MODELING THE EFFECTS OF PAST AND FUTURE LAND USE CHANGE IN THE SATILLA RIVER WATERSHED

by

DUNCAN C. ELKINS

(Under the Direction of Elizabeth Kramer)

ABSTRACT

Population growth and demographic trends are driving changes in land use in the Coastal Plain of Georgia, USA. I calibrated a watershed model of the Satilla River watershed using the Soil Water Assessment Tool (SWAT) and land cover data for 1974, 198, and 1998 developed by the Georgia Land Use Trends project (GLUT). I then used this model to assess the effects of observed land use change in the period between 1974 and 1998 and constructed land use scenarios to investigate the possible effects of several past and future land use scenarios. Simulation results indicate that current surface water yields may be 25% more than would be present under a pre-development land cover and that foreseeable development may further alter the balance surface to groundwater flows for this watershed.

INDEX WORDS: GIS, Soil Water Assessment Tool (SWAT), Satilla River, Hydrologic Model, Land Use Change

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DEDICATION

This study is dedicated to my parents.

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1. Introduction

Named for Saint Illa by an officer in the Spanish Army, the Satilla river was one of the earliest rivers explored by Europeans, even prior to the settlement of the Colony of Georgia in 1733. These hunters and trappers, and the Native Americans who frequented the banks of the Satilla for thousands of years before them, were lured by abundant fish and game. The Satilla River estuary continued to support a thriving, if modest, blue crab fishery until the 1990s, when crab harvests declined and many crabbers could no longer eke out a living (Wall 2004). Changes in land use higher in the watershed and pollution entering the estuary from upstream may be to blame, but the exact nature of these impacts is difficult to assess. Regardless of its past effects, it is certain that development will continue to impact the watershed, and the extent of these effects will be determined by land use decisions made today.

The Satilla River and the Little Satilla River together drain a watershed of 9,140 km^2 that lies entirely within the coastal plain of Georgia. The topography of the watershed is relatively flat, with a mean elevation of 66 m and a slope of 0.94 m per river kilometer (Slack, Lumb et al. 2001). The watershed is characterized by sandy, porous soils. The northern arm of the system is the Little Satilla River, which joins the main stem of the Satilla near Offerman, Georgia, and together they drain all or part of 13 counties, including the majority of Camden, Brantley, Ware, Pierce, Appling, Bacon, Atkinson, Coffee, and Jeff Davis Counties. These two river systems are identified by the USGS Hydrologic Unit Codes (HUCs) 3070202 (Little Satilla) and 3070201 (Satilla River) and will hereafter be referred to by the collective term "Satilla River System." The river is 420 km long and tidal influence extends 106 km upstream.

The USGS gage number 02228000, at Atkinson, Georgia, is the gage located farthest downstream and provides the best measurement of runoff from the upland portions of the Satilla River system into the estuary. This gage has been in operation since 1930, although stage records of lesser quality extend back to 1874. For the period of record, 1930-2002, freshwater inflow to the estuary averaged 62.7 $m^3 s^{-1}$ annually, although daily mean flows in excess of 1900 $m^3 s^{-1}$ have been recorded during flood stage (April, 6, 1948, USGS). In dry years, flow is strongly attenuated, dropping as low as 0.4 $m^3 s^{-1}$ during severe droughts (Sep 26, 1990, USGS). The annual mean rainfall is 120.7 cm, from which the mean runoff from the watershed is 26 cm.

The History of Land Use in the Satilla River Watershed

There are extensive wetlands in the Satilla watershed, particularly along the coast and adjacent to the river. Prior to European settlement, the Coastal Plain was covered by extensive longleaf pine forests, which were gradually converted to agriculture in the years prior to the twentieth century. Over the past 100 years much of the land of the Satilla watershed has been converted from agriculture to forest, although much of the forest is cultivated pine. In 1998, almost 39% of the watershed was covered in evergreen forest, while 19.8% was devoted to row crops or pasture (Georgia Land Use Trends (GLUT) 1998). Modern mechanized silvicultural and agricultural practices have disturbed natural hydrologic regimes and soil drainage through plowing and extensive ditching, used to convert seasonally flooded wetlands to pine plantations, and through increased use of irrigation.

Population growth in the Satilla watershed has exceeded 12% per decade since 1970 (U.S. Bureau of the Census, 2001), although the watershed is still primarily rural.

There has been an increase in urban and residential areas over the past 10 years, with about 109 km^2 classified as developed (low- and high-density urban) in 1974 increasing to about 180 km^2 in 1998 (GLUT 1998). A summary of other land cover changes between 1974 and 1998 derived from the GLUT project data is included in Table 1.

Table 1: Land cover changes in the Satilla River Watershed between 1974 and 1998.

Landcover Type	Change
Low Intensity Urban	+159%
Non-forested Wetland	+51%
Clearcut/Sparse	+41%
Open Water	+38%
Mixed Forest	+18%
High Intensity Urban	+13%
Evergreen Forest	+7%
Salt/Brackish Wetland	-1%
Row Crop/Pasture	-9%
Forested Wetland	-20%
Deciduous Forest	-33%
Beaches/Dunes/Mud	-99%

Development in the Satilla River Watershed has been accompanied by changes in water use. Alber and Smith (2001) compiled information on water use in the Satilla River watershed from the Georgia Water Use Program. As part of the USGS National Water Use Synthesis, this program conducts regular surveys of both water sources (groundwater and surface water) and water uses (domestic, commercial, industrial, mining, irrigation, livestock, thermoelectric, and hydroelectric.) In 1995, total water withdrawals in the

Satilla watershed amounted to about 182,000 m^3d^{-1}, of which 78% was withdrawal of groundwater. The largest withdrawals in the Satilla watershed were for public use (27%) and irrigation (49%). Domestic use accounted for 11% of the withdrawals, while mining, industrial, livestock and commercial accounted for the remaining 13% (ibid.) Of the water withdrawn, an estimated 63% (118,000 m^3d^{-1}) was classified as “consumed,” mostly via irrigation, although some portion of this irrigated water is likely to return to the channel via the transport of shallow groundwater. The amounts and proportions of these water uses have been consistent through the 20 year period of USGS water usage records. However, given the nature and extent of land use change in the watershed, it seems safe to assume that substantial alterations are likely to have occurred in the timing and delivery of fresh water to the estuary in the period before the USGS study began.

The Future of the Satilla River Watershed

The U. S. Census Bureau projects that Georgia will grow faster than any other state in the Southeast for the period of 1996-2025, and is expected to move from being the tenth to the eighth most populous state in the country (Campbell 1996). Within Georgia, the coastal area is expected to grow faster than other areas, with the exception of the Atlanta metropolitan area. The favorable climate, low cost of living, and access to coastal resources make it an attractive area for retirement (RDC 2005). As has been the case in recent years, timber industry projections for the southeast show little net change in the percentage of forest cover over the period of 1996-2025, but show the relative percentage of managed pine forests increasing to support the demand for lumber and wood products in nearby centers of population growth (Prestemon and Abt 2002).

Why Model the Satilla?

