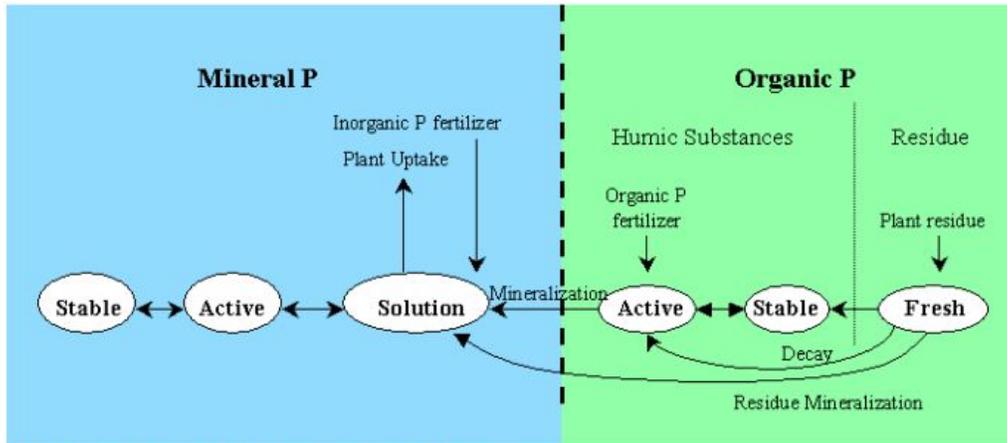


Figure 0.7: Partitioning of Phosphorus in SWAT

## NITROGEN

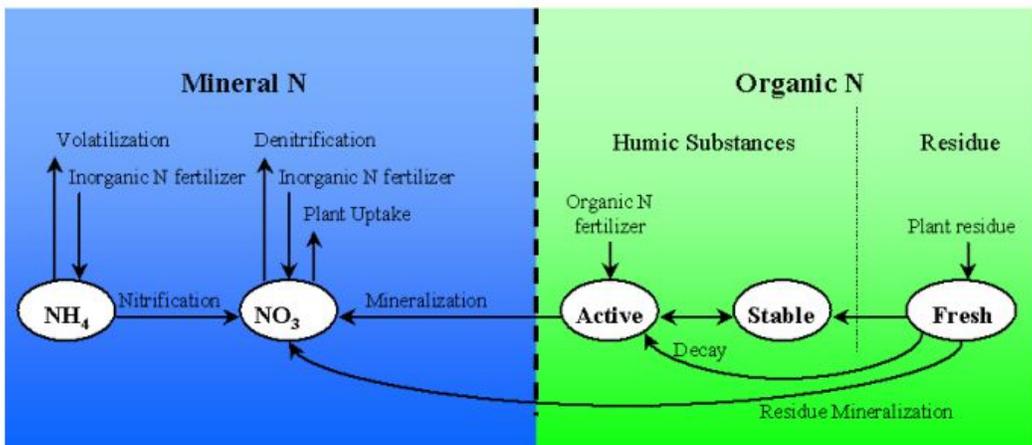


Figure 0.6: Partitioning of Nitrogen in SWAT

### Water Routing

ArcSWAT water routing equation. Each variable in the equation is itself calculated from model inputs.

$$V_{stored,2} = V_{stored,1} + V_{in} - V_{out} - loss - E_{ch} + div + V_{bnk}$$

### Sediment Routing

- Landscape Component = MUSLE - lag
- Channel Component = Simplified Bagnold Equation (default method) OR 1 of 4 Physically Based Methods (simplified Bagnold model, Kodatie model, Molinas and Wu model, Yang sand and gravel model)

## Sampling Effort

In order to validate the modeled data, data was collected in the field throughout the summer and fall of 2015. Nine Eureka Manta Multiparameter Water Quality Recorders were installed in the Passumpsic watershed and eight were installed in the Farmington watershed. Every fifteen minutes, the Eureka probes record air pressure, water depth, pH, specific conductivity, temperature, optical dissolved oxygen, turbidity, colored dissolved organic matter (at one or two wavelengths depending on the model), reduction potential, and chlorophyll-a (in some models).

Additionally, storm samples, low flow samples, and synoptic samples were taken throughout the summer and fall of 2015. Depending on the type of sample, several analyses were performed, including calculating orthophosphate, nitrate, and suspended sediment concentrations.

