Assessing the Hydrologic Implications of Land Use Change for the Upper Neuse River Basin

By

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Abstract

Land cover plays a vital role in the chemistry and the quantity of runoff, and therefore can indirectly have an immense impact on the water quality of stream and river systems. Simulation models have become extremely useful tools available to watershed managers as geospatial environmental datasets become increasingly more available. The Soil and Water Assessment Tool (SWAT) is a deterministic hydrologic model that can predict hydrologic conditions over various temporal and spatial scales. This project evaluates the accuracy of the SWAT model for the Upper Neuse River Basin, while comparing two land use scenarios in an effort to identify sensitive regions in the watershed. A regression analysis between observed and predicted stream velocity demonstrated that the initial model required calibration of stream parameters in order to more accurately model the natural system. After calibration, stream sedimentation values were compared by subbasin between a current (2001) and future (2010) land use scenario, in order to identify areas in the watershed that were the most susceptible to degradation via urbanization. Out of the 138 catchments delineated in the watershed, 29 experienced no relative change while the remaining 109 all displayed an increase in the relative difference of the sedimentation rate between scenarios. Subbasins with the greatest potential for degradation were identified and prioritized for conservation efforts or further analysis. The subbasins experiencing the highest increase in both the relative change as well as the percent change in sediment yield are all in either Wake or Durham County, suggesting a need for conservation planning in these regions. Moreover, through examining the spatial variability of these results, the influence of regional characteristics like slope, land use and soil type can be exemplified. The tremendous variation in sediment yield that occurs with urbanization suggests that local spatial conditions can exert a noticable influential on water quality and should be taken into account to maximize future management efforts. Overall, environmental tools such as the SWAT model demonstrate their usefulness in helping inform land use decisions, and can assist environmental managers in protecting water quality.

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I. Introduction

Throughout the last century anthropogenic activities have driven extensive changes in land cover, with land use conversion rates increasing exponentially to accommodate expanding cities and the growing demand for natural resources. This shift towards an increasingly urbanized landscape has generated a number of changes in ecosystem structure and function, resulting in an overall degradation of the ecological services provided by the natural system. Ecosystem services are defined as the multiple benefits available to humans, animals and plants that are derived from environmental processes and natural resources (Costanza *et al.* 1997). Ecosystem services provided by surface water systems are vital to the health and success of human development. For example, many urban areas depend heavily on streams to provide water for municipal, agricultural and commercial uses (Meyer *et al.* 2005). Additionally, the primary productivity and leaf litter breakdown within aquatic zones serve as fundamental processes in energy cycles and trophic food webs (Morgan and Cushman 2005). Effective protection and management of ecosystem services requires a complete understanding of the numerous mechanisms that drive these interactions. More specifically for successful water quality management efforts, understanding the hydrologic pathways within terrestrial ecosystems becomes crucial.

When examining the hydrologic cycle, it is clear that land cover plays a vital role in water transport and primarily aids in reducing overland flows. Land cover plays a crucial role in driving the energy balance within the hydrologic cycle due to its effect on evaporation, transpiration and solar radiation interception (Ma 2009). The relationship between land cover and hydrology is complicated even more when small-scale environmental parameters are taken into account. The local level hydrology of watersheds can vary drastically and water flow patterns as well as water quality is often dependent on a combination of elevation, soil and land use characteristics unique to the area. For example, forests have shown to play a critical role in reducing non-point source pollution, particularly when preserved around riparian areas in agricultural watersheds (Walsh *et al.* 2005*b*). Moreover, human activities to modify and redistribute fresh water resources have significantly altered the natural structure of hydrologic systems through the creation of reservoirs and extensive irrigation networks (Vorosmarty and Sahagian 2000). These variations in spatial features can influence the hydrologic characteristics of a regional watershed.

Furthermore, stream systems often display significant signs of ecological degradation as urbanization increases within a watershed. Urbanization can substantially affect the timing, temperature and volume of runoff by increasing the area of impervious surface present in the watershed and decreasing vegetative interception (Nelson *et al.* 2009). The various consequences of urbanization on surface waters has been labeled the "urban stream syndrome" by Meyer *et al.* (2005). Symptoms of affected basins include elevated concentrations of nutrients and contaminants, "flashier" hydrographs, a reduction in the number of smaller streams in the network, altered channel morphology and stability as well as a reduction in biotic diversity (Walsh *et al.* 2005*a*). Often times, species tolerant to the stressed environment dominate the ecosystems, reducing species richness and causing disruptions to local stream communities across varying trophic levels (Morgan and Cushman 2005). Additionally, other symptoms that have been associated with urban stream syndrome include reduced base flow or an increase in suspended solids that generally occurs as forested area is lost and developed land expands (Walsh *et al.* 2005*a*). Therefore, optimal water quality management plans should rely on assessments featuring a combination of natural and anthropogenic influences in order to understand the characteristics of the regional watershed.

In order to account for the natural heterogeneity within watersheds as well as anthropogenic activities, hydrologic simulation models are often employed as watershed management tools. Simulation models have proven useful for planning managers as a form of decision support for evaluating urbanized watersheds. While conservation efforts have often focused on maximizing the quantity of land conserved, research efforts in landscape ecology have shown that the spatial pattern of land conversion can have a significant effect on the function of ecological processes, particularly when examining watershed networks. Recently, many research efforts have been launched to predict the hydrologic response of varying scenarios of land use modification through the development and application of multiple models (Franczyk and Chang 2009; Im *et al.* 2009). Current models vary tremendously in their degree of complexity and can range from statistical simulations, such as a regression analysis or the Spatially Referenced Regressions on Watershed Attributes (SPARROW; Schwarz *et al.* 2006) model, to more process-based water quality models, such as the Soil and Water Assessment Tool (SWAT; Neitsch *et al.* 2005*a*) or the Hydrologic Simulation Program Fortran (HSPF; U.S. EPA 1997), both of which rely heavily on large quantities of input data in order to make predictions on fine spatial and temporal scales (Roberts and Prince 2010; Haverkamp *et al.* 2005; Abdulla *et al.* 2009).

1.1 Objectives

In this study, I used the SWAT 2005 model (Neitsch *et al.* 2005*a*) to explore the implications of land use change on water quality in the Upper Neuse River Basin in North Carolina. I had two primary objectives:

(1) I calibrated the SWAT model to represent the Upper Neuse River Basin. In this, I assessed the model's predictions by comparing the hydrologic simulations on three different temporal scales.

(2) I compared the sediment yield outputs from current land use and a future development scenario, to identify the subbasins with the greatest potential for increased sedimentation.

My results and evaluations can guide further studies on water quality, and inform land use decisions by local counties when reevaluating the region's watershed management plan to aid in protecting the region's natural resources while encouraging smart growth tactics.

2. The SWAT Model

The Soil and Water Assessment Tool (SWAT) is a basin-scale model that operates on a daily time step to predict the impact of land use and management practices on water quality within complex catchments (Arnold and Fohrer 2005). Originally developed by Dr. Jeff Arnold for the USDA Agricultural Research Service, SWAT was chosen for this study for its focus on modeling the hydrological impacts of land use change, while specifically accounting for the interactions between regional soil, land use and slope characteristics (Arnold *et al.* 1998). In SWAT, watersheds are delineated into subbasins, which are further divided into hydrologic response units (HRUs), each of which represents a unique combination of land use, management and soil characteristics. Subbasins are calculated based on topographical data and both temperature and precipitation values are considered homogeneous within a subbasin. HRUs are calculated as the area within each subbasin that reflect a unique combination of land cover, soil type and slope characteristics. It should be noted that HRUs are not synonymous to a field, but rather represent the total area in the subbasin with a particular land use, soil and slope type. Runoff is calculated for each HRU and routed to the subbasin level to obtain total watershed flows (Neitsch 2005*b*).

This model represents hydrological interactions by incorporating information from biogeographical datasets and using numerous pathways to model interactions among regional weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, stream routing and pond/reservoir routing (Arnold and Fohrer 2005). While calculations are completed with variables unique to HRU characteristics, the model predictions are aggregated to the subbasin level. The hydrologic balance of each HRU is simulated to include (1) canopy interception of precipitation, (2) the partitioning of precipitation, snowmelt water and irrigation of water between surface runoff and infiltration, (3) the redistribution of water within the soil profile, (4) evapotranspiration, (5) lateral subsurface flow from the soil profile and (6) return flow from shallow aquifers (Gassman *et al.* 2007). The detailed structure of this model emphasizes the critical role the terrestrial water cycle has on the hydrology and biogeochemistry of a watershed, appropriately highlighting the importance of land cover on hydrology.

The SWAT model was developed in the early 1990s and originated directly from features of several ARS models, most notably the Simulator for Water Resources in Rural Basins (SWRRB) (Arnold and Williams 1987). Overtime, the model has been significantly improved with software capabilities that have expanded to include multiple hydrologic response units (SWAT94.2), equations from the EPA QUAL2E Stream Water Quality Enhancement Model (US EPA 1996) used for modeling in-stream nutrient water quality (SWAT 96.2) and the addition of bacteria transport routes as well as a sub-daily precipitation generator (SWAT 2005) (Neitsch *et al.* 2005*a*). Recently the SWAT development team at Texas A&M University developed an ArcGIS (ESRI, Redlands, CA) interface extension for the SWAT 2005 model, known as ArcSWAT (SWAT 2009), which streamlines data entry, the creation of required input files and parameter editing, all while allowing spatial parameters to be easily observed in the ArcGIS environment. ArcSwat 2.14 was created as an ArcGIS extension interface for the Soil and Water Assessment Tool Version 2005 model. The SWAT2005 model inputs are generated with the ArcSWAT interface, which automatically creates the required input tables formatted in the correct file structure. The interface also generates obligatory default parameters based on user-supplied GIS data layers (Winchell *et al.* 2008).

Once assembled with the required datasets, the SWAT model functions on a daily loop calculating climatic conditions within each catchment and then routing the water, nutrients and chemicals through the watershed in order to synthesize hydrological conditions over a given period of time. The hydrology is simulated via two major processes: (1) the *Land Phase* of the hydrologic cycle, which controls sediment, nutrient and pesticide loading to each channel from subbasins, and (2) the *Water or Routing*

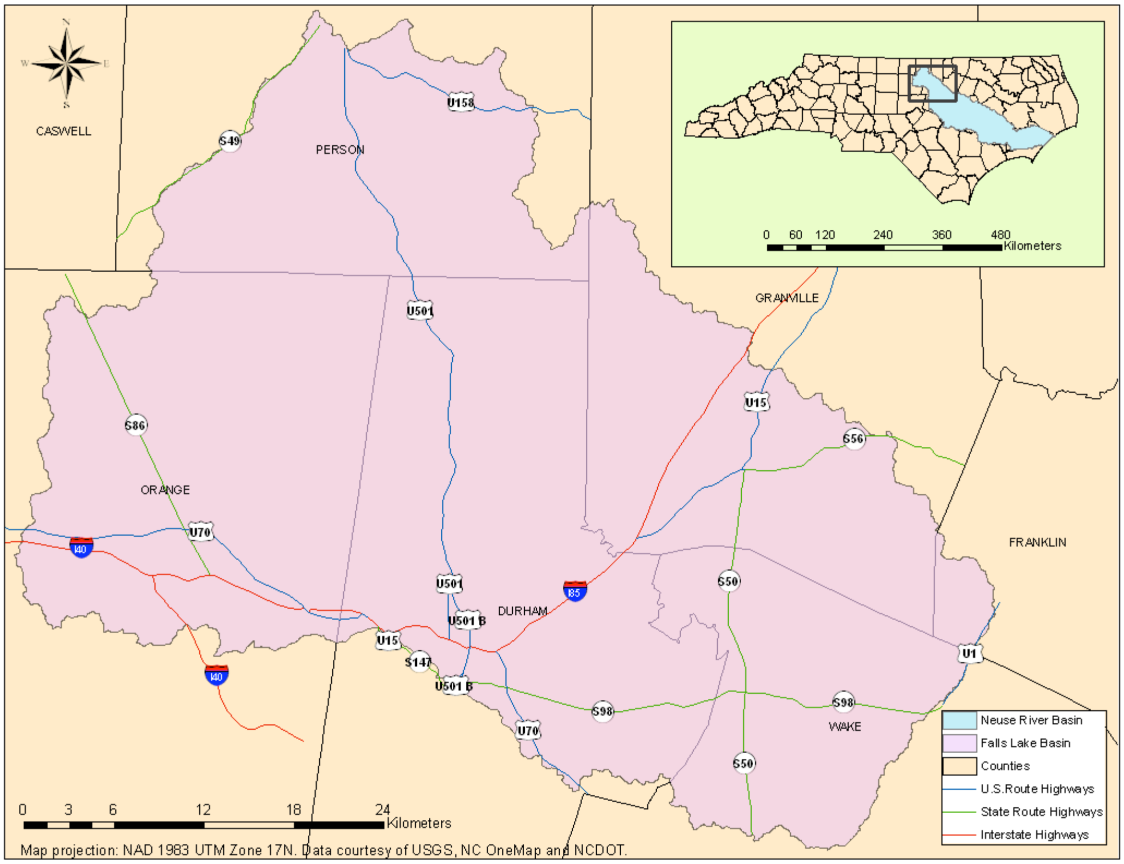
Phase that controls the movement through the channel network to the watershed outlet (Neitsch 2005*a*). The SWAT soil-water routing feature is calculated from the interaction of four main pathways: soil evaporation, plant uptake and transpiration, lateral flow and percolation. The strong emphasis on vegetation and hydrologic interactions within the SWAT model make it a preferable for a land-use based hydrological analysis.