There is both a scientific and a management need for models to understand land-use impacts, especially in light of incipient development pressure. From a research perspective, the study of large rivers as integrated systems is relatively immature. While hydrologic modeling, as an engineering discipline, has been practiced for close to two hundred years, a focus on the linkages between land use and stream processes e.g., (Vannote, Minshall et al. 1980) did not become prevalent until the late 20th century. Hunsacker and Levine, in their 1995 review of hierarchical water quality studies, marked the beginning of a broader perspective on the variety of spatial scales at which land use and stream functions can interact. A focus on determining the interactions between the natural and artificial variation in rivers, the cascades of influence that flow from management activities, and realistic approaches to the development of alternative scenarios is even more recent (Naiman and Turner 2000; Allan 2004).

Hydrologic models can be an invaluable tool for the support of land use and development decisions. The coastal counties of Georgia are among the poorest in the state, but the use of relatively inexpensive modeling environments and downloadable data makes the cost of hydrologic models affordable to planners in these areas.

Decision makers, especially those in economically disadvantaged communities such as many of those in the Satilla River watershed, are faced with immediate problems. Development pressures are mounting, even in the relatively unimpacted Satilla River watershed. On November 8, 2004, a permit was granted to build a 64-slip private marina, which would serve a proposed 165-lot subdivision along the banks of the Satilla River in Camden County, near Woodbine, despite two previous court rulings requiring the state to consider the total impact of the combined projects in its permitting decision (O'Day, DeScherer et al. 2004).

The time is short to make land use-planning decisions that balance economic growth with natural preservation, lest the mistakes of communities up and down the coast be repeated. The effects of agricultural land use decisions, such as the failure to enforce farming and forestry Best Management Practices, while lasting, are not irreversible. However, sprawl and urban build-out are process that have permanent effects on the landscape, and decision makers must weigh these decisions with the utmost care (Beach 2003). Ideally, these decision makers would have access to planning and scenario-modeling tools that would make use of easily available and inexpensive data to provide some estimate of the current and future impacts of their decisions. Accordingly, this study seeks to address the following four research questions:

Question #1: Is a calibrated SWAT model sensitive to land use change?

If this model is to be useful as a planning tool, the processes that affect runoff in the watershed must be amenable to human manipulation. Since local agencies can not directly or predictably affect climate or geology on a regional scale, the management activities that fall within their purview involve land use activities and land use change. Numerous studies have demonstrated that watershed runoff characteristics respond to changes in land use, although the mechanism of these effects is not always clear and many factors that could affect runoff covary e.g., (Allan 2004). In many cases in which the sensitivity of SWAT to land use change has been assessed, the land use changes involved shifts of 50% or more in the relative proportions of the dominant land cover. The first goal of this study was to evaluate whether the predictions of a calibrated SWAT model changed as a result of more subtle changes to land use inputs, such as might result from reasonably foreseeable management and development activities in the next 25-30 years.

Question #2: Do observed land use changes explain the modern hydrograph?

The second goal of this study was to assess whether the observed land use changes in the recent era, in the form of the land use information from 1975, 1985, and 1998, are sufficient to explain any changes in the observed hydrograph. This was assessed by comparing the simulation provided by a model calibrated using the 1975 land cover and precipitation from 1970-1976 against those from 1985 and 1998, using precipitation data from the 1980s and 1990s, respectively. More precisely, I was interested in determining whether the use of updated land cover data improved model fit for the relevant time period.

Question #3: What is the runoff under past and future development scenarios?

Finally, I constructed a series of development scenarios to assess the alteration in watershed runoff that has already occurred as a result of development activities and the effects that might be anticipated from future development.

The relationship of land use to runoff

One of the fundamental tenets of hydrology is that land cover and soils moderate the processes by which precipitation becomes runoff. The terrestrial portion of the hydrologic cycle consists of seven interacting and simultaneous processes: condensation, precipitation, interception, infiltration, surface runoff, subsurface flow, and evapotranspiration (Fulton and West 2002). Vegetation intercepts precipitation and prevents it from reaching the ground, while condensation forms on leaves. Plants and litter roughen the surface and impede overland flow. Most significantly, vegetation draws up water from the soil and transpires it, preventing its infiltration into streams or shallow groundwater (Stanley and Arp 2002). At the opposite extreme, urban land uses often accelerate the delivery of precipitation into streams by channeling water from impervious surfaces such as parking lots into storm sewers which empty directly into surface waters (Brabec, Schulte et al. 2002). Soil permeability interacts with vegetation and determines factors such as the balance between infiltration of water into the vadose zone and puddling or sheet flow.

At any given time, water moving through a stream channel, or streamflow, is derived from both baseflow and stormflow. During and immediately after storm events, the peaking hydrograph is dominated by stormflow. Between storm events, the primary input to streamflow is baseflow, which consists of ground-water discharge to the channel (Hewlett and Hibbert 1966).

The rainfall-runoff relationship for a watershed is primarily determined by three factors: climate, land cover, and soils. Although these interactions are bi-directional at some level (e.g., the "heat island" effect by which urban areas show an increased average temperature relative to surrounding areas) they are substantially asymmetric; climate affects land cover more than land cover affects climate, and precipitation is modified by soils more than the reverse. In modeler's terms, the climate signal, in the form of precipitation, moderated by wind and temperature, is the forcing function and this signal is then affected by land cover and soils.

Of the three primary factors affecting the runoff of rainfall in a watershed, soils show the least temporal variation, since orogenic processes operate on a geologic time-scale and large-scale alterations in soil cover are typically the result of only catastrophic events, such as flood or fire. Although soil characteristics may vary spatially within a watershed, the overall effects of a watershed's soils on the rainfall-runoff relationship are typically constant in the absence of erosion. However, where disturbance has removed vegetative cover or otherwise exposed the soil to rainfall that results in flow over the bare soil surface, erosion can quickly transport relatively large quantities of soil and drastically alter the local hydrologic conditions.

Climate, conversely, is typically quite variable, both in space and time. This variability is bounded by seasonal trends, however, and long-term weather datasets exist for many regions that allow this variability to be quantified (Aguado, Cayan et al. 1992).

Land use, the third component, is the most subject to anthropogenic manipulation. Human activities such as agriculture obviously affect land cover and can precipitate changes in hydrology at multiple scales (Bolstad and Swank 1997; Mark C. Scott 2002; Allan 2004). Even management activities that do not result in the clearing of land, such as fire suppression within a park, can affect the serality of plant communities and alter the water balance for a watershed (Fulton and West 2002). Most stark, however, are the effects on runoff caused by urbanization. Human-induced land use change is frequently "patchy," with plots of varying size undergoing manipulations of greater, e.g., the construction of a mall parking lot, or lesser degree, e.g., the reversion of abandoned fields to scrub forest. The effects of this mosaic of land use changes can be difficult to predict, as different conversions at different distances from a stream channel may have additive or mitigating effects (Leopold 1968; Allan 2004).