# Preliminary Results

InVEST

Passumpsic

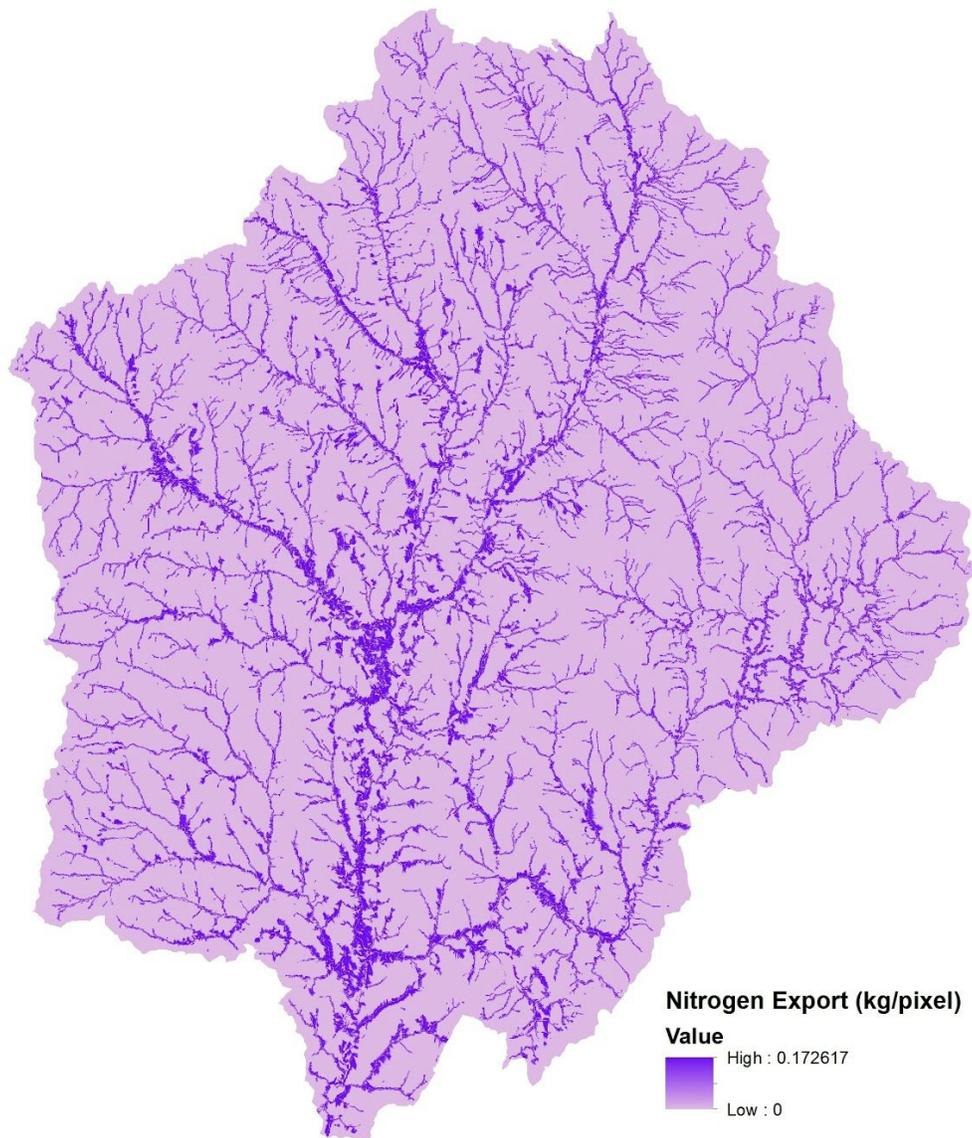


Figure 3. Spatial distribution of annual nitrogen export in the Passumpsic watershed for the year 2013.