Although other models were considered, including the simpler Long-Term Hydrologic Impact Assessment (L-THIA) tool (Tang *et al.* 2005) as well as the more deterministic Hydrologic Simulation Program – Fortran (HSPF) model, ArcSWAT was chosen for its complex representation of fine spatial scales and for the compatibility of available data and software (i.e., ArcGIS). Additionally, SWAT has become increasingly popular among managers since it has been adopted as a component of the U.S. Environmental Protection Agency's Better Assessment Science Integrating Point and Non-Point Sources (BASINS) software package and is used for multiple state and federal assessment projects (Gassman *et al.* 2007). SWAT has generated an expanding body of research and has shown to be successful for land-use change assessments.

3. The Upper Neuse River Basin

The Upper Neuse River Basin, also known as the Falls Lake watershed, is located within the central Piedmont region of North Carolina and is a component of a larger watershed network known as the Neuse River Basin. This area was selected as a focal region for studying land use change, with the growing centers of Durham, Raleigh and Research Triangle Park all contributing to the increasing rate of urbanization within the basin (Figure 1**)**. Based on the Multi-Resolution Land Characteristics Consortium's

(MRLC) 2001 National Land Cover Dataset, the dominant land uses in the subbasin include forest (61%), agriculture (16%) and urban/suburban developed land (17%). Due in part to the high rate of urbanization, the remaining 12% of the subbasin, or approximately 60,000 acres, has already been classified as protected open space in an effort to maintain a heterogeneous landscape (USGS 2009). However, the Upper Neuse River Basin Association has predicted that by 2025 about 20,235 hectares of forest and agriculture will be converted to urban uses and total developed land could jump from 36,420 hectares (or 18.24% of the basin) to almost 56,655 hectares or 28.37% (UNRBA 2003).



Map projection: NAD 1983 UTM Zone 17N. Data courtesy of USGS, NC OneMap and NCDOT.

Figure 1. Location of the Falls Lake watershed in the central Piedmont of North Carolina.

The Falls Lake basin is one of the most densely populated subbasins within the entire Neuse River Basin, with densities estimated around 100 people per km^2 (NC DWQ 2002). There are already nine public water supply reservoirs developed within the watershed, which is estimated to provide service for about 500,000 people (NC DWQ 2009). Falls Lake, which covers almost 5,060 hectares and extends for 45 kilometers, is the largest man-made reservoir in the basin, operated by the U.S. Army Corps of Engineers Wilmington District. The reservoir currently operates as a source of recreation, drinking water, flood control as well as fish and wildlife enhancement. Furthermore, the reservoir is often utilized for water-quality control and pollution abatement through the augmentation of low flows (US ACE 2005). The entire watershed covers six counties, although Wake, Durham and Granville County have all been identified as the primary counties of concern due to their high development rate.

Aside from anthropogenic development, local environmental variables also play a role in the influencing the structure of regional hydrologic networks. For example, the Upper Neuse watershed overlies a geologically unique zone known as the Triassic basin, which is characterized by extremely erosive soils, low infiltration rates and a resulting lack of flow in dry seasons (NC DWQ 2009). Actively managing land use changes in ecologically sensitive regions could prove vital in maintaining a healthy watershed. The combination of high development pressure, locally sensitive environmental conditions and increasingly stressed water resources makes this watershed a prime study area that could greatly benefit from a detailed analysis of the sedimentation effects of land use change.

Numerous efforts have already been invested in the protection of both hydrologic and terrestrial resources within the Falls Lake watershed. Many stream segments in the basin are currently listed on North Carolina's 303(d) List of Impaired Water bodies, under the criteria authorized by the Clean Water Act (CWA) of 1972. The regulations from Section 303(d) of the CWA require that states create a prioritized list of waters that do not meet water quality standards or their designated uses, and subsequently necessitates the creation of a Total Maximum Daily Load (TMDL) watershed plan (or similar alternative assessment) for the respective water bodies (NC DWQ 2007*a*). A TMDL is a quantitative assessment of the biochemical features of an impaired waterway, which is established to ensure that future water quality standards can be met, while determining the maximum amount of allowable pollutant loading that a water body can receive without exhibiting signs of impairment (Novotny 2003).

Many of the watershed's streams that are listed on the most recent N.C. 303(d) list from 2006 cite urban runoff, storm sewers and land development as the primary potential sources of contamination (NC DWQ 2007*b*). Moreover, "impaired biological integrity" was the dominant cause of most stream listings, being responsible for 82.14% of the twenty-eight stream segments within the Upper Neuse River Basin for which impairments were reported (US EPA 2007). The overwhelming number of streams exhibiting disruptions to ecological communities highlights the interconnected nature of terrestrial and aquatic ecosystems, while illustrating an alarming chain of consequences derived from anthropogenic activities. To mitigate sediment and nutrient runoff, management regulations have already begun placing an emphasis on the importance that forests serve to stream systems. On August 1st, 2000 a mandatory buffer rule (15A NCAC

2B .0233) was put into effect for lakes, ponds, estuaries as well as intermittent and perennial streams in the Neuse River basin. This law required that all included waters bodies shall maintain a 50-foot wide riparian buffer directly adjacent to the surface waters (NC DWQ 2002). However, more recent water quality research for the Falls Lake region has demonstrated that both the extent and rate of development is continuing to cause a significant increase in nutrient pollutants and sedimentation loadings for local water quality (Atasoy *et al.* 2006) and that more actions are needed to protect regional water resources.

Although developing TMDLs and passing state regulations are effective management tools for watershed protection, they require a tremendously in-depth and extensive process that creates time lags between problem identification, data analysis and the implementation of management solutions. Hydrologic models such as ArcSWAT, however, are proving to be useful in simplifying the analytical process and decreasing temporal lags since the program can be updated with new, current research and expanded with supplemental data that can be easily added or corrected in light of new information. When developed to incorporate detailed management scenarios, ArcSWAT has demonstrated its usefulness in estimating long-term TMDL loads for both the Bosque River in Erath County, Texas (Saleh *et al.* 2000) and the Poteau River in Oklahoma/Arkansas (Winchell *et al.* 2008). Although this project did not include fine scale details of land management practices within the Upper Neuse River Basin, it has the potential to be further expanded for additional analysis now that the hydrologic parameters have been established and calibrated.

4. Methods

A few crucial tasks were required to successfully complete this analysis. First, the data required to run SWAT was collected and included elevation, land use, soil, reservoir, climate and stream flow information. After model set-up was completed, the simulation was run and calibration procedures were used to improve model accuracy. Next, a future land used scenario was created based on previous land use change for the region and the output from the future scenario was compared to the current baseline results, in order to assess the variance in sediment yield. Finally, I used my model results to create a relationship between an index of development pressure and change in sediment load, to identify sensitive subbasins and highlight the degree to which spatial parameters can influence sedimentation processes.

4.1 Data Preparation

The ArcSWAT model requires input data including a Digital Elevation Model (DEM), a U.S. soils map, a Land Use /Land Cover (LULC) map, as well as a number of tables and text files (Table 1). In order to simulate regional climate for the 2001-2006 timeframe as accurately as possible, the recommended weather inputs consist of regional minimum and maximum daily temperatures as well as daily precipitation from a one or more stations. The climate data used within this simulation was collected from the National Climate Data Center (NCDC) for three locations during 2001-2006 and transformed to correct units (Fahrenheit to Celsius and inches to millimeters) (US DOC and NOAA 2009). Daily stream flow data was collected for six locations from the USGS National Water Information System (NWIS) from 2001-2006 (US DOI and USGS

2009*a*). This data was converted from feet per cubic second to cubic meters per second and reformatted for use in the calibration process.

Table 1. Datasets for the Upper Neuse River basin used in the ArcSWAT simulation. Data only used for [a] calibration process, [b] validation process, or [c] as a spatial reference.

Dataset	***Description***	***Source***
Precipitation	2001-2006 Daily precipitation	3 Stations from the NCDC
Temperature	2001-2006 Daily min/max temp	3 Stations from the NCDC
Stream Flow [a]	2001-2006 Daily stream flow	6 Gages from USGS NWIS
Sediment [b]	Sediment samples	4 stations from EPA STORET
Soils	STATSGO raster	NSRC Soil Data Mart
Elevation	National Elevation Dataset (30m)	USGS Seamless Data Server
Land Cover	2001 NLCD (30m resolution)	USGS Seamless Data Server
LULC Change	92/01 LULC Change raster (30m)	USGS Seamless Data Server
County Boundaries [c]	N.C. Counties shape file	NC OneMap Database

Sedimentation data was collected from the EPA Storage and Retrieval (STORET) Data Warehouse (US EPA 2009). There were only four stations within the watershed that had sample data for the sediment unit of tons/day, with most of the available data ranging from 2002 – 2005 (Table 2**)**. The sample points from this dataset each represents a single day’s measurement usually taken once every month or two. This data was not used in the calibration process, but served as a validation that SWAT sediment predictions were statistically acceptable when compared to observed data. Although the ArcSWAT model requires extensive data preparation, the free online availability of the required datasets makes ArcSWAT accessible to students and environmental professionals. Moreover, the ArcSWAT interface allows data to be easily viewed spatially via the ArcGIS software.

Table 2. STORET Sediment Stations for the Falls Lake Watershed.

Station ID	*Station Name*	*Samples*
J0836000	UT to Mountain Creek off US 501 Near Bahama	27
J0840000	Little River Reservoir at SR 1628 at Orange factory	22
J810000	Eno River at SR 1004 Near Durham	25
J0090000	Eno River Near SR 1134 at Hillsborough	6

4.1.1 National Elevation Dataset

Topographical data was obtained online from the USGS National Seamless Data Server and was retrieved as a National Elevation Dataset (NED) Digital Elevation Model (DEM) with 1-arc second (30-meter) resolution (US DOI and USGS 2009*b*). As shown below, the watershed ranges in elevation from 270 meters in the Northwest portion of the basin and decreases to a low of approximately 54 meters at the southeast end (Figure 2**)**.

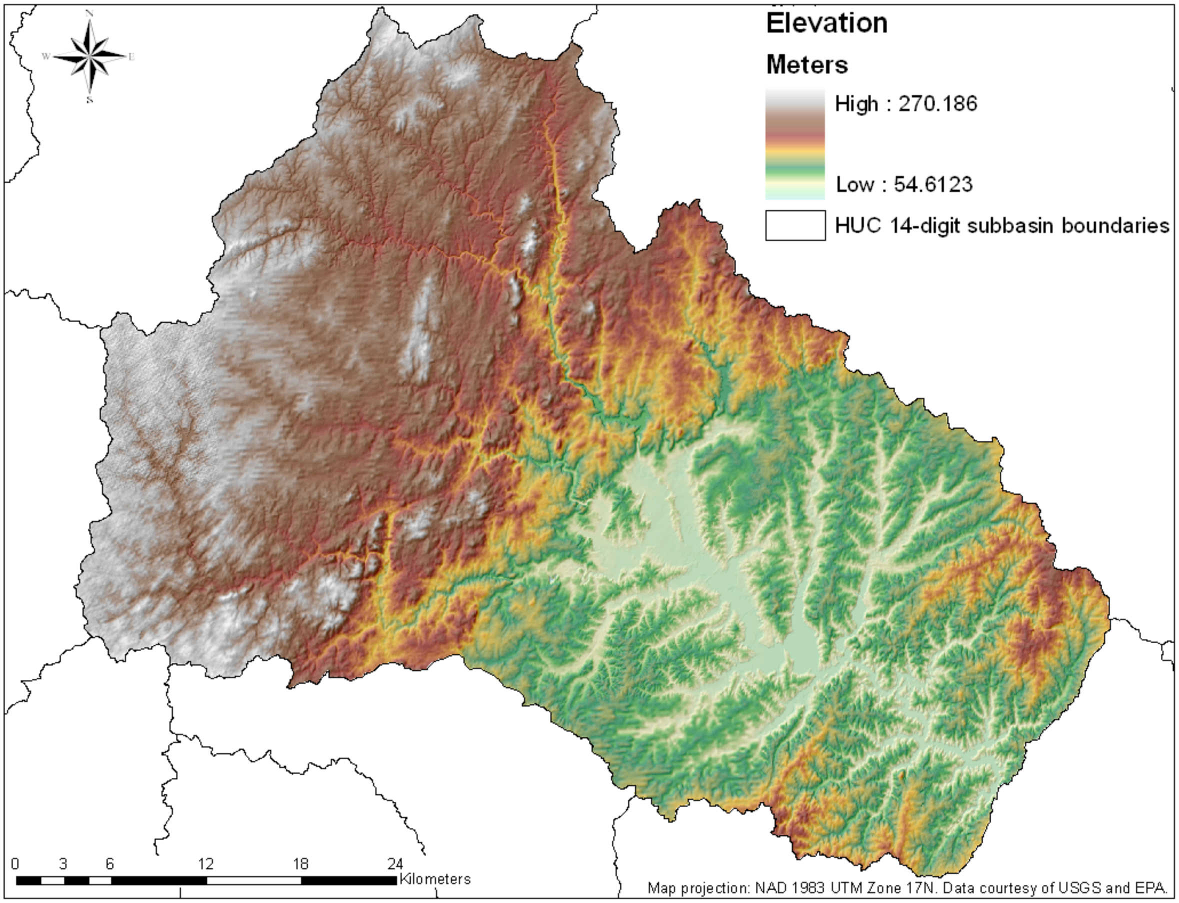


Figure 2. National Elevation Dataset Digital Elevation Model representing the topographical features of Falls Lake watershed (USGS 2009).