The hydrologic effects of land use change

The effects of forest harvest and timber management are variable, due to the interactions of scale and local conditions. For instance, Bosch and Hewlett (1982) reported negligible effects on streamflow for any reduction in forest cover of less than 20%. For a Southern California Forest, Meixner and Wohlgemuth (2003), found that fire and, by analogy, clearcutting, acts to increase streamflow on the scale of a decade, but eventually decreases runoff over longer periods.

Buildings, roads, and parking lots constructed on the surface of the land intercept precipitation and channel runoff, disrupting the infiltration of water into the soil. As the extent of impervious coverage increases, a larger proportion of the precipitation falling on a catchment strikes impervious cover, further increasing the velocity and volume of surface runoff. Whereas water that has infiltrated the soil moves gradually into stream channels through processes such as percolation and lateral flow, water that is intercepted by urban structures is often delivered directly into stream channels. Thus, urban areas may be characterized by storm flows that have a steeper hydrograph with greater volume and a more rapid time to peak than is the case in rural areas (Carter 1961; Anderson 1968; Leopold 1968; Tourbier, Westmacott et al. 1981).

As impervious surfaces route more water directly into streams, groundwater recharge is reduced, which has the effect of lowering water tables. This imperils the water supply in areas that depend on groundwater for drinking or irrigation. Further, runoff delivered in the sharper storm peak flows downstream quickly. Without the moderating effect of percolation and lateral flow, dry streambeds may form in low flow periods (Dunne and Leopold 1978; Harbor 1994).

The in-stream biological effects of land use change

Urbanization has myriad in-stream effects, many of which stem from hydrologic alteration, discussed above. Increased storm flows also have significant erosive power, and streamside or riparian habitat may be lost. The eroded materials, in turn, affect in-stream habitat, as the silt and sediment covers the varied natural substrate of pebbles, rock ledges, and deep pools (Schueler 1992). In addition, urbanization can affect stream temperature directly thought the transfer of heat to runoff on streets and in sewers, or through the removal of shade-providing vegetation (Galli 1991). Urbanization is often particularly damaging to invertebrate communities, as pollutants may be delivered directly to the stream (Arnold Jr and Gibbons 1996; Paul and Meyer 2001).

Less severe types of land use change can have substantial and persistent effects on stream communities. Zimmerman and Covich (2003) found a marked "legacy" of agricultural land use change in the decapod community of two tropical streams(Mulvaney 1850) many years after the disturbance had occurred.

Hydrologic Modeling

Hydologists have been trying to describe runoff mathematically since the mid-19th century, when an Irish engineer attempted to predict peak runoff as a function of rainfall and catchment size (Mulvaney 1850). In general, hydrologic simulation models calculate results such as runoff volume or peak flow using mathematical equations and measured parameters. The equations may describe a simple empirical relationship, such as a regression, or may be modeled as a more detailed theoretical representation of the processes that determine the response. The Soil Conservation Service Curve Method (SCS, 1984; SCS, 1986) is an example of an empirical model that predicts runoff from a plot as a function of soil characteristics and rainfall intensity. Frequently, more complex mechanistic models that attempt to simulate the hydrologic process explicitly will contain one or more nested empirical models describing a portion of the modeled process. Hydrologic models may be further subdivided according to the time scale of the process they simulate: Event-based models attempt to simulate a single runoff event, usually a storm, while continuous models operate over an extended period of time and attempt to simulate both storm and baseflow processes.

Hydrologic models vary in their characterization of spatial variability. Models that do not explicitly address the spatial variability of inputs, outputs, or parameters are called “lumped” models. These usually handle spatial variability implicitly, incorporating average values of the watershed characteristics. This can be an effective approach on small scales for many processes. However, such models may be limited in their ability to capture patchy phenomena such as thunderstorms or changing land uses, especially if the processes modeled exhibit non-linear or threshold responses which are not triggered by smoothed or averaged inputs.

“Distributed” models, conversely, incorporate spatial variation in inputs, outputs, and parameters. Typically, spatial variation is accommodated by subdividing the watershed into smaller units that are modeled separately before their outputs are combined. These models are more computationally intensive than lumped models, but are better suited for the detailed simulation of larger watersheds.

The SWAT Model

SWAT, the Soil and Water Assessment Tool, is a complete river-basin scale model developed to quantify the impact of land management practices in large, complex watersheds. (Srinivasan and Arnold 1994). The model can simulate a basin subdivided into grid cells or an unlimited number of subwatersheds. Operating on a daily time step and efficient enough to simulate many years, it can be driven through ESRI's ArcView 3.x (ESRI 2002) family of GIS software, which provides a convenient visual interface for the assembly of the necessary input data layers. Although it operates using a daily time step, SWAT is a continuous model and is "semi-distributed" in that it subdivides large watersheds into smaller, homogeneous areas that are modeled individually. The model includes detailed process simulations of weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, stream routing and pond/reservoir routing (Arnold and Fohrer 2005).

AVSWAT, the ArcView SWAT interface, is used to manage input data layers and databases, from which text files are generated for use as inputs to the SWAT model itself. Upon successful execution, AVSWAT reads the SWAT output summary files and formats them for tabular and graphic display. AVSWAT also performs rudimentary data file management, placing the input and output files of each successive simulation run into sequentially numbered directories.

This project employed the 2003 version of the SWAT model, which was initially furnished to me as part of an Advanced SWAT Calibration Workshop at Texas A&M University in February, 2005. Improvements in this release include the addition of modules for sensitivity analysis and the autocalibration and uncertainty analysis of model parameters (van Griensven, Francos et al. 2002). The interface was revised several times during the project, and the final simulations were performed using version β2.03.

Examples

Many of the applications of SWAT within the United States, to date, have focused on the simulation of watershed response under changing environmental, management, or land use conditions (Arnold and Fohrer 2005). Notably, the SWAT model has been included in the BASINS software package and endorsed by the U.S. Environmental Protection Agency for use in the determination of the Total Maximum Daily Load (TMDL) of pollutants in impaired water bodies across the United States (DiLuzio, Srinivasan et al. 2002). As part of the Hydrologic Unit Model of the USA (HUMUS) project, the National Resources Conservation Service (NRCS) validated the model against measured USGS stream flow data from gauges across the country, then linked it national economic models and the outputs used for national planning.(Srinivasan, Arnold et al. 1993).

SWAT has been extensively validated for a variety of watersheds, such as a small (5.5 km^2) Central Kentucky karst stream(Spruill, Workman et al. 2000), six watersheds in Texas (Muttiah and Wurbs 2002) and four mesoscale watersheds in Germany ranging from 0.26 to 81.7 km^2 (Fohrer, Haverkamp et al. 2001). SWAT has been used to simulate systems watersheds as large as 8-digit HUCs, such as a 3.2 million km^2 area of the Upper Mississippi River Basin (Gassman, Jha et al. 2003). More local to the Satilla River watershed than the Upper Mississippi, Bosch, Sheridan et al. (2004), applied SWAT to a 22 km^2 agricultural subwatershed on the Georgia Coastal plain. The prediction efficiency achieved in selected applications of SWAT, including the 5 mentioned, above, is summarized in Table 2.

Table 2: Selected applications of the SWAT model and the Nash-Sutcliffe Efficiency (NSE) obtained by each simulation, where available. For a description of the NSE statistic, please see page 35.