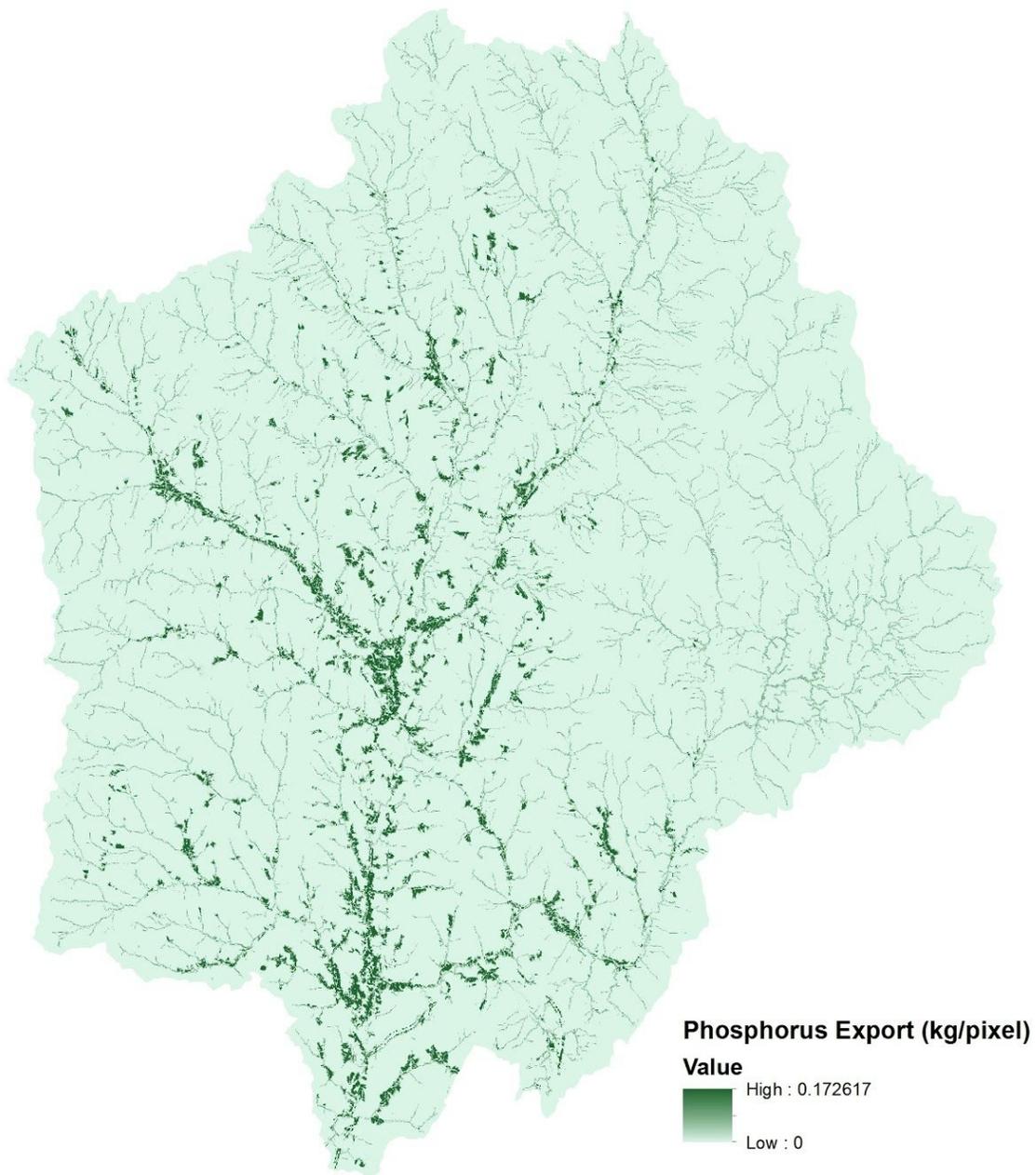


Figure 4. Spatial distribution of annual phosphorus export in the Passumpsc watershed for the year 2013.

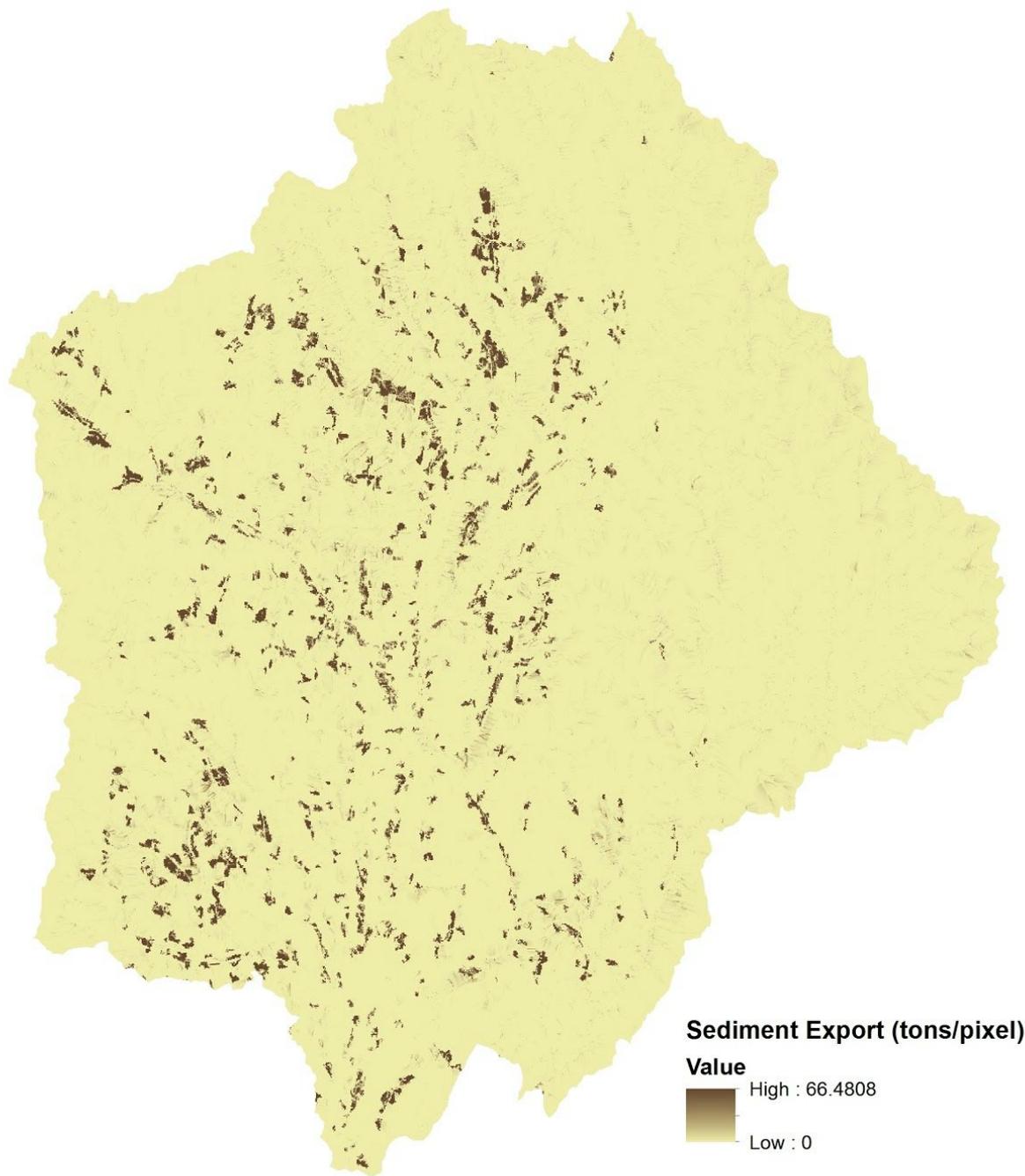


Figure 5. Spatial distribution of annual sediment export in the Passumpsic watershed for the year 2013.