4.1.2 National Land Cover Data

The 2001 National Land Cover Dataset (NLCD) for North Carolina was downloaded from the USGS Seamless Data Server (US DOI and USGS 2009*b*) and clipped to the Falls Lake watershed (Figure 3**)**. The Land Use image shown in the map below divides the regions into 15 land use classifications. As displayed in the map, forest and agriculture dominate the watershed, although urban land uses are highly prevalent in the southern portion of the basin.

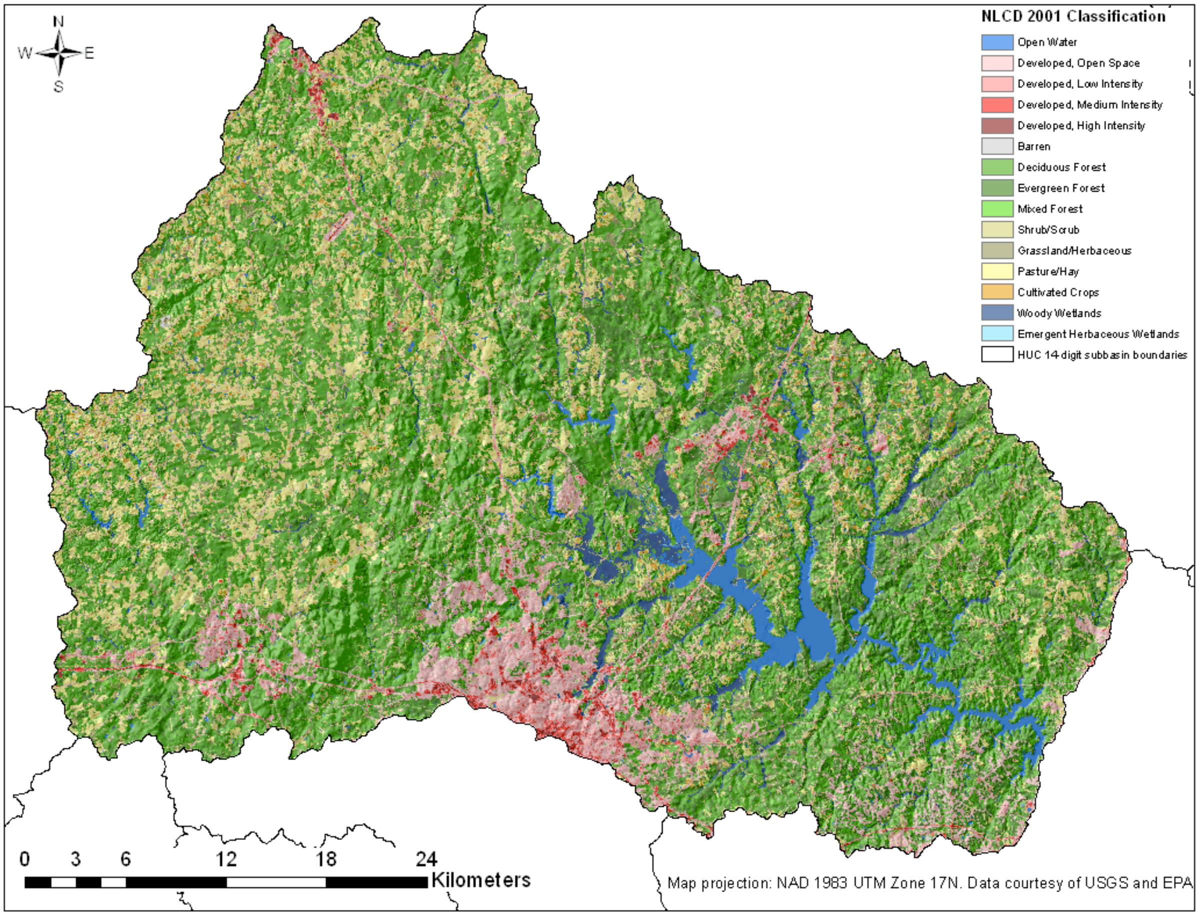


Figure 3. National Land Cover Dataset from 2001 representing the land use characteristics of Falls Lake watershed (US DOI and USGS 2009*b*).

4.1.3 State Soil Geographic Database (STATSGO)

The North Carolina State Soil Geographic Database (STATSGO) developed by the Natural Resource Conservation Service was downloaded from the Soil Data Mart (USDA 2006) and identified by state soil MUID (Figure 4**).** The local soils show a high degree of variability, with 11 unique soil types identified within the watershed. Although data was also available from the Soil Survey Geographic (SSURGO) database at a higher resolution, previous SWAT studies have demonstrated a simpler time working with STATSGO data since it takes far less computer processing space and time as well as requires less editing and preparation. While many studies have demonstrated a higher level of model efficiency when working with SSURGO due to the increased resolution, most studies suggest either dataset can yield a highly acceptable level of accuracy (Geza and McCray 2008).

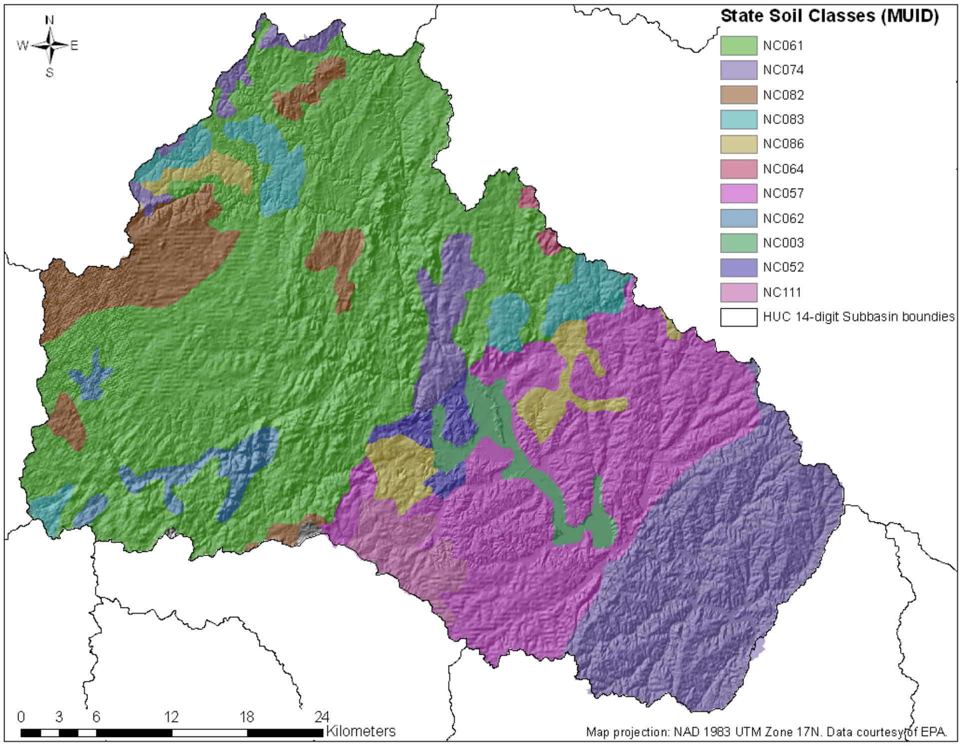


Figure 4. State soil class distribution for the Falls Lake watershed (USDA 2006).

4.2 Model Set-Up

4.2.1 Watershed Delineation

The watershed delineation interface in ArcSWAT is separated into five sections including DEM Set Up, Stream Definition, Outlet and Inlet Definition, Watershed Outlet(s) Selection and Definition and Calculation of Subbasin parameters. The Upper Neuse Watershed was manually delineated to define a polygon boundary around the Falls Lake area. In order to delineate the networks subbasins, a critical threshold value is required to define the minimum drainage area required to form the origin of a stream (Winchell *et al.* 2008). The critical threshold value for stream generation was chosen to be 1,000 hectares for this simulation and was based on recommendations from both the ArcSWAT Set-up Interface as well as other SWAT studies with similar watershed characteristics (Arnold and Fohrer 2005; Tolson and Shoemaker 2007). This value has important implications for the detail of the stream network as well as the size and number of subbasins delineated. In SWAT, subbasins are calculated as the contributing area to an individual stream channel. When a critical threshold of 1,000 hectares was utilized, 138 stream channels were identified and therefore 138 subbasins were delineated (Figure 5).

After the initial subbasin delineation, the generated stream network can be edited and refined by the inclusion of additional subbasin inlet or outlets. Adding an outlet at the location of established monitoring stations is useful for the comparison of flow concentrations between the predicted and observed data. Therefore, five additional subbasin outlets were manually edited into the watershed based on known stream gage locations that had sufficient stream flow data available from 2001-2006. After the subbasin parameter calculations are complete, reservoirs can be added to the model.

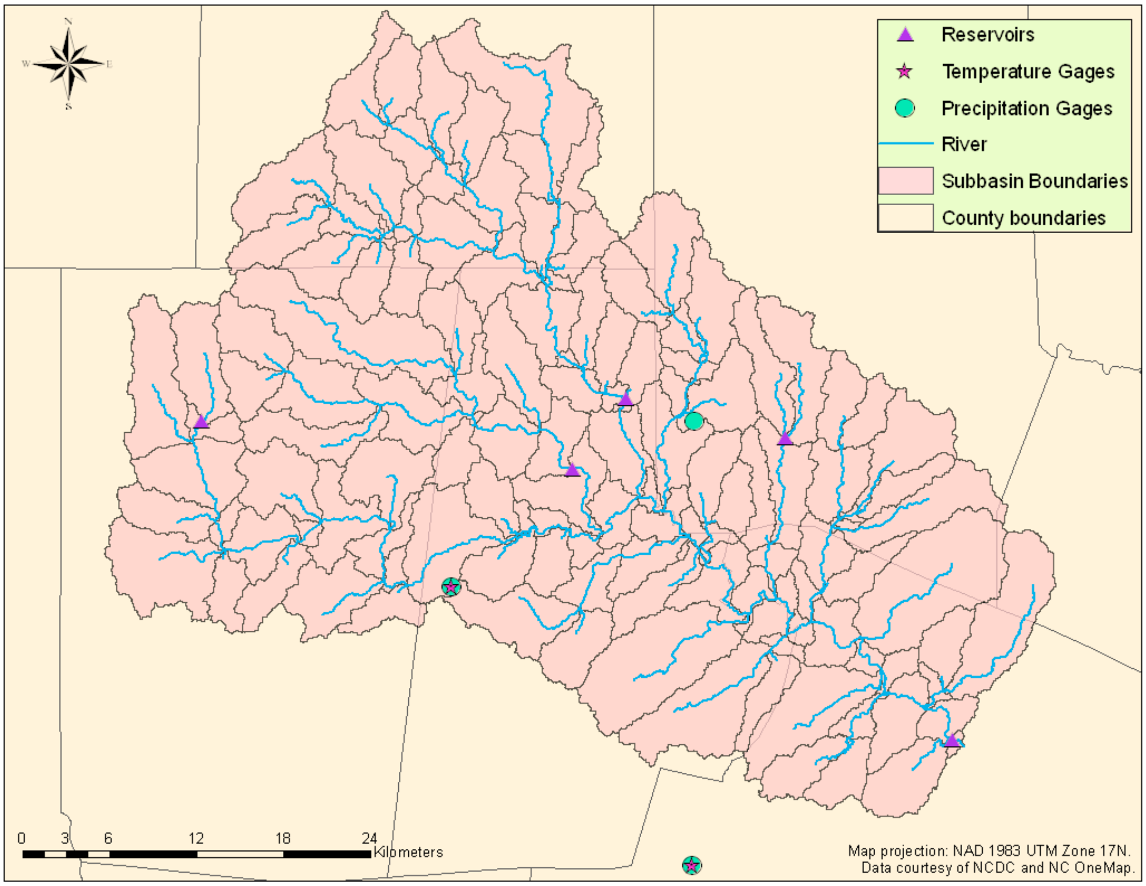


Figure 5. Falls Lake watershed delineated by ArcSWAT into 138 subbasins.

Although the Upper Neuse River Basin contains nine reservoirs, only the largest five were included in the model to mimic the seasonal management release practices of each reservoir, in an effort to increase the flow accuracy (Table 3**)**. Although detailed management data wasn't readily available for each reservoir, minimum monthly flow values for the Falls Lake Dam were edited to more accurately reflect local flow patterns. The seasonal minimum flows were set at 1.84 and 2.83 cubic meters per second (cms) for November-April and May-October respectively (US ACE 2005). Additionally, variables such as average monthly consumptive use adjusted based on previous water usage. Once watershed delineation was complete, the data needed to be overlaid with land use and soil classes in order to calculate Hydrologic Response Units.

Table 3. Reservoir information included in SWAT model for Falls Lake watershed.