Watershed Size	Location	NSE, monthly flows	Reference
5.5 km^2	Kentucky, USA	0.58 (1995) 0.89 (1996)	Spruill, Workman et al. 2000
22.1 km^2	Georgia, USA	0.64 (low-resolution inputs) 0.80 (high-resolution inputs)	Bosch, Sheridan et al. 2004
59.8 km^2	Germany	0.74 (calibration series) 0.53 (validation series)	Fohrer, Eckhardt et al. 2001
114 km^2	Texas, USA	0.86	Srinivasan and Arnold 1994
230 km^2	Quebec, Canada	0.67	Beaudin, Deslandes et al. 2004
2180 km^2 (7 catchments)	New Zealand	0.36 to 0.78	Cao, Bowden et al. 2003
3.2 million km^2	Upper Midwest, USA	Mean annual flows within 10% of measured values	Gassman, Jha et al. 2003

In particular, the utility of SWAT for the prediction of watershed responses to land cover change has been tested for watersheds in southeastern Arizona, (Hernandez, Miller et al. 2000; Miller, Kepner et al. 2002), Upstate New York (ibid.), and Greece (Varanou, Pikounis et al. 2004). The first of these studies demonstrates that the model outputs respond in reasonable ways to large scale changes in land cover for the semi-arid San Pedro watershed, as scenarios were run in which the existing land-cover, derived from satellite imagery, was altered in the GIS to be complete coverage of each of the land uses present. In subsequent work on the same watershed, Miller, et al. (2002), assessed the sensitivity of the SWAT model to three decades of actual landcover change by using inputs derived from remotely-sensed (LANDSAT MSS and TM) data taken in the 1970s, 1980s, and 1990s. Total annual simulated runoff increased an average of 6.57 mm for the San Pedro Basin, in Arizona, where oak and mesquite woodland and urban landcover had increased at the expense of grassland and desert scrub. These results were compared to a similar series of analyses conducted on six watersheds in the Catskill Mountains in New York, USA, where landcover changes have been more subtle. In the watersheds of the Catskill study area, landcover varied form 80-96 % forest, with up to 19% agricultural and at most 1% urban cover. Over the past 25 years, the only significant change in these watersheds was the reversion of agriculture to forest, and the simulated total yield increased an average of 3.58 mm simulation period.

Varanou, Pikounis et al. (2004), generated a series of development scenarios for the Pinos catchment in the Thessaly region of southern Greece with a scenario-planning tool and assessed the impacts of each land use option on the model output. Under their deforestation scenario, the model simulated a shift in the seasonality of flows, with a 23% increase in yield during wet months and decreases of up to 38% in dry months. The simulated monthly water yields displayed similar seasonal shifts under their urbanization scenario, in which urban landcover increased by 130%.

The SWAT model is sensitive not only to temporal changes in input landcover, but also to changes in the resolution or detail of landcover inputs. In a well-studied experimental watershed in Georgia, Bosch, Sheridan, et al, (2004) performed a series of 1-year simulations using detailed annual land use data to test the sensitivity of the model to the resolution of the input data. Although the prediction efficiency of the model was good using readily available coarse-grained data inputs, they were able to improve their model predictions significantly through the inclusion of field-level landcover, annual crop management activities, and SSURGO soil data layers. The goal of this project was to assess the suitability of SWAT for TMDL determination, and the authors noted that the detailed data they used is rarely available for such purposes.

2. Methods

The AVSWAT interface requires, at a minimum, digital maps of land cover, elevation, and soils in order to construct the inputs for the SWAT model. AVSWAT uses the elevation map and, optionally, a digital map of the existing stream channels, to delineate the watershed and subwatershed boundaries on the basis of runoff and flow accumulation calculations. AVSWAT will use daily precipitation files from one or more gauges within the watershed to create the precipitation time series for simulations. Before I could test the three study questions, I had to determine if the SWAT model, using readily available input data such as USGS flow data, precipitation data from the National Climate Data Center (NCDC), and land cover from the Georgia Land Use Trends (GLUT) project, can be calibrated to simulate the delivery of freshwater into the Satilla River estuary on a monthly time step.

The first step in my model set-up was the selection of the output point of the simulated watershed. I chose to model the portion of the Satilla River Watershed that contributes to runoff at the USGS gauge at Atkinson, Georgia. This gauge is located just upstream of the head-of-tide, which makes it the last gauge in the system before the tidal potion of the estuary begins. Thus, water flows at this point are unidirectional and not complicated by tidal action. A map of the modeled area relative to the entire watershed is provided in Appendix C. Preparation of the input maps and datafiles for SWAT follows:

Data Inputs - Land use

The SWAT model can accept land use data in the form of ArcInfo grids or shapefiles. For this analysis, I used four landcover grids developed for the Georgia Land Use Trends, or GLUT (Georgia Land Use Trends (GLUT) 1998), project by the Natural Resources Spatial Analysis Laboratory (NARSAL) lab at the University of Georgia. The mission of the GLUT project is to track and analyze the land use changes in Georgia that have occurred in the past 25 years. I used three of the GLUT project datasets, describing the land use in 1974, 1985, and 1998.

This GLUT land cover maps were produced from Landsat imagery with a spatial resolution of 60x60m. The 1974 and 1985 datasets were derived from the Landsat Multi-Spectral Scanner (MSS) sensor, while the 1998 dataset was derived from the Landsat Thematic Mapper (TM). The classification process used four of the original six bands of the imagery; the 120x120m thermal infrared band was removed from the data sets before processing. Additional ancillary geospatial and non-geospatial statistical data were incorporated in the mapping process. Image interpretation and analysis were performed on blocks, which were clipped by either county or multi-county units constrained by ecoregion.

An accuracy assessment of the GLUT datasets was performed using aerial videography, digital ortho quarter quads (DOQQ) and other ground information. The overall statewide accuracy is 85%. Although the data are available at a 30 m pixel resolution, accuracy was not assessed on patches of less than 4 pixels, due to the resolution of the original MSS data. Summaries of the 1974, 1985, and 1998 GLUT datasets appear in Appendix B.

During the land use definition process within SWAT, I reclassified each map into the SWAT land use scheme. In SWAT, each cell must have a land cover corresponding to an entry in either an urban or a plant land cover database. These databases are preconfigured with parameters describing 8 urban and more than 100 plant categories, primarily different agricultural crop types. All of the plant classes within the GLUT schemes, such as deciduous forest, fit neatly into predefined SWAT classes, with the exception of the Row Crops/Pasture GLUT class which spanned at least two SWAT categories and was assigned to the Agriculture-Row Crops (AGRR) designation. The assignment of GLUT categories to SWAT categories is listed in Table 3. I created new SWAT land use categories for Clearcut, Beaches/Dunes/Mud, and Quarries/Strip Mines/Outcrop by modifying existing land cover classes. However, because the semi-distributed design of the SWAT model utilizes Hydrologic Response Units (HRUs) of homogeneous land cover and soil type, patches of uncommon or widely dispersed land uses which are less than the user-specified size threshold are lumped into larger adjacent patches of more common land uses. Although there are portions of the state with extensive dune and beach complexes, after the 1974 GLUT grid was clipped to contain only pixels contributing to runoff at the Atkinson gage, only 0.03% of the pixels were classified as Beaches/Dune/Mud and no pixels were classified as Quarries/Strip Mines/Outcrop. After the HRU distribution step (see below), with 3% land cover and 6% soil cover thresholds, none of the 765 HRUs were classified as Beaches/Dunes/Mud or Quarries/Strip Mines/Outcrop. Thus, only the Clearcut category parameters had an effect on model output.