# Farmington

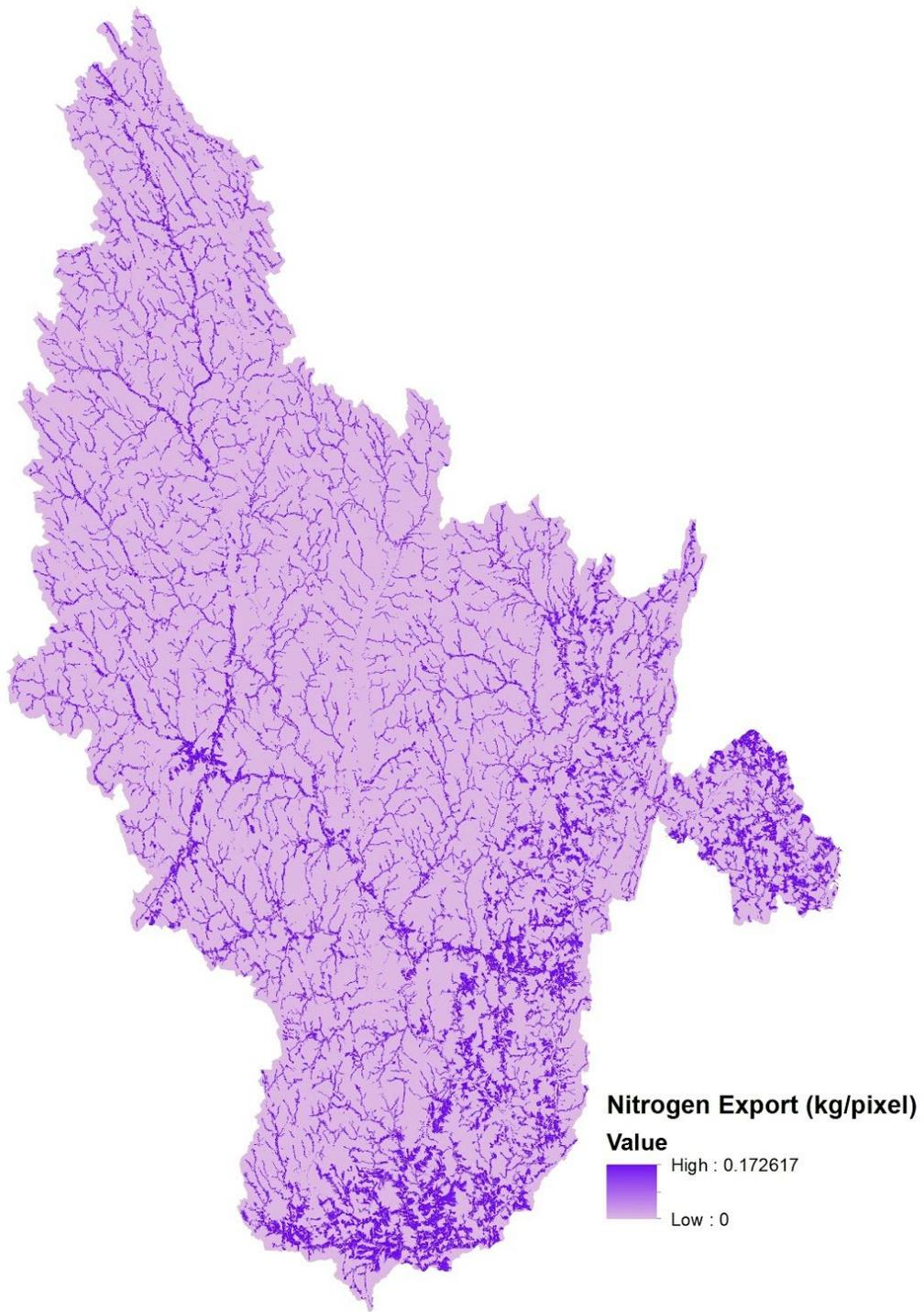


Figure 6. Spatial distribution of annual nitrogen export in the Farmington watershed for the year 2013.