Name	*Surface Area (Ha)*	*Mean Depth (m)*	*Volume (x $10^4 m^3$)*	*Watershed (mi^2)*
Falls Lake	5054.81	5.00	17660	769.9
Lake Orange	63.01	4.00	30	10
Lake Mitchie	218.98	7.99	1560	169.9
Little River	214.00	7.50	1800	97.7
Lake Rogers	56.98	2.59	50	17.4

4.2.2. HRU Definition & the Creation of SWAT input files

The ArcSWAT model requires the creation of Hydrologic Response Units (HRUs), which are the unique combinations of land use, soil and slope classes within each subbasin. The land use and soil classifications for the ArcSWAT model are slightly different than those used in many readily available datasets (NLCD and STATSGO) and therefore these files need to be reclassified into SWAT land use and soil classes prior to running the simulation. Both the U.S. General Soils Map (STATSGO) and the National Land Cover Dataset (NLCD) are such commonly used datasets that reclassification tables for both files are already included with the ArcSWAT 2005 model. Slope classification for the Upper Neuse River Basin were split into two categories, one group representing slopes from 0-5% and the other representing slopes greater than 5%, intervals commonly used in other SWAT studies. The reclassified land use, soil and slope distributions for the Upper Neuse River Basin can be examined in **Appendix Table A.1.** By overlaying the NED-derived slope raster along with the reclassified Land Use and soil datasets prepared earlier, all three datasets are used to determine HRU combinations. For this simulation, the option to create multiple HRUs per subbasin was enabled, since the spatial detail of the HRU distribution is responsible for multiple parameter calculations including evapotranspiration, runoff and nutrient loading concentrations (Winchell *et al.* 2008). Within the Falls Lake Watershed, 1,698 unique HRU combinations were created.

In order to run daily SWAT simulations, numerous input files need to be created, all of which can be automatically written by the ArcSWAT Interface based on the data supplied by each required file. Once all of the required datasets are loaded properly, the ArcSWAT interface can create the 12 necessary databases required to run the simulation. This model was run for six years, starting on January 1st of 2001 and ending on December 31st of 2006. After calibration, the model was again run for both the current 2001 land use and future development scenarios.

4.2.3 Calibration/ Sensitivity Analysis

After the SWAT model was initially run, a sensitivity analysis was performed on the model's stream flow parameters. The ArcSWAT interface contains a sensitivity analysis tool that determines the relative rankings of model parameters that influence the output variance the greatest based on input variability. Conducting a sensitivity analysis is often useful for identifying influential parameters within the model that can cause over-parameterization of the outputs (van Griensven *et al.* 2002). This embedded feature conducts a sensitivity analysis by combining a Latin Hypercube (LH) simulation with an One factor At a Time (OAT) sampling design; thereby enabling users to ensure that a wide range of parameters are sampled and that changes in model output can be attributed unambiguously to changing input parameters (van Griensven *et al.* 2006). In this simulation, there were 27 parameters associated with stream flow that were analyzed with a Latin Hypercube interval value of 10 and so the sensitivity analysis required 270 simulations.

The sensitivity analysis can only be executed at the subbasin level. Therefore, the subbasin encompassing the USGS gage 02087183 /Neuse River Near Falls, NC was selected for calibration since it is the closest station to the base of the watershed and therefore can adequately represent overall flow within the basin. Observed daily values were input into the model and the sensitivity analysis was executed, producing a list ranking the most influential model parameters and recommended values for calibration.

From the results of the sensitivity analysis, the top six parameters were chosen and manually calibrated for the entire subbasin with a range of values around the recommended change through trial and error, as well as through the consultation of similar SWAT calibration studies. The flow output from the manual calibration simulations were compared to observed data in five locations throughout the basin until a satisfactory calibration level was achieved. The default value, method of change and final value chosen for the manual calibration of the most sensitive flow parameters, as listed in the sensitivity analysis (Table 4**)** aided in increasing the model's accuracy to a satisfactory level. Although more parameters could have been edited to increase accuracy, only the top six were chosen in an effort to minimize calibration time and maximize model efficiency.

Table 4. Summary of parameters changed for manual calibration.

Parameter	***Description***	***Initial value***	***Method of Change***	***Calibration Value***
Alpha_Bf	Baseflow alpha factor [days]	0.048	Replace value	0.91
ESCO	Soil evaporation compensation factor	0	Replace value	1.0
Cn2	Initial SCS CN II value	Varying	Add	-20
Gwqmn	Threshold water depth in shallow aquifer for flow [mm]	0	Replace Value	100
Canmx	Maximum canopy storage [mm]	0	Add	5.0
Revapmn	Threshold water depth in shallow aquifer for "revamp" [mm]	0	Replace value	50

4.3 Future Land Use Scenario

A development scenario representing future land use was created to run in an ArcSWAT simulation, in an effort to assess the hydrological impacts that could occur when a probable development rate was used to represent land use change in Upper Neuse River Basin. To determine the rate of urbanization within the watershed, the quantity of forested and agricultural lands that were converted to urban uses over roughly a 10-year period were calculated. After identifying "business as usual" development rates from USGS Landsat data within the watershed, those same transition rates were applied to land cover data from 2001 to simulate a development scenario that represents the potential land use distribution for Falls Lake in 2010. Under the future scenario, approximately 928.08 hectares of forest and 188.37 hectares of agricultural land were converted to urban uses (Table 5).

Table 5. Comparison of land use/land cover (LULC) class distribution for the current and predicted development scenarios within the Falls Lake watershed. Data was derived from the National Land Cover Data (NLCD) 2001 for the current scenario and 1992/2001 NLCD Retrofit Product Change for the development scenario.

LU Class	*Current (Ha)*	*Basin %*	*Developed (Ha)*	*Basin %*	*% Diff*
Open Water	5946.93	2.98	5946.93	2.98	0.00
Dev, Open Space	18459.27	9.24	19325.79	9.68	0.43
Dev, Low Intensity	5188.23	2.60	5382.00	2.70	0.10
Dev, Med. Intensity	1684.71	0.84	1731.51	0.87	0.02
Dev, High Intensity	506.61	0.25	515.97	0.26	0.00
Barren	289.71	0.15	289.71	0.15	0.00
Deciduous Forest	76337.46	38.23	75868.74	37.99	-0.23
Evergreen Forest	27707.58	13.87	27432.90	13.74	-0.14
Mixed Forest	10356.21	5.19	10171.53	5.09	-0.09
Shrub/Scrub	3241.35	1.62	3241.35	1.62	0.00
Grass, Herbaceous	9049.41	4.53	9049.41	4.53	0.00
Pasture/Hay	34071.03	17.06	33882.66	16.97	-0.09
Cultivated Crops	2575.53	1.29	2575.53	1.29	0.00
Woody Wetlands	4182.48	2.09	4182.48	2.09	0.00
Herbaceous Wetlands	105.93	0.05	105.93	0.05	0.00
Total	199702.44	100	199702.44	100	0

In order to develop a future development scenario, previous land use changes were examined from the USGS National Land Cover Datasets from 1992 and 2001. However, it is not recommended to compare the two land cover files directly since there are significant differences between these two datasets due to changes in classification methods. To mitigate this problem the Multi-Resolution Land Characteristics Consortium (MRLC) developed a 1992/2001Retrofit change product, illustrating the probable land use conversions between the two datasets based on the Anderson I classification system (Figure 6). The Anderson classification system categorizes land uses on an increasing degree of detail as the system levels increase. Therefore, an Anderson I classification consist of the most basic land cover categories, with only 7 primary land uses while there are 21 Anderson II categories to distinguish more specifically among forest types and agricultural uses (DOI and USGS 2009*c*).

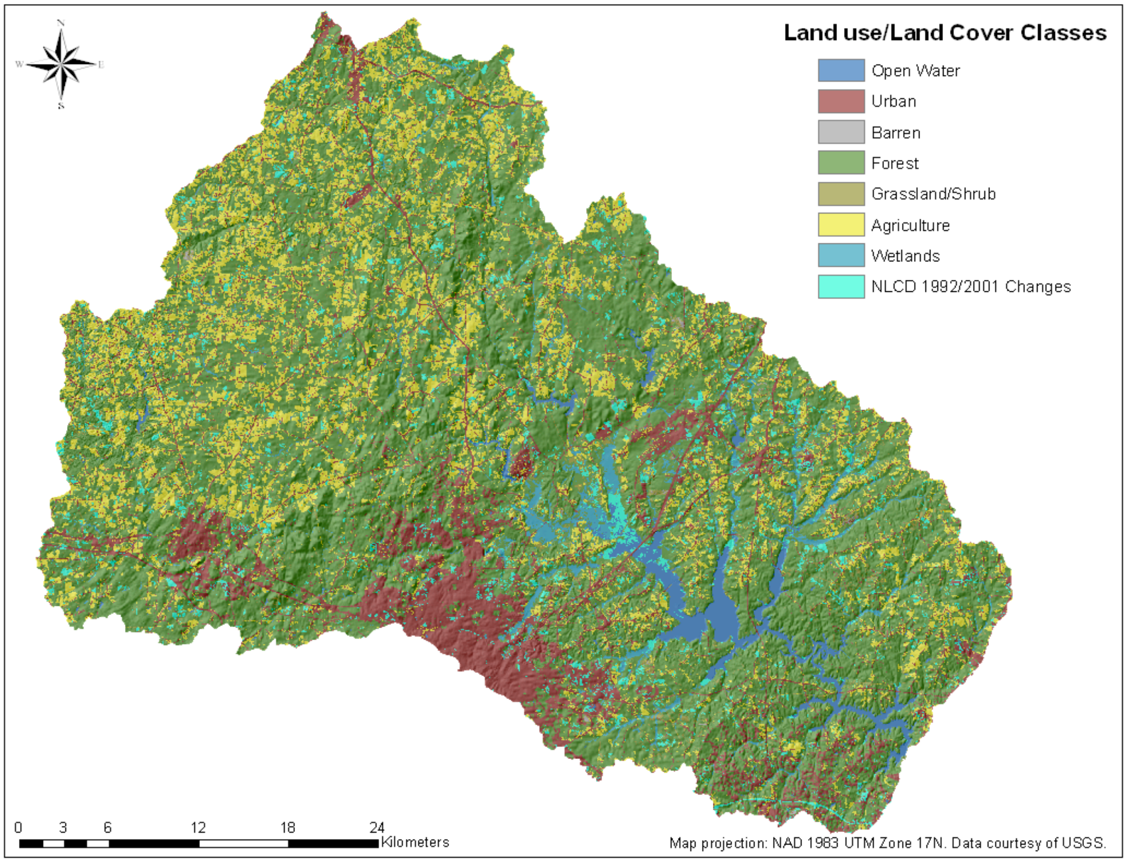


Figure 6. NLCD 1992/2001 product change for the Falls lake watershed. All areas highlighted in blue experienced land cover change between 1992 and 2001.

The NLCD 92/01 retrofit change product data was used to identify the percent of forests in 1992 that had changed to urban uses by 2001. Additionally, the percent of agricultural land in each catchment that had been developed between 1992 and 2001 was calculated. These results were summarized by subbasin using Hawth's Analysis Tools for ArcGIS (Beyer 2004). Between 1992 and 2001, 126 out of the 138 subbasins delineated experienced a decrease in forest cover, while 103 exhibited a decline in agricultural land use as urbanization expanded.

Using the expected transition percentage, the number of cells expected to be lost from forest and agricultural land cover change for the 2010 development scenario was calculated for each subbasin and subtracted from each respective land cover class. To do this for forests, the expected change was subtracted from each of the three forest classes represented in the 2001 land use. There was only one subbasin (#9) that only contained deciduous forests and so the total change was subtracted from that one forest type. For agricultural change, the number of cells expected to change was subtracted from the NLCD category representing Pasture and Hay, while cultivated crops was left unchanged, a trend supported by data from the 2007 NC Agricultural Census (USDA 2008). For the future development scenario, only 6 of the 138 subbasins in the Falls Lake watershed experienced no change in forest cover and 23 catchments did not experience any change in agricultural land.

Next, the area subtracted from forest and agricultural land had to be added to the urban land use categories to represent increasing development. In order to determine the relative transition percentages among the four urban land uses (open space, low, medium, and high intensity), a change matrix was created from a random sample from one percent of the watershed area (full table can be seen in **Appendix Table A.2**). Forested land that experienced urbanization under the development scenario had approximately 78.9% of the converted land change to developed open space, 16.7% to low-intensity development, 3.7% to medium-intensity development and 0.7% to high intensity development. For agricultural land, the change matrix determined about 71.3% would develop into developed open space, 20.5% to low-intensity development, 6.7% to medium-intensity development and 1.5% to high intensity development. The resulting changes yielded a new land use distribution, representative of future development in the Upper Neuse River Basin. Before running the ArcSWAT model with the development scenario, the model was run with the 2001 land cover data and calibrated with daily climate data. By comparing the overall output from both land use scenarios, the influence of land use on critical sedimentation processes can be identified. . From the output of each scenario, comparisons can be drawn about the expected changes in sedimentation that may occur over the next decade with “business as usual” development, at a level of spatial resolution corresponding to the 138 subbasins. Through the comparison of each scenario, the subbasins that are the most susceptible to the effects of land use change can be prioritized for conservation efforts.

4.4. Evaluation Techniques

4.4.1 Hydrologic Accuracy

Ensuring the accuracy of the hydrologic simulation was a crucial concern in this comparison, since sedimentation processes are influenced by functions of the water cycle and predictions could vary tremendously based on water availability. While the future may not experience the same climate conditions that were recorded for the region historically, this assessment assumes weather patterns for the next decade will mimic previous climate observations in the region and efforts to minimize variations in climate helped to exemplify the effects of land use change. In order to assess SWAT accuracy, a number of statistical evaluations were used to compare modeled stream flow with observed data from five stream gage locations.