Table 3: GLUT 14-class classifications and their SWAT equivalents.

Cell Value	GLUT Land Use	SWAT Land Use
7	Beaches/ Dunes/Mud	*SAND*
11	Open Water	WATR
22	Low Intensity Urban	URLD
24	High Intensity Urban	URHD
31	Clearcut/ Sparse	*CLCT*
41	Deciduous Forest	FRSD
42	Evergreen Forest	FRSE
43	Mixed Forest	FRST
81	Row Crops/ Pasture	AGRR
91	Forested Wetland	WETF
93	Non-forested Wetland (freshwater)	WETN

Italics indicate user-defined SWAT land cover classes. Note: Only those GLUT classes that appear in the land cover grid after the SWAT HRU threshold definition are shown.

After visually inspecting the 1974 GLUT grid and consulting the technicians who had performed the classification of the LANDSAT images, it was clear that many of the pixels that had been classified as Clearcut were in low-lying areas, often adjacent to open water or forested wetland. Based on this, I defined a new SWAT plant cover type for Clearcut (CLCT) based on the SWAT Forested Wetland (WETF) cover type. I reduced the Leaf Area Index parameter, from 5 to 3 m^2m^{-2} and reduced the Canopy height from 6 m to 3 m to simulate the overall reduction in plant structure. I then increased the Manning's roughness coefficient for this land use to 0.09, equivalent to that of a roughly plowed agricultural field, to simulate the effects of understory clearing and raised rows of pine seedlings.

Data Inputs - Digital Elevation Model

The SWAT watershed autodeliniation procedure uses data about the topography of the watershed to predict the direction of runoff from each cell of the watershed grid. Elevation information is provided, in digital form, by a Digital Elevation Model (DEM.)

The DEM used for this study was a portion of the USGS National Elevation Dataset, or NED, which had been clipped using the 8-digit HUC code boundaries for HUCs numbered 3070202 (Little Satilla) and 3070201 (Satilla River). I then merged these clipped grids into a single file using a grid mosaic procedure, part of the GridPig utility extension to ArcView (Hare 2003). The resulting grid has a horizontal resolution of 30x30 m and the vertical units (elevation) are in centimeters. (U.S. Geological Survey (USGS) 1999). A map of this DEM is shown in Appendix C.

Data Inputs – Soils

The soil data layer used as input to the land use and soil overlay procedure was the 1994 STATSGO database, constructed by the Natural Resources Conservation Service of the U.S. Department of Agriculture. The digital form of this database was an ArcView Shapefile, clipped to the boundary of the State of Georgia. The STATSGO database is not derived from a comprehensive soil survey, but is a general soil association map developed by the National Cooperative Soil Survey. It consists of a broad based inventory of soils and nonsoil areas that occur in a repeatable pattern on the landscape and that can be cartographically shown at the scale mapped. These soil maps are generalizations of more detailed soil survey maps, where available. If detailed soils data are not available, data on geology, topography, vegetation, and climate are assembled, together with Landsat images. This information is used to determine the probable classification and extent of the soils though comparison with similar areas (U.S. Department of Agriculture 1994)

Data Inputs - Stream Network

Although the SWAT autodelineation procedure uses the DEM to derive a stream network, it will use a digital map of the actual stream network, if available, to "burn in" stream channels on the DEM. This process overcomes inaccuracies in the modeled stream network that may result from errors or imprecision in the Digital Elevation Model and insures that the derived stream network closely matches the actual streams in the watershed. The actual stream network used was the Reach File Version 1.0 (RF1) for the Satilla and Little Satilla rivers, constructed by the USEPA. The RF1 is a vector database of approximately 700,000 miles of streams and open waters in the conterminous United States. In this case, the relevant RF1 data were provided in the form of an ArcView shapefile. RF1 was prepared by the U.S. Environmental Protection Agency (EPA) in 1982 from National Oceanographic and Aeronautical Administration (NOAA) 1:500,000 aeronautical charts. These charts provided the best nationwide hydrographic coverage available on a single scale at that time (U.S. Environmental Protection Agency (USEPA) 1998).

Data Inputs - USGS Gauge Locations and Streamflow

I used data from three stream gages in the Satilla River network for the calibration of the SWAT model. The system outlet location corresponded to the USGS gage at Atkinson Georgia, number 02228000. The two upstream gages were the USGS gage on the Satilla River at Waycross, GA, number 02226500, and the USGS gage on the Little Satilla River near Offerman, GA, number 02227500. The use of multiple gages allowed me to calibrate the two upstream reaches independently of the main stem. A map showing the locations of these three gauges and their contributing areas is shown in Appendix C

The USGS discharge gage at Atkinson, Georgia, lies at an elevation of 4.51 meters and, as the downstream-most gage that lies above the area of tidal influence, runoff at this location represents the delivery of freshwater into the estuary. There are extensive brackish and saltwater marshes downstream of this point that contribute freshwater runoff to the estuary after rain events and, although measuring and modeling the hydrologic processes in these low-gradient areas is beyond the scope of this project, land use change in these areas has probably been minimal. Thus, any significant past or future changes in the delivery of water to the estuary will likely be the result of changes in the upland portions of the watershed, above the Atkinson gage, and the river hydrograph at this gage was the focus of my analysis.

Flow data for each of the three gages was downloaded as plain-text files from the Georgia page of the USGS National Water Information System (U.S. Geological Survey (USGS) 2005). I reformatted these files use as inputs to SWAT and as inputs to the Baseflow Filter program for SWAT (Arnold, Allen et al. 2002). This program uses a signal-processing algorithm to derive several parameters from an input hydrograph. I used the program to calculate values for baseflow days (the number of days for the baseflow recession to decline through one log cycle), baseflow fraction (the fraction of flow contributed by baseflow), and groundwater alpha (the baseflow recession constant.) from the flow data for the period of 10/1/1965 though 9/12/2003. This period approximates the water years 1966-2003 and encompasses the modern simulation period, from just before the calibration flow dataset (1967-1976) until the last date available at the time of download. These calculated parameters were used as inputs to the groundwater portion of the SWAT model.