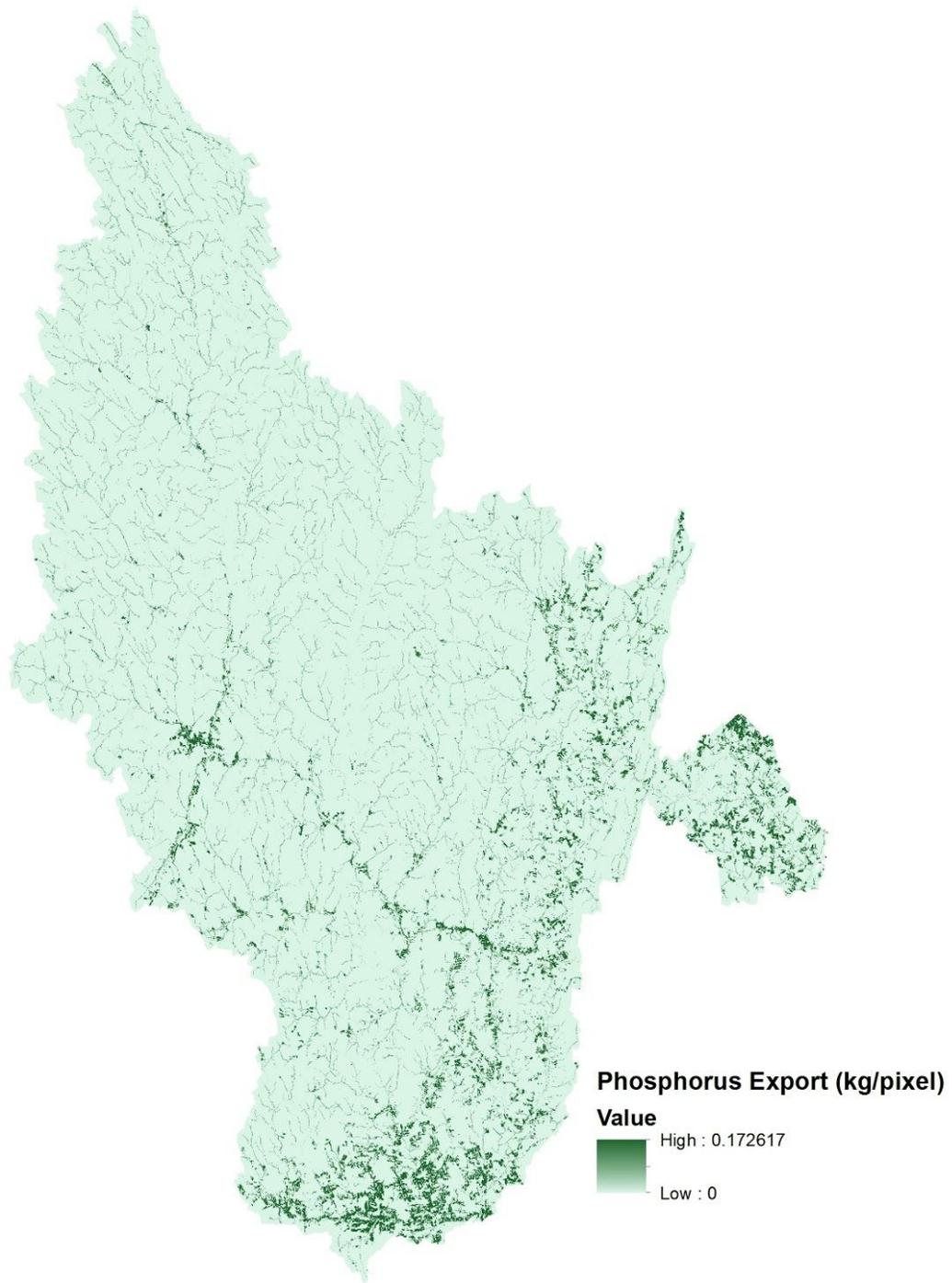


Figure 7. Spatial distribution of annual phosphorus export in the Farmington watershed for the year 2013.



Figure 8. Spatial distribution of annual sediment export in the Farmington watershed for the year 2013. Soil erodibility (K Factor) data was more available in the MA portion of the watershed than the CT portion.

Table 1. Results for both watersheds from the Nutrient Retention and SDR models. Low sediment export values for the Farmington are probably due to incomplete soil data coverage.

	<b>Passumpsic</b>	<b>Farmington</b>
<b>Total Annual N Export (kg)</b>	17,533.95	35,157.53
<b>Total Annual P Export (kg)</b>	1,600.33	2,494.72
<b>Total Annual Sediment Export (tons)</b>	21,385,969.11	34,224.85

## ArcSWAT

### Passumpsic

Table 2. Monthly and annual results from 2013.

<b>Month</b>	<b>PRECIP</b>	<b>ET</b>	<b>PET</b>	<b>Water Yield</b>	<b>Sediment Yield</b>	<b>NO3 SURQ</b>	<b>P Organic</b>
	<i>(mm)</i>	<i>(mm)</i>	<i>(mm)</i>	<i>(mm)</i>	<i>(mm)</i>	<i>kg/ha</i>	<i>kg/ha</i>
1	54.99	5.49	12.13	14.98	0.03	0	0.01
2	58	14.32	20.18	65.46	0.3	0	0.14
3	93.05	33.89	47.75	62.18	0.21	0.01	0.12
4	64.46	48.34	109.98	15.35	0.01	0.02	0
5	43.75	53.79	158.14	14.77	0.02	0.03	0.01
6	53.09	61.07	173.64	8.18	0.02	0.05	0.01
7	80.83	95.96	159.83	9.28	0	0.01	0
8	41.53	59.55	163.1	4.75	0	0	0
9	116.55	66.51	105.37	19.46	0.03	0.02	0.02
10	102.4	57.87	88.27	27.07	0.03	0.02	0.02
11	122.23	30.41	38.52	21.04	0.03	0.03	0.01
12	36.35	17	23.91	36.74	0.1	0.01	0.04
<b>Total 2013</b>	867.23	544.2	1100.84	299.25	0.78	0.22	0.37

## Farmington

Table 3. Monthly and annual results from 2013.