The goodness-of-fit measures used to evaluate the models predictions included both the Nash-Sutcliffe efficiency (E_{NS}; Equation (1)) value and the coefficient of determination (R^2; Equation (2)) while model error was evaluated through average percent difference (*APD*; Equation (3)) as shown below;

$$E_{\mathrm{NS}} = \frac{\sum_{i=1}^{n}(O_i - \overline{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum(O_i - \overline{O})^2} \tag{1}$$

$$R^2 = \frac{\left(\sum_{i=1}^{n}(O_i - \overline{O})\,(P_i - \overline{P})\right)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2 \sum_{i=1}^{n}(P_i - \overline{P})^2} \tag{2}$$

$$\mathrm{APD} = \frac{P_i - O_i}{O_i}100 \tag{3}$$

where n is the number of observations during the simulated period, O_i and P_i are the observed and predicted values at each comparison point i, and O-bar and P-bar are the arithmetic means of the observed and predicted values (Green and Griensven 2008). The R^2 value is an indicator of the strength of the relationship between the observed and simulated values, while the Nash-Suttcliffe simulation efficiency indicates how well these values fit the 1:1 line.

If R^2 and E_{NS} values are less than or close to zero, the model is considered ‘unacceptable or poor’. If the values are 1.0 then the model is considered ‘perfect’ (Moriasi *et al.* 2007). From a synthesis of existing peer-reviewed SWAT literature, Gassman *et al*. suggested that NSE values should exceed 0.5 in order to be considered satisfactory for hydrologic evaluations performed on a monthly time step (Gassman *et al.*

2007). This accepted criterion has been employed in other previous SWAT research efforts (Santhi *et al.* 2006; Tolson and Shoemaker 2007) and therefore a value of 0.5 or higher was considered an acceptable level of accuracy for this simulation.

4.4.2 Spatial Variability

After achieving a satisfactory level of accuracy, the sedimentation results were compared between scenarios and critical subbasins were identified (as seen in the maps included in Section 5: Results). However, although this assessment is useful for identifying immediate regions in danger of being degraded, an additional evaluation method was employed to highlight the sedimentation sensitivity that exists between subbasins due to variations in spatial properties.

I used my model results to create a relationship between an index of development pressure and sediment load. To do this, I compared the total annual change in sediment load for each subbasin against a measure of development pressure that the subbasin experienced between the two scenarios. First, to create this development index, the difference in cell number for each of the four urban classes between scenarios was calculated for each subbasin. Next, a relative weight ranging from one through four was assigned to each development class, with weight increasing with the development intensity. For example, the number of cells changed to the developed open-space category was multiplied by one, while the sum of cells changed to developed, high intensity land was multiplied by four. The total weighted sum for each subbasin was then obtained, with the highest development value equaling 819. To normalize this index, all of the summations were divided by the highest value and so the resulting index ranged from zero to one. This relationship was then plotted on a log scale due to the tremendous variation in sediment loading difference. In order to make management recommendations, the data was separated by two arbitrary lines, which highlighted natural separations in the results. The blue line represents a slope of 20% and the red line represents a slope of 5%. From this evaluation method, conservation efforts can be focused on sensitive subbasins, while development and urbanization can be directed towards less sensitive regions.

5. Results

The results generated from this assessment begin with a comparison of hydrologic flows, which illustrates changes in the model's predictions between calibration trials and on three temporal scales. Additionally, comparing the estimated sediment yields to observed sedimentation data validated the model's sediment predictions. Subsequently, the sedimentation values were compared between scenarios to highlight potential variance in the watershed. Finally, from a comparison of sediment change and an index of development pressure, the crucial implications of spatial influences can be highlighted and used to direct management efforts efficiently.

5.1 Hydrologic flows and model calibration

The model values were examined at daily, monthly and yearly time steps. While the model was run from 2001 to 2006, the first year of data was excluded for analysis since it is recommended that the first year is not included in evaluation of the model since its is considered a "warm-up" year. The calibrated model produced an adequate representation of the true system and while the flow patterns may not be exact, the calibrated simulation exhibits a more accurate range of minimum and maximum values than the uncalibrated trial (Figure 7**)**. When examining the monthly time series, accuracy increases (Figure 8**)**. However, one area the model appears to have increased difficulty is predicting values for 2006, demonstrating that the model is not able to adequately account for the increase in drought conditions that the region experienced that year.

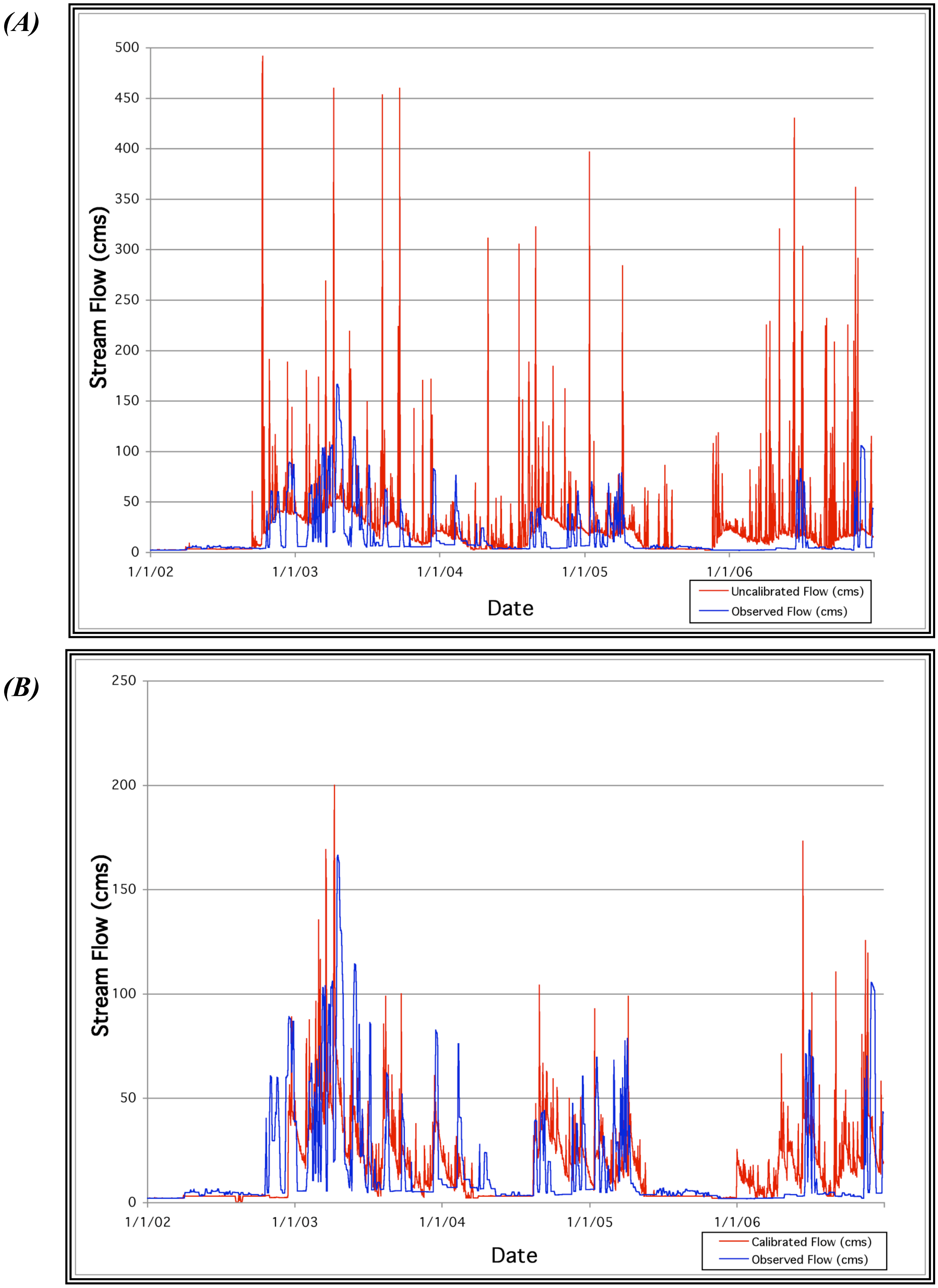


Figure 7. Daily time series from 2002-2006 for modeled and observed stream flow at the Neuse River near Falls, NC USGS stream gage with ***(A)*** representing uncalibrated flows and ***(B)*** illustrating the calibrated simulation.

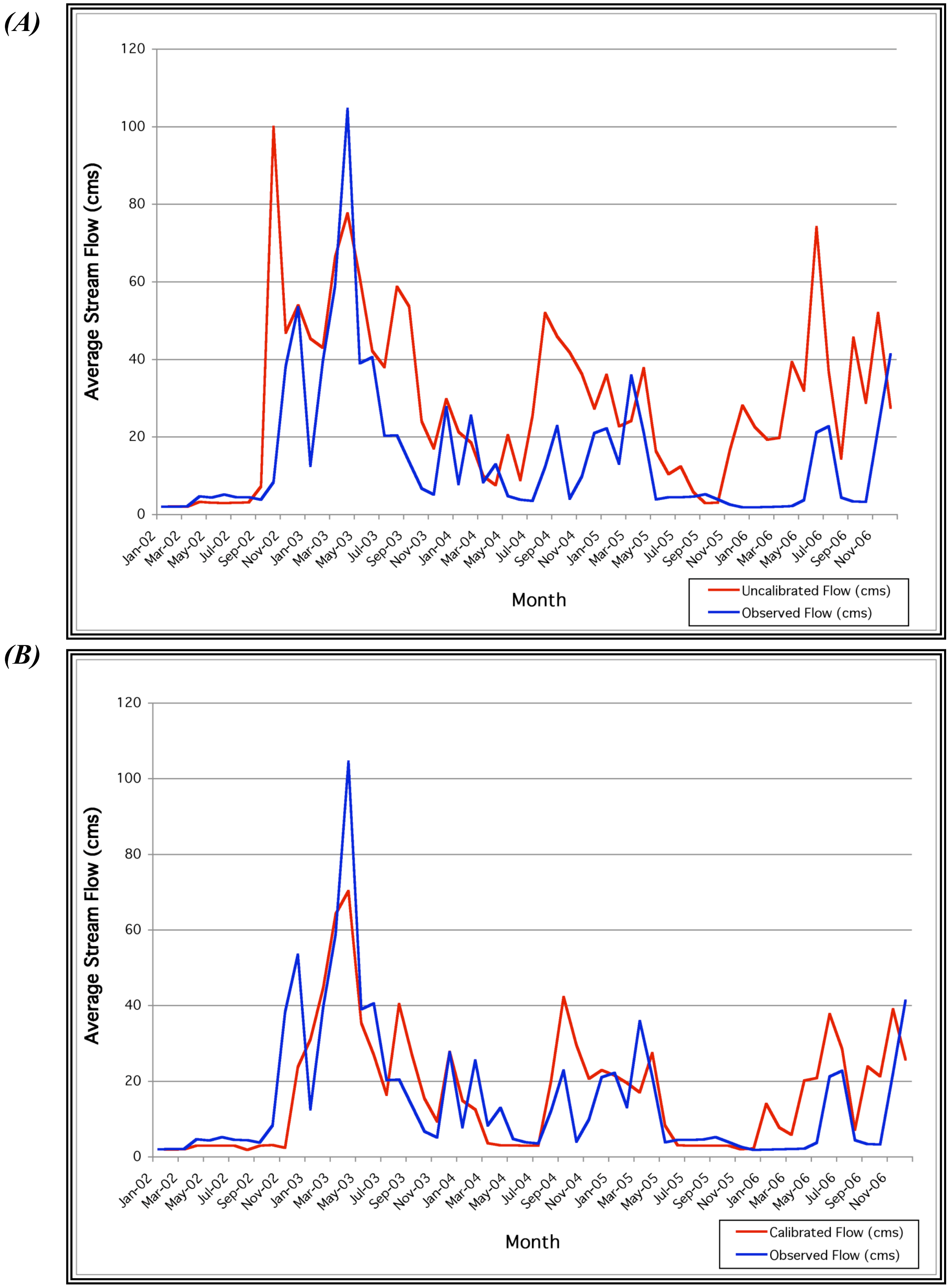


Figure 8. Monthly time series from 2002-2006 for modeled and observed stream flow at the Neuse River near Falls, NC USGS stream gage with ***(A)*** representing uncalibrated flows and ***(B)*** illustrating the calibrated simulation.

When evaluating simulations graphically, the accuracy of the model can clearly be demonstrated (Figure 9). For the daily time series, R^2 values increased from 0.0149 to 0.1807 between the uncalibrated and calibrated model showing creditable improvement. The monthly time series exhibited a much better correlation between observed and predicted values, having an uncalibrated R^2 value of 0.3372 and yielding a R^2 value of 0.5294 for the calibrated simulation.