Data Inputs - Precipitation

Although SWAT contains a weather generator, its output is highly smoothed, relative to actual precipitation record. The weather generator will adequately recreate monthly average conditions, but simulated precipitation is generally unsuitable for daily runoff simulation and measured data is preferred for the purposes of model calibration (Srinivasan 2005). Furthermore, hydrologic models, generally, are very sensitive to precipitation inputs (O'Connell and Todini 1996; Nandakumar and Mein 1997), and the extent of this sensitivity in SWAT is well documented (Hernandez, Miller et al. 2000). I downloaded daily measured precipitation data as tab-delimited text files from the National Climate Data Center's (NCDC) Climate Data Online system. (National Oceanographic and Atmostpherec Administration (NOAA) 2005). Beginning with the NCDC station at Alma, GA, which is near the center of the watershed, I performed a proximity search for stations within 100 miles. I selected for download all of the stations that were located either within or near the boundary of the Satilla watershed, then re-selected for those providing near-continuous coverage beginning before 1966. The resulting 10 stations are listed in Table 3, along with their location, elevation, and station name. A map of the locations of these stations is provided in Appendix C.

These ten stations provided the best available spatial coverage, but did not provide the uniform and complete temporal coverage required for the SWAT precipitation inputs. In order to remedy this, I replaced all "trace" precipitation readings with an estimate of 0.005 inches, or half of the minimum measurement resolution of the gages. I discarded snow readings, since the conversion of snow accumulation to inches of rain can be quite variable and snow is infrequent in this region. No gage showed more than one event of more than 2 inches of snow during the simulation period.

Missing data was a far larger estimation challenge in the construction of the precipitation dataset. Each station contained multiple periods of missing data, during which the recorder was offline or mis-calibrated, ranging from several days to over a year, in one instance. Beginning with the Alma station, I performed a modified Thiessen calculation (Burrough 1986) to estimate the missing data points based on the values for adjacent gages. Where data for the three closest gages existed, I used the mean of these three values for the missing data point. For any remaining missing data, I used the mean of the two closest points, followed by a simple substitution of the nearest available data for any remaining gaps. This procedure was performed first on the interior stations, because these were most likely to be surrounded by the stations used as estimators, then data from these stations were used to fill any remaining gaps from the stations along the edge of the watershed. This last procedure is analogous to the algorithm used by the model itself, which assigns precipitation to a sub-basin based on the gage closest to the sub-basin centroid. The area-based averaging I performed in the first two estimation passes should provide a slightly more realistic precipitation input to the model than would have been afforded by simply dropping the gage from the input during the period of missing data. In addition, dropping the gages would have required the preparation of multiple input datasets, one for each constellation of precipitation gages. By manually estimating the missing data, I was able to simplify the model setup and simulation procedure substantially.

Preparation of SWAT Inputs

I performed some additional processing on the data input files, described above, to format them for use within SWAT. First, all data were projected from their delivery projection, typically geographic decimal degrees, into UTM Zone 17. Grids were projected using the BASINS Grid Projector extension, shapefiles were projected using the BASINS Data Download tool (U.S. Environmental Protection Agency (USEPA) 2004).

Although the GLUT land use data and the DEM were ostensibly clipped to the HUC boundary, these grids did not perfectly overlap. The process of overlaying the land cover and soils data on the elevation grid is a fundamental step in the SWAT model setup, yet I experienced some difficulties in importing the GLUT grids into SWAT. Frequently, the land cover definition tool would exit, without error, but leave large polygonal areas of missing data in the imported grid. Suspecting that the poor registration of the GLUT and DEM grids might be the cause, I used the following procedure to restrict the SWAT overlay procedure to only those cells for which data existed in both grids: I created an intermediate grid by multiplying the input grids, which resulted in a smaller grid with NODATA values in the cells where either input grid had NODATA. I then used a map query to generate a grid containing a 1 in any cell where the intermediate grid did not contain NODATA. This grid identified the overlapping cells of the GLUT and NED grids. I specified this grid as a mask grid in the overlay tool, which instructed the resulting SWAT land use and soil layers to be clipped to the area of overlap. The resulting Modeled Area is shown in Appendix C.

Watershed Autodelineation

I performed an autodelineation of the watershed as described in the SWAT user's manual (Neitsch, Arnold et al. 2002), using the NED, GLUT, and mask grids, as described above, and the Reach File, version 1, to burn in the streams. I selected a

Threshold Area of 11,550 ha for the watershed delineation, which yielded approximately 40 subbasins. The threshold area, or critical source area, defines the minimum drainage area required to form the origin of a stream. This threshold value is inversely related to the number of subbasins, and there is a substantial trade-off between the increased resolution provided by additional subbasins and the additional time required to parameterize and process this additional information. Trial runs with approximately 20 subbasins has demonstrated that the resulting stream network was unrealistically simplified and that larger subbasins actually resulted in fewer HRUs, due to the interaction of the HRU thresholding procedure and the fine grain of the less-extensive land uses. Conversely, the channel erosion routines within SWAT have a tendency to incise short, wide subbasins that receive substantial flow from upstream (Srinivasan 2005). A threshold area that generated approximately 35 subbasins resulted in a realistic stream network without risking these incision effects.

After the threshold area procedure had derived the stream network, I manually added nodes in locations corresponding to the USGS gages at Atkinson, and Waycross, Georgia. The SWAT output files contain simulated flow at each node. Thus, subbasins contributing to these additional nodes would match the gauged areas of the USGS stations. There was a natural node in the stream network very close to the Offerman gage and adding a new node would have created a tiny subbasin as an artifact, so I did not add a third additional node. This autodelineation resulted in 42 subbasins, which are shown in the figures in Appendix C.

HRU Thresholds

The next step of the SWAT model setup process is to further divide the subwatersheds defined in the delineation process into hydrologic response units (HRUs). An HRU is the minimum unit of simulation for the SWAT model, and each HRU is a uniform area of a single land use and soil type. Runoff, erosion, and agrichemical transport are determined separately for each HRU. The HRU outputs are routed in sequence to obtain the total runoff for the subwatershed. Each subwatershed contains one or more HRUs, and the simulation routes flow from each HRU directly into the channel system of that subwatershed. The minimum threshold area for inclusion in an HRU is selected by the user after the watershed had been delineated and the land cover and soil data overlaid on the DEM. Land uses and soils that cover a percentage of the subbasin area less than the HRU threshold level are eliminated, and these areas lumped into adjacent HRUs.

I chose 3% land area and 6% soil area as the threshold for an HRU. These values represent a compromise between the 10% land 10% soil threshold used in my training simulations, levels that lost all but the most common land cover types, and the computational time required to simulate at the maximum HRU resolution of 1% land and 1%. soil Since the STATSGO soils input reflects association and not measured data, it is composed of large polygons that cover a substantial portion of most of the 42 subbasins and I was able to relax the threshold area for soil coverage. At 3% land area and 6% soil area, the thresholding procedure created approximately 700 HRUs for the three GLUT grids.

Management Inputs

In addition to being the minimum area of the hydrologic simulation, the HRU is the unit of management action within SWAT. I defined management activities for the HRUs that contained the Row Crops/Pasture (AGRR) classes. The first activity I specified was an auto-application of fertilizer. Initially, this was a response to the Nitrogen Stress Days values in the early simulation runs. The initial simulations displayed more than 40 nitrogen stress days indicating that the plant growth simulation was running out of nitrogen during the growing season and attenuating plant metabolism.