<b>Month</b>	<b>PRECIP</b>	<b>ET</b>	<b>PET</b>	<b>Water Yield</b>	<b>Sediment Yield</b>	<b>NO3 SURQ</b>	<b>P Organic</b>
	<i>(mm)</i>	<i>(mm)</i>	<i>(mm)</i>	<i>(mm)</i>	<i>(mm)</i>	<i>kg/ha</i>	<i>kg/ha</i>
1	85.31	10.83	16.16	54.33	9.33	0.03	0.01
2	98.32	17.63	22.65	82.51	13.89	0.07	0.02
3	77.32	29	42.54	62.37	6.4	0.11	0.01
4	29.17	35.87	103.78	28.21	0.33	0.06	0
5	63.17	55.55	130.86	26.33	2.12	0.1	0
6	39.44	49.38	139.33	10.22	0.63	0.08	0
7	143.11	79.35	144.52	42.9	4.5	0.03	0.01
8	42.2	53.94	124.17	13.65	0.35	0	0
9	91.68	43.09	86.79	42.9	2.99	0.01	0.01
10	63.61	33.95	62.39	17.66	0.72	0	0
11	161.75	16.91	21.83	47.45	2.88	0.01	0
12	150.64	17.84	22.43	94.04	13.24	0.02	0.01
<b>Total 2013</b>	1045.72	443.33	917.47	522.57	57.39	0.52	0.08

Table 4. Annual results for 2013 for both watersheds.

	<b>Passumpsic</b>	<b>Farmington</b>
<b>Total Annual NO<sub>3</sub> Export (kg)</b>	24,763.2	81,570.32
<b>Total Annual Organic P Export (kg)</b>	41,647.2	12,549.28
<b>Total Annual Sediment Export (m<sup>3</sup>)</b>	6.46*10 <sup>7</sup>	8.99*10 <sup>7</sup>

# Model Validation

Passumpsic

InVEST

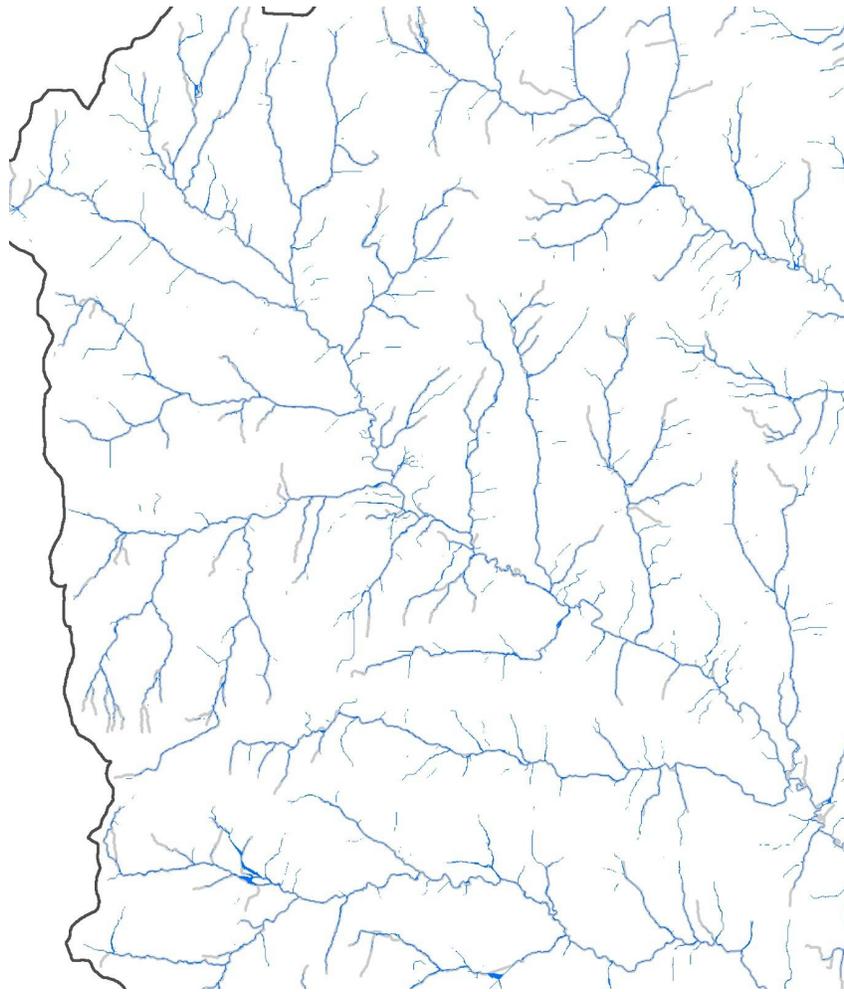


Figure 9. Stream network created by InVEST (blue) and NHD High Resolution stream network (grey).