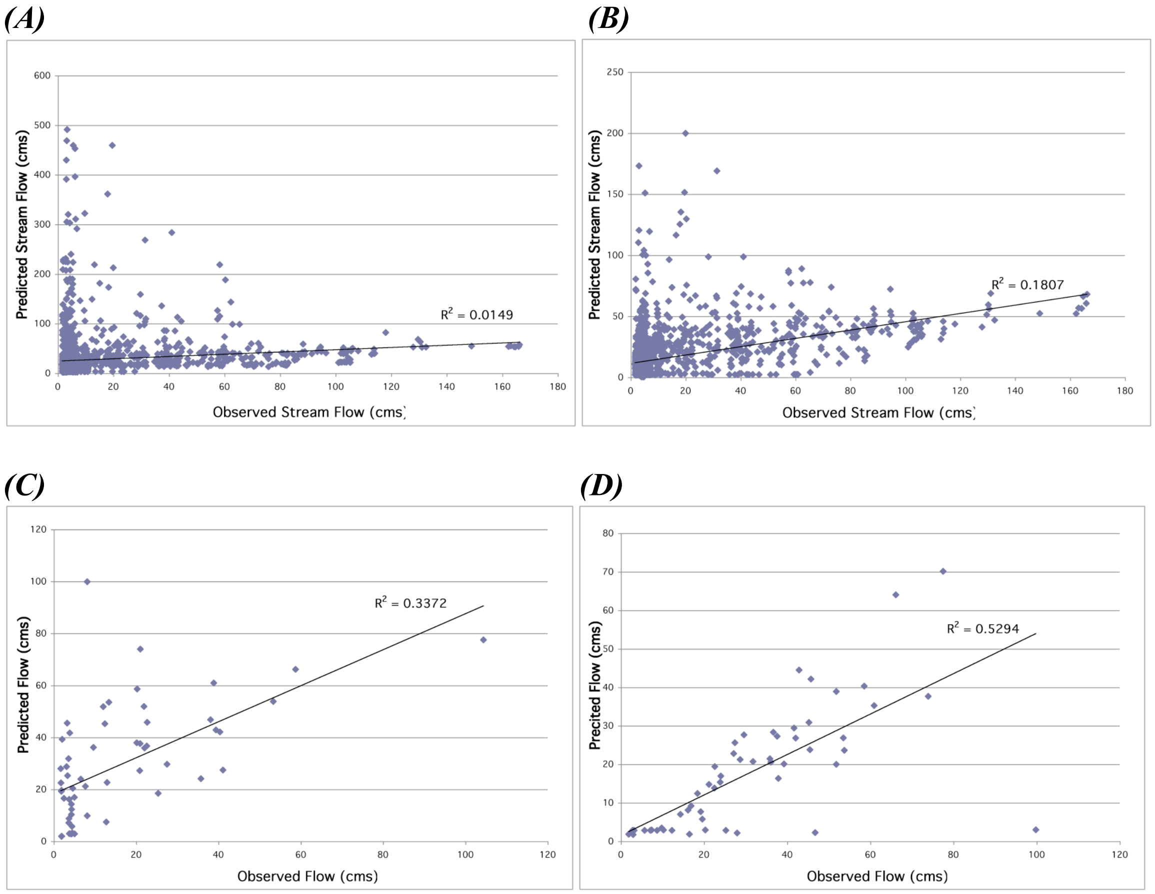


Figure 9. Modeled and observed stream flow for *(A)* uncalibrated daily flows *(B)* calibrated daily flows, *(C)* uncalibrated monthly flow and *(D)* calibrated monthly flows at the Neuse River near Falls, NC USGS stream gage.

When examining the yearly time series data, the total flow in millimeters per year was examined instead of the cubic meters per second unit that was evaluated for the daily and monthly time series. This was done in an effort to examine the accuracy of the model in executing a realistic water balance for each year. Additionally, the cubic meters per second value would not be useful as a yearly measurement since flow velocities changes seasonally and any averaged value would be drastically simplified. The uncalibrated model predicts yearly flow values to be much higher than they truly are, resulting in a R^2 value of 0.5566. However, once the parameters were calibrated the total water flow in the system is represented extremely well with a R^2 value of 0.9959 (Figure 10**)**.

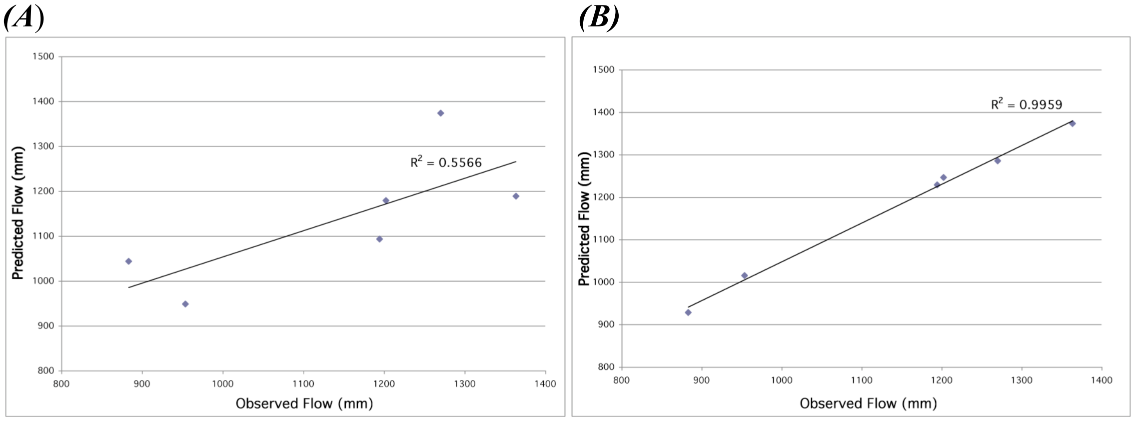


Figure 10. Modeled and observed stream flow for *(A)* uncalibrated yearly flows and *(B)* calibrated yearly flows at the Neuse River near Falls, NC USGS stream gage.

A summary of the statistical measures of each time series can be seen in Table 6**.** In an effort to validate the calibrated model, the results for the calibrated and uncalibrated simulations at five other USGS gage stations throughout the basin were compared. All of the comparisons yeilded similar results, with R^2 values for monthly calibrations all resulting in 0.5 or greater, which in turn achieves a satisfactory statistical level according to relevant literature (Gassman *et al* 207; Wang *et al.* 2008).

Table 6. Flow statistics for ArcSWAT predicted versus observed flow data at Neuse River near Falls, NC USGS gage.

	Uncalibrated			*Calibrated*		
	Daily[a]	*Monthly*[a]	*Yearly*[b]	*Daily*[a]	*Monthly*[a]	*Yearly*[b]
NSE	-3.311	-0.601	0.434	0.021	0.540	0.923
APD	42.098	47.519	-3.51	-0.490	9.239	2.646
R2	0.015	0.337	0.557	0.181	0.529	0.996
Slope	0.228	0.692	0.584	0.341	0.525	0.913
Yintercept	24.46	18.269	469.29	11.38	1.532	134.61
Observed Mean	14.220	15.061	1196.95	14.220	15.061	1196.95
Predicted Mean	24.559	28.697	1156.334	14.151	16.593	1229.487

[a] Values calculated from cubic meters per second data and [b] values calculated from yearly flow in millimeters (mm).

5.2 Sedimentation Validation

Although the model was only calibrated for hydrologic variables, the sediment yeild values were assumed to be reasonable. However, in order to explore the accuracy of the sediment output, an observed sample was compared to the model predicted values when run with 2001 land use data (Figure 11**).** While the observed sample was extremely limited with only 29 observations over a five-year interval, the results suggest that the model does a fairly good job, with an R^2 value of 0.582, of simulating sediment transport accurately. Additionally, the observed data was a daily value taken during the month, while the predicted value was derived from monthly data and divided by the days per month in order to find an average daily value. This drastic simplification of average daily values could be responsible for some discrepancies shown between the predicted and observed data.

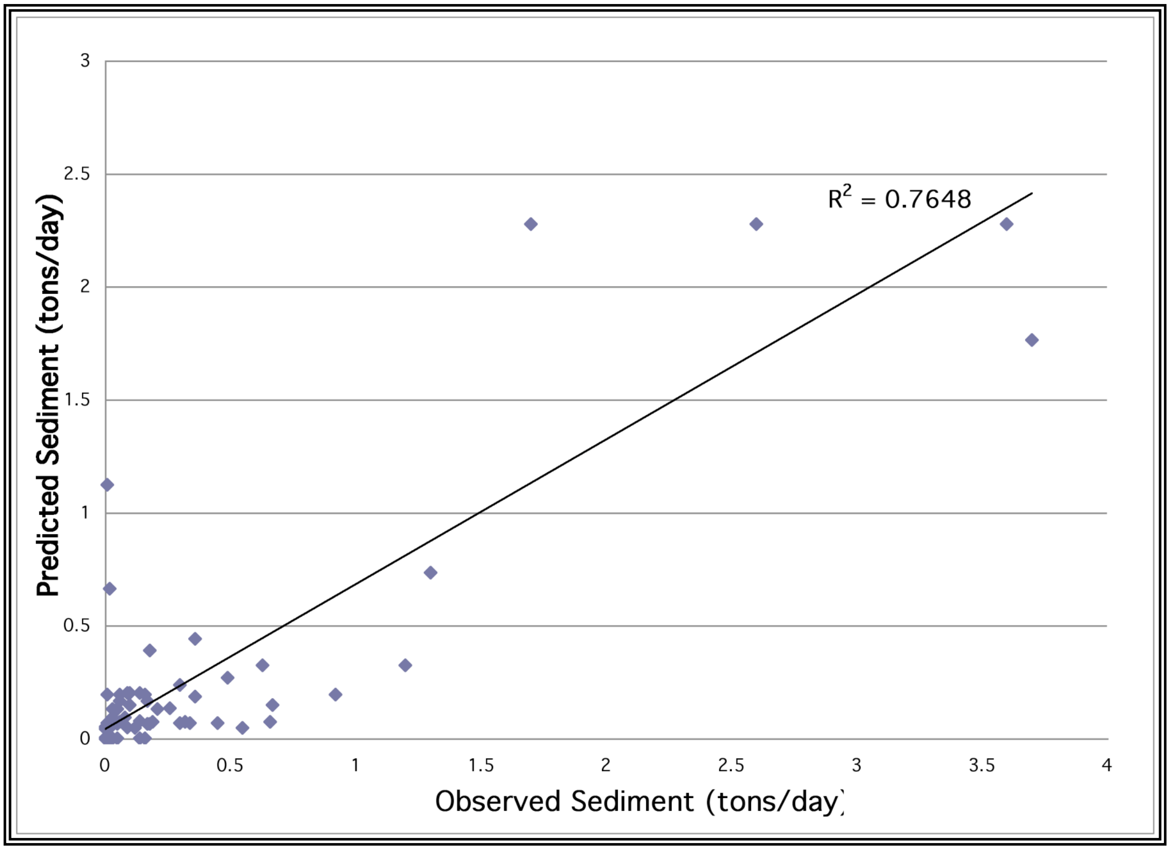


Figure 11. Predicted and observed sediment runoff (tons/day) for the Falls Lake Watershed.

The sedimentation data was evaluated using the same statistical measures of NSE, APD and R^2, as shown in Table 7**.** Two of the stations (Sub 54 and 93) exhibited a strong association between observed and predicted data, while the other two (Sub 63 and 80) displayed that there was some disagreement between the model and observed values. The negative APD values suggest that the model under-predicts sediment values. The unsatisfactory performance illustrated in subbasins 63 and 80 is most likely due to the fact that these subbasins contain NPDES Dischargers, with flow additions that influence sedimentation, that were not included in the model. However, when analyzed as a whole the model appears to adequately represent the regionally sedimentation process.

Table 7. Summary of statistical evaluation of four sedimentation gages for the Falls Lake watershed.

Subbasin	***Statistical Evaluation***		
	NSE	***APD***	***R2***
Sub 54	0.8603	-21.6472	0.8894
Sub 63	0.1391	-42.6634	0.1979
Sub 80	0.0631	-39.2675	0.1667
Sub 93	0.4979	-3.4186	0.6174
Total	0.7648	-23.9223	0.6127

5.3 Development Scenario Comparison

When the calibrated model was run with the future development scenario, the predicted total sediment yield increased 6.14% from 100,603.9 tons/year to 106,781.8 tons /year. Results were calculated by determining the average annual sediment value from 2002-2006 with the monthly time series data. Monthly average sediment yeild were summed to annual values and these five yearly quantities were averaged to determine the average sediment load per year during the chosen time interval. The subbasins located in eastern Durham and northwest Wake County were the largest contributors to sediment runoff, accounting for 5-38% of the total sediment load. These five subbasins, illustrated in red, remained the largest contributors under the development scenario (Figure 12**)**. Additionally, the second largest group of contributors also remained the same between scenarios and included eight subbasins that represented 1-5% of the total sediment yeild as shown in orange.