Since evapotranspiration should make up approximately 50-60% of the water budget, and the model output was reporting nitrogen limitation of plant growth, I specified the automatic application of Elemental Nitrogen to insure that plant growth was not unrealistically limited. In the SWAT model, the auto-application of fertilizer is triggered when plant growth declines to a specified threshold percentage of the maximum growth rate. I specified an application threshold of 0.85, beginning just 0.05 heat units after planting. In this case, when nitrogen stress was sufficient to depress plant growth by 15%, the model simulated the application of fertilizer. In later simulations, both Nitrogen and Phosphorous stress were still present, so I simulated the application of a 22-14-00 (N-P-K) formulation.

The farmers in this watershed apply as much as 79,000 m^3d^{-1} of irrigation water, 75% of which is derived from groundwater (Alber and Smith 2001). In order to simulate these withdrawals, I specified an auto-irrigation routine in the agricultural land uses HRUs as well. This was set to begin irrigation at 0.05 heat units after the initiation of fertilization, and to irrigate with water from the deep aquifer whenever water stress depressed growth by 25%.

Urban Water Withdrawals

In addition to the pumping of groundwater for irrigation, I specified water withdrawals for the urban HRUs in subbasin 37, corresponding to the location of Waycross, GA, and equivalent to the roughly 64,000 m^3d^{-1} cited as water withdrawal in urban or semi-urban areas of the Satilla River watershed by Alber and Smith (2001). This report did not contain detailed statistics on urban withdrawal, either as a function of time or location, so I specified that the withdrawals should occur throughout the year and that all withdrawals should be in the only consistently high-density urban HRU.

Model Calibration

I calibrated the SWAT model for the 1974 GLUT land cover dataset according to the principles in the SWAT User's Manual (Neitsch, Arnold et al. 2002). This procedure involved computing the annual water balance of the observed and modeled runoff datasets. I ran calibration simulations over the period of 1/1/1968 to 12/31/1976. For each model run, I calculated the water balance using the yield lines in the run summary file (Output.std). After checking the biological components of the model to ensure that plant growth was reasonable, I then adjusted the model parameters based on the relative fit of the annual water balance to the observed values and set-up a new simulation. I repeated this process until the amount and proportions of runoff approximated the observed data, then I began manipulating more subtle factors affecting the shallow groundwater and plant growth to fine-tune the model behavior.

Water Balance Calculations

The water balance is a separation of the total water yield into baseflow and surface flow components. For these calculations, all yields are expressed in terms of millimeters of water over the watershed area. I had already performed the necessary calculations for the observed dataset for the period of 1966-2003 during the baseflow parameterization, described above. I ran these calculations again, restricting the analysis to a calibration dataset spanning 1/1/1968 to 12/31/1976, and used the second-pass baseflow fraction (BFR) to separate the total water yield into baseflow and surface flow yields. I used the following equation to calculate the baseflow ratio from the SWAT summary outputs:

$$BFR = \frac{(LateralQ + GroundwaterQ)}{(SurfaceQ + LateralQ + GroundwaterQ + TileQ)}$$

Where BFR is the baseflow fraction and the Q terms refer to lines listing the Surface Water Yield, Lateral Flow Yield, Groundwater Yield, and Tile Flow in the output.std file produced by the model. Results for these yield calculations are shown in Appendix X.

Crop Yields

I periodically assessed the potential crop yields produced by the model to assess if the model was realistically simulating biological activity. I assembled crop yield data at the county level for the period 1970-2004 and district level (District 9) for 2003 and 2004 from the National Agricultural Statistics Service QuickStats database (National Agricultural Statistics Service 2005). In order to compare the county-level data with the model output, I built a PivotTable within Microsoft Excel to summarize the yield, in kg/ha, by crop, for all counties in the Satilla River watershed. I then built a similar table that multiplied the HRU-level crop yields by the area of each HRU derived from the SWAT output.hru file to summarize the total potential yield for the Row Crops/Pasture land cover class. Due to the vagueness of this land cover definition, i.e., individual crops are not specified, and the management and yield of row crops is fundamentally different than pasture lands, it would be impossible to calibrate these values exactly. I sought to ensure, however that these HRUs were producing yields that were on the lower end of the range of actual crop yields for the watershed. For the years from 1970-1976, corresponding to the model calibration period, the average crop yield (weighted by harvested area) for the 10 crops reported by the NASS was 18,130 kg/ha. During the calibration runs, the simulated potential crop yield for this period varied from 13,378 to 16,367 kg/ha. Assuming that the yield of pasture land ranges from 2459 kg/ha for Bermudagrass "Tifton 78" (Hill, Gates et al. 1995) to 13,500 kg/ha for Tall Fescue (Hannaway, Fransen et al. 1999), the simulated yield for the combined Row Crops and Pasture class should be somewhat less than that of the actual yield for harvested cropland, though exactly how much less is impossible to calculate.

Sensitivity Analysis

Having establishing that the potential crop yields predicted by the model were realistic, I returned to the calibration of the model. I performed a Sensitivity Analysis on the watershed, as described in the Advanced SWAT BASINS Training Manual (Srinivasan 2005). This procedure uses a multivariate parameter shuffling algorithm to efficiently test the entire parameter space against a global optimization criterion and returns an ordered list of the model parameters in terms of their relative effect on the model output (van Griensven and Bauwens 2003). This procedure varies only the coefficient parameters in the model; it does not alter the input layers, such as land cover and management, described above. The top ten variables returned by the initial sensitivity analysis, along with the default and adjusted values, are listed in Appendix F.

Hydrology

The next step of the typical SWAT calibration procedure is to adjust the CN2 values, or the SCS Curve number for runoff condition #2 for each management unit. Because the Surface Flow component of the water yield was too high, I reduced the curve numbers in the .mgt file for each HRU by 10%. Having reduced the surface flow, I then began to adjust the groundwater parameters by varying GWQMN, GW_Revap, Rchrg_dp, and ESCO. I did not adjust sol_z, the plant rooting depth, because this is a factor more of plant growth than of hydrology, nor did I adjust SLOPE, the watershed slope, as this should have been calculated by the watershed delineation, and I had no reason to believe that the DEM was inaccurate. I adjusted the remaining parameters in small increments and re-ran the simulation with a monthly time step over the calibration period of 1968-1976

Model Validation

After calibration, I performed a simulation of the period 1968-1982, an addition of 5 years to the calibration simulations, and assessed the accuracy of the model flow predictions using these "novel" precipitation inputs. This provides a check against a calibration that is over-fit to the observed data at the expense if general predictive power. After a visual inspection of the monthly hydrograph and the water yield calculations suggested the model was approaching the measured data, I calculated the Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970) and Root Mean-Squared Error of the simulated output of the watershed relative to the measured flows at the USGS station at Atkinson. The Nash-Sutcliffe E statistic is a measure of model prediction efficiency. A score of NSE=1 indicates that the simulated data points predict the actual data points exactly. A score of NSE=0 indicates that the simulated data are points no better predictors than the mean of the observed dataset. The NSE statistic is calculated using the following equation:

$$NSE = 1 - \frac{\sum_{i}^{n} (O_i - S_i)^2}{\sum_{i}^{n} (O_i - O')^2}$$

Where O_i = ith Observed point, O' = Population mean of the observed points, and S_i = ith Simulated point.