Table 5. InVEST Water Yield for the Passumpsic is good approximation of actual yield, but tends to overestimate yield.

Subshed ID	Number of Pixels	Precipitation (mm)	PET (mm)	AET (mm)	Water Yield (mm)	Water Yield (m <sup>3</sup> )	Actual Water Yield (m <sup>3</sup> )	Predicted /Actual
1	152068	1,238.73	558.31	403.72	826.24	113,000,000.00	119,077,278.38	0.95
2	8101	1,245.26	550.49	349.64	895.52	6,529,161.00	Ungaged	N/A
3	208530	1,228.57	546.08	368.09	858.77	161,000,000.00	140,433,436.31	1.15
4	9036	1,247.47	560.13	395.42	851.93	6,928,227.00	6,067,507.35	1.14
5	114640	1,144.53	545.60	393.16	749.83	77,364,450.00	65,519,048.45	1.18
Passump Outlet	1,250,631	1,181.22	534.33	389.34	783.57	882,000,000.00	749,452,147.14	1.18

### ArcSWAT

Table 6. ArcSWAT water yield underestimated water yield, but actual weather station data has yet to be incorporated.

	Predicted Water Yield (m <sup>3</sup> )	Actual Water Yield (m <sup>3</sup> )	Predicted/Actual
Passumpsic Outlet	336,800,000	749,452,147.14	0.45

# Farmington

InVEST

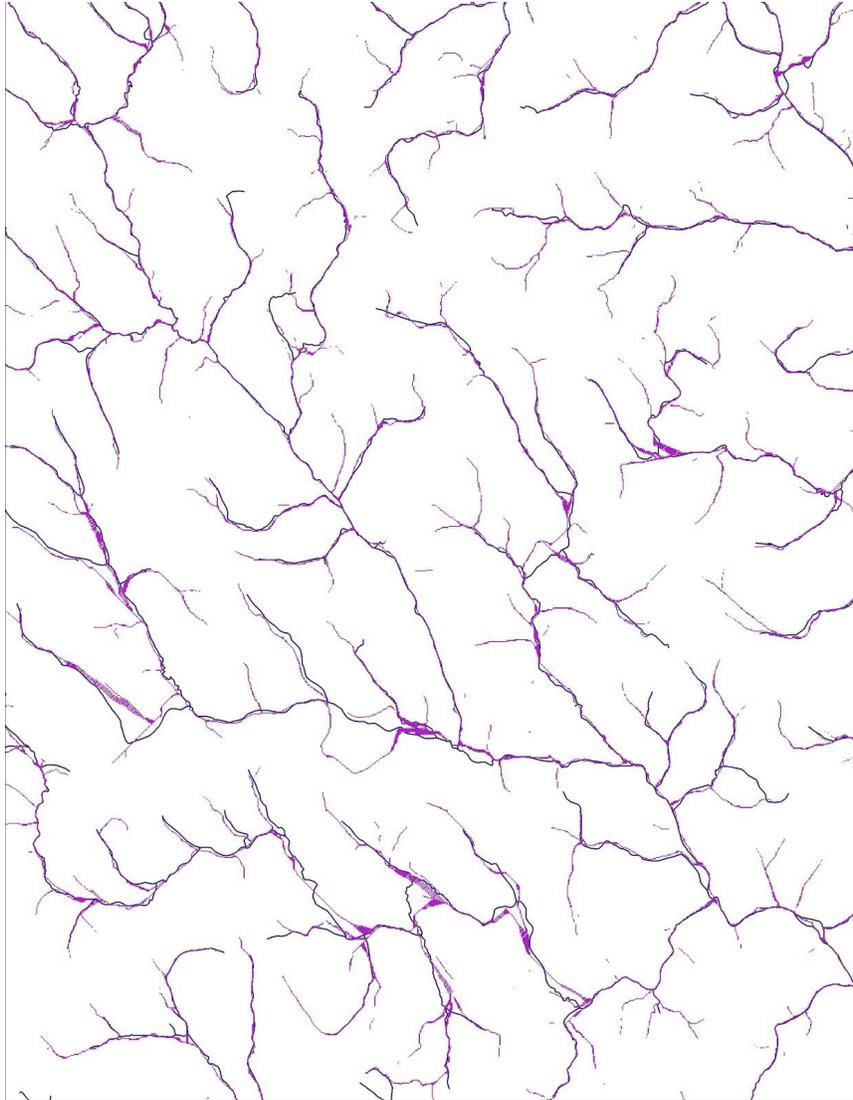


Figure 10. InVEST approximation of Farmington stream network (pink) and NHD High resolution stream network (grey).

Table 7. InVEST Water Yield for the Farmington is good approximation of actual yield, but tends to overestimate yield. Five gages were not active in 2013, and their yield could not be validated.