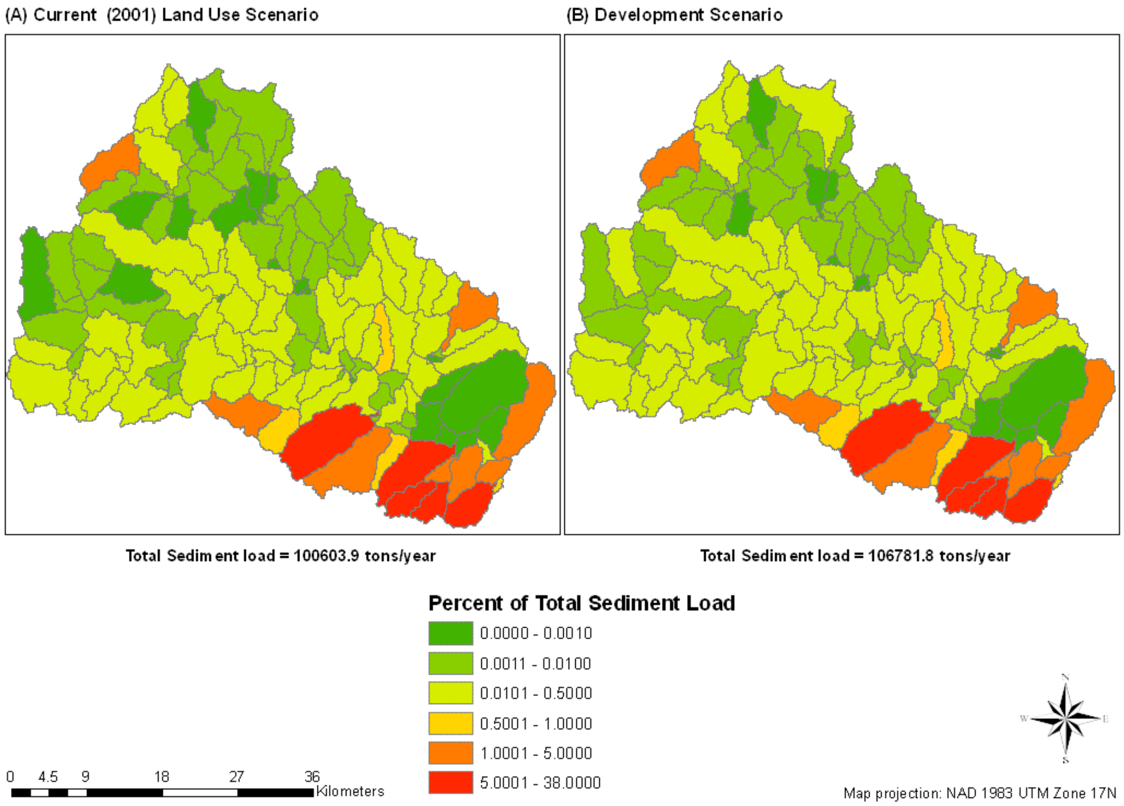


Figure 12. Percentage of Total Sediment load for the Falls Lake watershed under ***(A)*** Current land use and ***(B)*** the development scenario. For each scenario, the same five subbasins, highlighted in red, remained the largest contributors to the total sediment load.

In order to determine the relative percent change for each subbasin between the two scenarios, the percent of the total sediment yeild produced by each subbasin under the current scenario was subtracted from the percent under the development scenario. However, the largest percent increase predicted under the development scenario was 1.08% percent from subbasin 138 which is located in at the base of the watershed in the northwest portion of Wake county, along the edge of the city of Raleigh. Moreover, the second and third largest changes were even smaller, with a 0.330 and 0.307 percent increase from subbasin 130 and 137 respectively. Both of these subbasins were also located in the northern portions of Wake county. Additionally, the largest decline in percent difference that was observed was also relative small and came from a subbasin in cental Durham with a decrease of 0.964 percent. As illustrated by this comparison, the relative change in percent diference between scenarios was generally quite small, although these small variations amounted to an overall increase of more than 6,000 tons/year of sediment for the basin.

Additionally, the relative change in sediment yield was calculated between the two land use scenarios (Figure 13). The total average sediment yield from each subbasin, derived from the monthly time-step data, for the development scenario was subtracted from the current land use scenario producing a measure of the relative change. Of the 138 subbasins delineated, 29 illustrated no change in sediment yield while the remaining 109 all displayed an increase. The catchment with the largest increase in sediment loading of 1,967 tons per year can be found at the southwest portion of the watershed, located along the Durham - Wake County borderline.

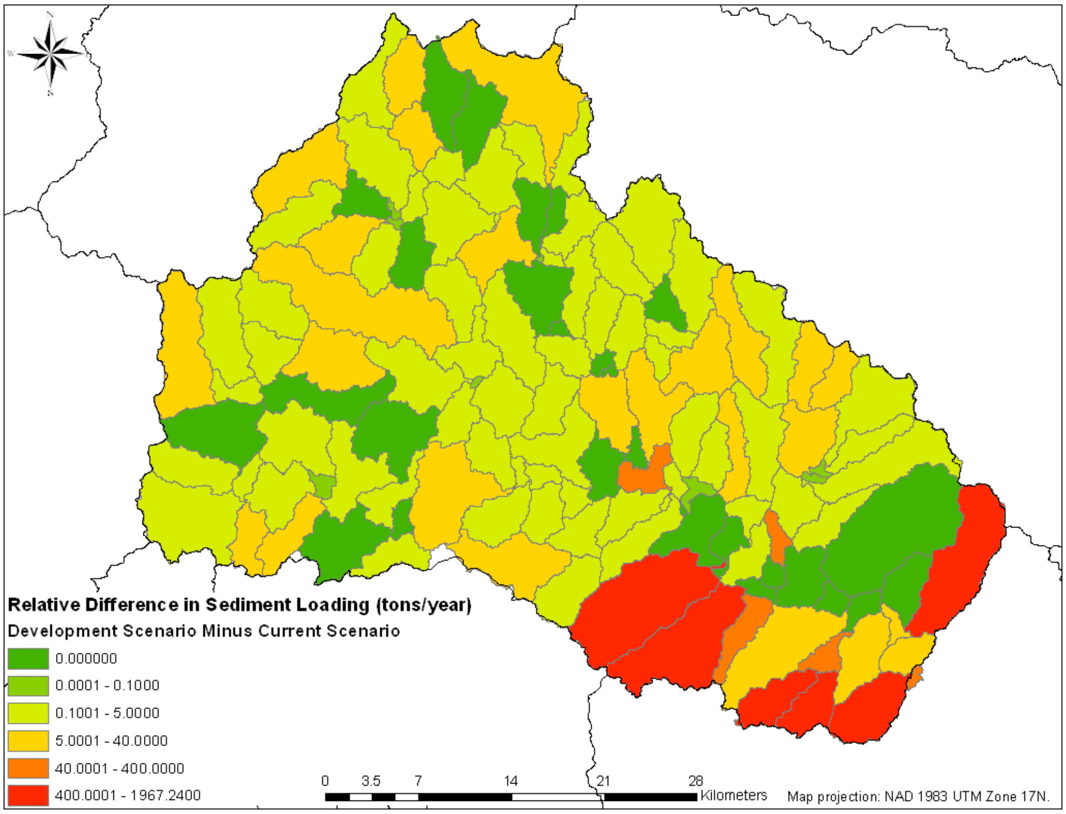


Figure 13. Relative difference in sediment loading between land use scenarios (total sediment yield from the development scenario minus the total sediment yield under the current land use scenario) of total sediment load for the Falls Lake watershed. While 29 subbasins displayed no increase (shown in dark green), the remaining 109 catchments exhibited a positive increase in sediment loading (tons/year).

Of the 138 subbasins in the Falls Lake watershed, only 6 experienced no change in forest cover, 23 experience no change in agricultural land and 5 experienced no land use change at all between the land use scenarios. Out of the six subbasin that did not experience any change in land use, four exhibited no change in sediment loading, while the remaining two displayed increases of 0.001 and 0.002 tons per hectare per year. The remaining subbasins and their respective increases in sediment loading illustrate the potential impact that development and reduced forest cover can have on water quality.

When examining these relative differences between scenarios, the results can be overlaid to identify the most crucial subbasins in the Falls Lake watershed (Figure 14**).** The five subbasins labeled in red should be prioritized as the most critical subbasins for management efforts aimed at reducing sediment loading. Subbasin 130 resides in eastern Durham while subbasins 135, 137 and 138 fall completely within the Northwest portion of Wake County. The only critical catchment to fall outside either of these regions is Subbasin 125, which is located equally in Wake and Franklin County.

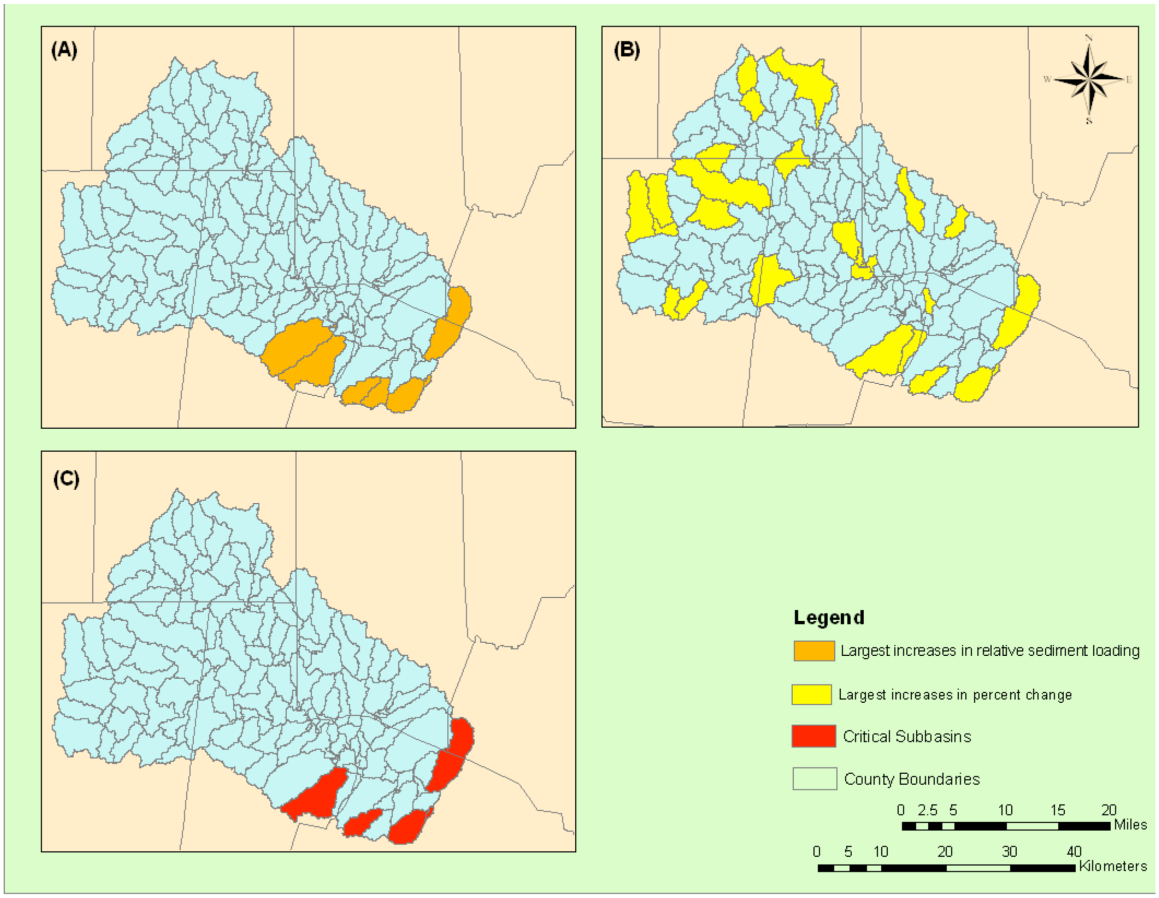


Figure 14. Summary of sediment loading for Falls Lake subbasins with emphasis on ***(A)*** the largest increase in relative sediment loading, ***(B)*** the largest increases in percent change and ***(C)*** the most critical subbasins.

5.4 Spatial Variability

Although the direct comparison of sediment yield can help local organizations and government agencies target areas of immediate concern in the watershed, the true variance caused by the differing spatial characteristics represented in each subbasin is not adequately illustrated. However, by calculating an index of the development pressure that was experienced in each subbasin and plotting this value against the estimated change in sediment load, the spatial sensitivity of each subbasin can be evaluated (Figure 15). The development index was calculated as a relative measure of change that each subbasin experienced, with values close to one representing subbasins with the highest level of urbanization and values close to zero representing subbasins that experienced little to no change in developed land. Each index value represents the change in urban land that occurred for each catchment relative to the other subbasins. While this index only symbolizes a relative measure of change, it is an accurate representation of development pressure specific for the region.

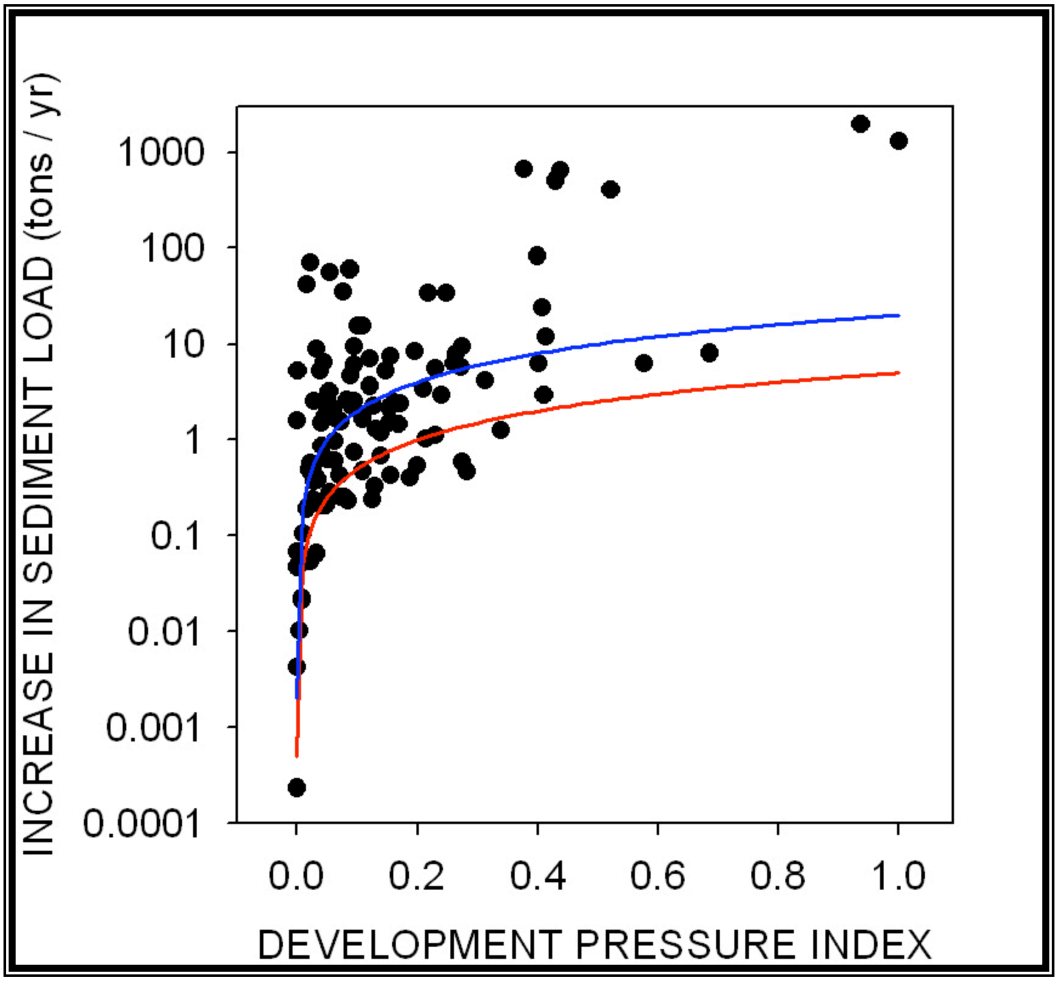


Figure 15. A comparison of change in sediment load relative to development pressure. Points below the **red line** represent insensitive subbasin, while points above the **blue line** represent extremely sensitive subbasins.

As expected, sediment load broadly increases with development pressure. However, it also becomes obvious that for a given development pressure, there is a wide range of sediment loads that can result because of differences in vegetation and the physical attributes of the watershed. This evaluation technique can be extremely useful in identifying sensitive subbasins that conservation efforts should be directed towards; like those falling above the blue line in Figure 16, which experience a very small change in development and yet they experience very large changes in sediment load. Additionally, subbasins suitable for development can be targeted for smart growth; like those falling below the red line on the chart, which can experience a relatively large change in development pressure and yields only a small change in sediment load. These lines were constructed as arbitrary breaks in the data, in an effort to guide interpretation of the figure. The red and blue lines were designated on a linear axis with slopes of 5% and 20% respectively and were then log-transformed. However, future evaluations can incorporate much more specific data breaks in order to improve management efforts or pinpoint critical thresholds. Moreover, this analysis also suggests that past a certain point of development (roughly 0.4 for the Upper Neuse River Basin), most of the subbasins illustrate sensitivity to urbanization and sedimentation changes will increase significantly in magnitude. This should be examined in further detail to determine the maximum development the region can withstand before exhibiting major degradation or loss of ecosystem services.

6. Discussion

Overall, the ArcSWAT model has proven to be an effective watershed management tool that can be run with readily available data. The model not only demonstrated a satisfactory level of accuracy in modeling regional hydrology, but also provided relevant land use scenario comparisons, highlighting the changes that urbanization can have on sedimentation yield. Moreover, evaluating these results in the context of their spatial sensitivity, highlighted how variations in land use, soils and slope can impact the sedimentation process. This assessment showed a lot of promise for directing conservation efforts to critical regions of the watershed, while guiding development towards the more resilient subbasins.

More specifically, this assessment suggest that with an approximate 4% increase in urban land, an approximate 6% increase in sedimentation will occur in the Upper Neuse River Basin, demonstrating that urbanization can have a measurable impact on water quality and directly effects sedimentation processes in a watershed. However, the magnitude of urban impacts on sediment is highly variable due to the different individual characteristics of each subbasin in a watershed. Variations in spatial properties such as slope, land use or soil type can directly affects the degree to which development influences sedimentation, with changes in yield varying multiple magnitudes.

Nonetheless, sediment loading for the entire basin increased by roughly 6,000 tons per year with scenario distinctions that were based solely on differences in land use composition. The positive difference in sediment yield between the two scenarios illustrates that the decline in forested land and the increase in urbanized landscapes has a direct influence on sediment erosion. While the model was calibrated to an acceptable degree of accuracy, the results should still be interpreted with caution since a number of project assumptions may impact this assessment. By determining land use transition rates from previous development patterns in the region, the “business as usual” scenario assumes that transition rates remain the same and therefore represents a fairly conservative estimate of future land use change. Hence, the predicted change could be underestimated by the model and future water quality conditions may be impacted greater than expected.

Moreover, by constructing the model so climate conditions between scenarios were held constant, a clear assessment of the implications of land use change on regional hydrology was obtained in order to highlight the characteristics of local hydrologic mechanisms. However, by making the assumption that climate conditions for the region will be the same for the future scenario, this project fails to account for any potentially larger climatic changes, such as shifts in precipitation patterns that could cause increased droughts or flooding for the region.

Although the SWAT model is a relatively complex model, there are certain limits to its analytical capabilities due to the structure of the model. One of the primary weaknesses of this assessment was the lack of more fine-scale predictions. Although HRUs are calculated to represent variation in each subbasin, the spatial definition of these classes is not determined. Therefore, the smallest spatial level the results can be presented in is on the subbasin level, which can dramatically over simplify the true variation present in local watersheds. Additionally, since the sensitivity analysis tool can only be executed on the subbasin level, calibrated changes may not accurately reflect the true environmental characteristics of each catchment. Finally, the watershed delineation tool should be improved to delineate subbasins on a much smaller scale or higher resolution data should be formatted for use in SWAT.

The poorest model accuracy was generally recorded when the model was run on a daily time-step. Factors that could have potentially affected the accuracy of SWATs hydrological predictions could include the relatively short calibration periods used (Muleta and Nicklow 2005) or the lack small-scale climate data could have represented rain distribution too coarsely over the watershed (Coa *et al.* 2006). Moreover, a lack of effective calibration (Bosch *et al.* 2004) and inaccuracies in stream flow data (Harmel *et al.* 2006) are potential factors cited in previous research that could affect SWAT's hydrological output. Nonetheless, when monthly or yearly values were analyzed the overall accuracy of the model increased drastically.

Moreover, although the model exhibited an acceptable level for accuracy for simulating local hydrology via stream flow calibration, the sedimentation variables were not calibrated due to time constraints and a general lack of sediment data. The overall lack of site-specific sediment data, sampled in units of tons/hectare, complicated efforts to accurately simulate local sedimentation cycles. For the Upper Neuse River basin, there were only a limited number of stations that had sediment data recorded, less were recorded in the desired unit and even fewer stations had observations that were taken during the 2001-2006 interval. Observed sedimentation data had to be combined for the entire Falls Lake Watershed in order to have an adequate sample size of data for sediment validation (as shown previously in Figure 11). Future research efforts should focus on increasing both the spatial and temporal frequency at which sedimentation values are monitored in the watershed.

A number of additional datasets could have been useful for the SWAT simulation, such as water quality data including nutrient, chemical or bacteria observations. Due to the lack of these supplemental datasets, the capabilities of this model to calculate nutrient cycles was limited and the resulting nutrient predictions could not be used with statistical confidence. Furthermore, weather conditions in SWAT are calculated at the subbasin level and so if there are only a limited number of climate stations included in the model, the fine grain details of local precipitation patterns may be distorted or not adequately represented. Interestingly, this study initially sought to analyze the entire Neuse River Basin. However, the entire central region (between Kingston and Clayton) had very few stations with sporadic intervals of climate data. This region in particular may be a crucial component for understanding how the sedimentation loss occurring upland is affecting the downstream Neuse estuary, and should be examined for future monitoring efforts.

7. Conclusion

This analysis suggests that SWAT has the potential to be an extremely powerful model, which once calibrated effectively, can produce useful watershed predictions to aid management decisions. This study found that increased urbanization resulted in an increase in sediment yield suggesting developed lands may be contributing to erosion at a greater rate than expected. Water quality managers should explore this correlation since a number of chemicals and pesticides travel through water systems via sediment attachment. Furthermore, the large-scale implications of this study highlight the need for research efforts to further clarify the links between land use characteristics and the ecological structure and function of stream systems.

Now that the hydrologic features of the model have been constructed and calibrated, this model could be expanded with additional research to incorporate nutrient data, account for agricultural practices or model potential climate change scenarios. Additionally, the model could be updated with more climate data or can expand the analysis beyond the 2001-2006 time frame for future advances. Moreover, the evaluation techniques employed in this analysis provide evidence that small-scale spatial characteristics within regional subbasins exhibit a notable degree of influence on sedimentation processes and future research should be directed towards further identification of sensitive environmental regions. In conclusion, environmental management tools such as the SWAT model show tremendous promise in their ability to assist environmental managers in protecting water quality and directing smart development simultaneously.

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Appendix

Table A.1 Output from SWAT Land Use, Soil and Slope Classification for the Falls Lake Watershed.

Detailed LANDUSE/SOIL/SLOPE distribution SWAT model class Date: 11/12/2009 12:00:00 AM Time: 15:18:12.7450708

	Area [ha]	Area[acres]
Watershed	199702.5300	493474.9368

Number of Subbasins: 138

LANDUSE:	**Area [ha]**	**Area[acres]**	**%Wat.Area**
Water --> WATR	5946.9300	14695.1614	2.98
Residential-Low Density --> URLD	18459.2700	45613.7791	9.24
Residential-Medium Density --> URMD	5188.2300	12820.3757	2.60
Residential-High Density --> URHD	1684.7100	4163.0026	0.84
Industrial --> UIDU	506.6100	1251.8586	0.25
Southwestern US (Arid) Range --> SWRN	289.7100	715.8879	0.15
Forest-Deciduous --> FRSD	76337.4600	188633.6805	38.23
Forest-Evergreen --> FRSE	27707.5800	68466.8156	13.87
Forest-Mixed --> FRST	10356.2100	25590.7127	5.19
Range-Brush --> RNGB	3241.3500	8009.5379	1.62
Range-Grasses --> RNGE	9049.4100	22361.5446	4.53
Hay --> HAY	34071.0300	84191.2187	17.06
Agricultural Land-Row Crops --> AGRR	2575.5300	6364.2634	1.29
Wetlands-Forested --> WETF	4182.4800	10335.1172	2.09

Wetlands-Non-Forested --> WETN	105.9300	261.7583	0.05

SOILS:	**Area [ha]**	**Area[acres]**	**%Wat.Area**
NC003	4496.5800	11111.2740	2.25
NC052	2414.0700	5965.2877	1.21
NC057	38286.0000	94606.6203	19.17
NC061	82317.8700	203411.5727	41.22
NC062	3923.4600	9695.0658	1.96
NC064	512.3700	1266.0919	0.26
NC074	35867.9700	88631.5473	17.96
NC082	12671.4600	31311.8112	6.35
NC083	7986.0600	19733.9536	4.00
NC086	6591.8700	16288.8404	3.30
NC111	4634.7300	11452.6496	2.32

SLOPE:	**Area [ha]**	**Area[acres]**	**%Wat.Area**
0-5	101615.8500	251097.8461	50.88
5-9999	98086.5900	242376.8682	49.12

Table A.2 A NLCD 1992 and 2001 Land cover change matrix. The change matrix was generated by sampling one percent of the 1992 and 2001 raster from the Falls Lake Watershed in order to determine the rate at which forests and agricultural lands change to open space, low-intensity, medium-intensity and high-intensity urban areas.

			NLCD 2001 LULC Categories and Number of Pixels (30 x 30m)														
			11	21	22	23	24	31	41	42	43	52	71	81	82	90	95
NLCD 1992 LULC Categories and Number of Pixels			Open Water	Open Space	Low Intensity	Med Intensity	High Intensity	Bare	Deciduous Forest	Ever green Forest	Mix Forest	Shrub / Scrub	Grassland/ Herbaceous	Pasture /Hay	Cultivated Crops	Woody Wetlands	Emergent Herbaceous Wetlands
	11	Open Water	527	7	2	1	0	0	25	29	1	0	5	14	3	1	0
	21	Low Intensity	2	442	118	30	3	0	221	81	38	5	30	93	4	3	0
	22	High Intensity	0	61	75	33	8	0	1	3	0	0	1	2	0	0	0
	23	Commercial, Industrial	3	94	108	58	17	0	9	5	1	0	5	7	1	0	0
	31	Barren	1	6	5	1	2	0	3	2	2	0	7	12	2	0	0
	32	Quarries, Stripmines, Gravel	4	1	0	0	0	1	2	1	0	0	9	15	10	0	1
	33	Transitional	0	0	2	0	0	0	4	10	3	0	1	4	2	1	0
	41	Deciduous Forest	51	557	119	30	5	7	5849	578	415	209	416	905	59	125	4
	42	Evergreen Forest	41	335	63	16	4	10	1250	1818	379	85	263	296	20	31	3
	43	Mixed Forest	17	220	54	6	1	4	829	505	250	42	122	292	19	20	0
	81	Pasture/ Hay	11	200	41	9	2	2	425	98	84	33	114	1587	103	5	0
	82	Row Crops	4	143	58	23	5	0	66	35	6	9	78	676	109	1	1
	85	Urban/ Rec Grasses	0	34	8	2	2	0	5	2	1	2	15	15	1	0	0
	91	Woody Wetlands	15	22	3	3	4	1	103	31	15	7	15	17	0	295	5
	92	Herbaceous Wetlands	0	1	1	5	0	5	16	12	1	0	5	4	0	12	2