Subshed ID	Number of Pixels	Precipitation (mm)	PET (mm)	AET (mm)	Water Yield (mm)	Water Yield (km3)	Actual Yield (km3)	Predicted/Actual
1	265,118.00	1,251.59	623.10	407.84	784.57	0.19	0.17	1.09
2	246,668.00	1,317.26	620.36	421.00	855.11	0.19	0.20	N/A
3	59,750.00	1,306.06	659.35	413.46	866.04	0.05	0.05	0.99
4	20,442.00	1,307.60	666.03	413.28	888.13	0.02	N/A	N/A
5	66,138.00	1,354.02	611.34	429.62	917.43	0.05	N/A	N/A
6	11,232.00	1,330.40	578.19	417.36	899.49	0.01	0.01	1.14
8	128,367.00	1,264.24	470.33	334.08	905.99	0.10	N/A	N/A
9	21.00	1,243.43	387.72	348.34	895.09	0.00	N/A	N/A
Farmington Outlet	1,746,127.00	1,281.38	580.79	396.11	841.48	1.32	1.15	1.15

### ArcSWAT

Table 8. ArcSWAT Water Yield for the Farmington underestimates yield, but weather station data has not yet been incorporated.

	Predicted Water Yield (km <sup>3</sup> )	Actual Water Yield (km <sup>3</sup> )	Predicted/Actual
Farmington Outlet	0.82	1.15	0.71

# Discussion

Currently, the models are in agreement that N loading is higher in the Farmington River watershed than the Passumpsic River watershed, both in terms of total loading and when normalized to watershed area. This would make sense given the higher level of development (agricultural, industrial, and residential) in the Farmington watershed. The models were not in agreement with regards to phosphorus loading normalized to watershed area, with the InVEST model predicting similar loadings and the ArcSWAT model predicting higher loadings in the Passumpsic watershed. Similarly, the models were not in agreement in predicting sediment loading. The InVEST model predicted much higher loads in the Passumpsic than the Farmington, probably due to missing soil data in the Farmington. The ArcSWAT model predicted little difference.

Once fully calibrated, the results of this study will help to locate the areas that contribute the most nitrogen, phosphorus, and sediment to each river system. These areas can be targeted for land protection and other conservation practices, which ultimately can improve urban drinking water quality.

Often models that are meant to aid in land management decisions are built to accept very coarse data in order to facilitate ease of use of the model in data poor regions. While these models can provide some insight, they may be too simplistic to take advantage of the higher quality data available in data-rich areas, like the Connecticut River watershed. This project compares the utility of a simplistic model (InVEST) to a model that accepts many types of detailed data (ArcSWAT). This study improves understanding of the appropriateness of widely used models in a well-studied ecosystem. An accurate hydrologic and watershed erosion model for these watersheds will inform and facilitate optimized conservation activities, such as planting riparian buffers, for sediment/nutrient retention and surface water quality protection.

## Next Steps

### Modification of Models

Both the InVEST and ArcSWAT models can be modified in order to more closely fit data collected in the field. This can be done by adding more data (ArcSWAT) or modifying the model's code (InVEST).

My initial attempts to modify the Python code of InVEST were only partially successful. I was able to un-compile, modify, and recompile the code, but the resulting water yield values

were all negative. InVEST has several sub-programs that are called into higher level programs, so I may be able to find the problem later on in the geoprocessing. Ideally, I will be able to get the water yield model to use the MOD16 ET values as actual ET (AET) in the following equation:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \cdot P(x)$$

Currently, the MOD16 values are considered to be reference ET values within the model, and are converted to AET values.

Additionally, my initial attempts to use the NOAA weather station data within ArcSWAT yielded strange results. I hope to be able to combine weather station data for missing dates, which will hopefully improve the water yield predictions.

## Further Validation

While I have been able to validate the water yield results from both InVEST and ArcSWAT, I need to create estimates of annual (and ideally monthly) nutrient and sediment loading in these watersheds. This will allow me to validate the results I obtain from both models with regards to sediment and nutrients, as these results vary widely. The biophysical table in InVEST can easily be modified to match field measurements, as can the Access database associated with ArcSWAT.

To do this I will need to gather all  $\text{NO}_3$ , orthophosphate, and TSS results and plot them against discharge at the time of sampling. This will give me a means to estimate average flux over the month and year, though I will not have access to concentrations taken at all discharges, and will have to extrapolate quite a bit.

For the InVEST SDR model, values might be high due to lack of in-stream process deposition, which isn't included in the model. However, the model also doesn't take into account bank erosion, so these values could be low for that reason. For the InVEST Nutrient Retention model, the predicted values could be high due to lack of modeling of in-stream uptake and nutrient degradation. However, the model also doesn't include saturation in plant uptake, so these values could also be low.

## Incorporating RIOS

In the spring term, I want to use a calibrated InVEST model in conjunction with the RIOS model as a means of valuing the ecosystem services provided by the watershed. This will require further research on the cost of dredging and treating the water in these watersheds.

## Conclusions

Though there is not yet agreement between these models, processing the required spatial data and creating a “baseline” run without modifications is an important first step. This baseline data, created with the best data available, will serve as a comparison point for future model runs.

Still, these baseline runs produced very different results in all areas. The InVEST model tended to moderately overestimate water yields, while the ArcSWAT model tended to drastically underestimate them. Additionally, the predicted nutrient values vary by an order of magnitude between the two models.

Ideally, once calibrated, these models will together be able to predict the spatial and temporal patterns of sediment and nutrient loading in the Passumpsic and Farmington watersheds. These calibrated models could then simplify future land use planning.