I used HydroFunctions.xla, a Microsoft Excel add-in (Heberger 2004) for the Nash-Sutcliffe E calculations. These calculations were performed on the predictions for the period of 1/1/1970 though 12/31/1982. The initial 2 years of the simulation were discarded. Since the SWAT model starts with no initial conditions, on day 1 of the simulation, there are completely dry soils and empty channels, so the first several years of a simulation should be viewed as a "warm-up" period, during which these stocks will equilibrate. A calibration/validation plot of monthly mean flows is shown in Appendix G.

Simulations using modern data layers

After calibrating and validating the model using the 1974 land cover map, I ran a final baseline simulation for the period of 1/1/1968 to 12/31/2002. I then created two new projects in AVSWAT by copying the 1974 project files. I imported a new land cover grid to each, using the 1985 and 1998 GLUT land use grids, and performed the overlay and HRU distribution, as above, to set up the model with the new land cover information. Because the HRU distribution resulted in a different number of HRUs, I repeated the assignment of parameters to the new models, placing or updating entries in the appropriate tables to transfer the 74 calibration to the new project.

After setting up the projects, I simulated the same 35-year period as the baseline 1974 project in each and compared these results to those obtained using the 1974 coverage, above.

Construction of past and future scenarios

Beyond the three measured time points provided by the GLUT datasets, I created additional development scenarios using the Spatial Analyst extension to ArcView and the Land Cover Splitting tool with AVSWAT 2004. Spatial Analyst is a flexible tool for manipulating raster data within ArcView. This AVSWAT Land Cover Splitting Tool allows existing land use classes to be split into one or more new classes through a random reassignment of a user-specified percentage of the grid cells in the class. I used Spatial Analyst for directed manipulation of development, or to remove development in the creation of the pre-development scenario, while I used the Land Cover Split tool for smaller, random changes. While this is a less sophisticated approach than a coupled development and hydrologic simulation, it does reproduce the patchy nature of actual land use change, and the semi-distributed design of SWAT merges the random arrangement of the pixels into uniform parcels once their density crosses the HRU threshold. I created the following simulations, using the 1998 land cover as a base:

Reforestation

I created a layer consisting only of "changed" cells that were the result of land use change. For this layer, I selected the cells in high-density and low-density urban classes, along with clearcuts and row crops/pasture from the plant classes. I then passed these cells through a series of filtering equations using the Map Calculator and distance calculation functions within Spatial Analyst. First, I assigned all cells within 30 m of open water or adjacent to cells in the non-forested wetland class to the non-forested wetland class. Then I assigned all the other cells within 120m of open water or those adjacent to cells in any of the three wetlands categories in the forested wetlands category. Next, I selected cells that were closer to mixed forest than to either of the other forest types and assigned those to mixed Forest. I repeated this process with cells that were closer to deciduous forest than to evergreen forest and assigned them to deciduous forest. All remaining cells in the "changed" were assigned to evergreen forest. A map of the land cover grid after this procedure appears in Appendix D.

I ran the simulation using the Reforested land use grid over the same 3-year time period as the three GLUT simulation, from 1/1/1968 to 12/13/2002. I compared these simulations with those using the 1998 GLUT land cover over the same time period. The 1998 is the most developed of the modern datasets, thus it provides the best contrast with the pre-development scenario. I also ran a simulation from 2005-2030, matching the period used for the Sprawl scenario, described below.

Sprawl

I applied a process of urban contagion to develop a sprawl scenario, with the goal of increasing the area of urban and suburban land use by 50% over the 1998 pattern, an increase in urban cover roughly proportional to that which occurred during the period between the 1974 and 1998 GLUT land cover maps. The theory I applied was to build the urban cells up first, then to build out. I began by using the existing high-density urban pixels, which include pixels defining major roads, as the basis for a distance grid calculation, in which each cell is assigned a value reflecting its distance to the nearest cell in the high-density urban class. I selected only low-density urban cells and began converting these to high-density urban, using first the cells adjacent to existing high-density urban cells. I increased the distance threshold for this conversion gradually until the number of converted cells first exceeded 50% of the original number of high-density cells.

Having built the low-density urban cells up into high-density cells, I then began extending the urban footprint. I created two more distance grids, the first using the current low and high-density cells as the input. This gave me a new grid, with low values in cells adjacent to existing urban cells and roads and values that increased with distance from developed cells. I then created a second grid, using a point coverage of city-centers as input (U.S. Geological Survey 1995). This resulted in a set of bulls-eyes around the cities in the watershed, with low values at their centers. I then multiplied these two grids, using the grid calculator, to create a rough suitability surface for urban development. Through this multiplication operation, cells received a low score if they were both near an existing developed land use, or road, and close to a city center. Conversely, cells in the interior of undeveloped parcels received the highest scores. I then selected the cells with the lowest scores that were not wetlands, open water, or currently in an urban class and assigned them to the low-density urban class. I continued selecting cells until the total area of low density urban cells (the low-density urban cells that were not converted to the high-density class, above, plus the newly selected cells) passed 50% of the original area of low-density urban land use. During the land use overlay process, I used the Land Cover Splitting Tool within AVSWAT to split off 20% of the high-density urban category, assigning 10% to the pre-defined Urban-Commercial and Urban-Institutional categories.

Finally, based on the predictions of the Southern Forest Resource Assessment (Wear 2002), which projects an increase of land under timber management but minimal loss of forest cover, overall, I used a procedure similar to the one above to select forested cells near roads and urban centers and converted 25% into monoculture stands of pine. Through this process, I have simulated development occurring first as expansion of existing city centers, then outward from these centers along major roads. Maps of the reclassified cells and the resulting future land use scenario are in Appendix D.

I used the Sprawl land use coverage to simulate the next 25 years, from 2005 to 2030, using simulated precipitation and assuming a water withdrawal rate in the urban uses of 50% more than the rate for 1995 used in the GLUT simulations. Water withdrawal does not precisely scale with urban area in the SWAT model, so I manually adjusted the surface and deep aquifer pumping rates to accommodate both the 25% increase in urban area and the simulated increase in population density. I simulated the same period, under the same water-use assumptions, using the model with the 1998 GLUT land use grid, as well, as a basis for comparison to the Sprawl scenario.

Simulations using scenario data layers

For each scenario, I performed the land cover and soil overlay, as described above. I used simulated precipitation for a period from 2005-2025 and compared the simulated flows to those produced by the 98 land cover model using the same precipitation data. The SWAT weather generator produces a highly-smoothed climate signal, which reduces the variability of output flows, and tends to artificially increase the

Nash-Sutcliffe efficiency, so I did not calculate the NSE for these simulations. Instead, I recorded the annual water yield statistics from the Output.std file for each scenario. I used these statistics to calculate the baseflow ratio, as above, for each of the scenario simulations.

3. Results

The goal of this calibration was to achieve a Nash-Sutcliffe E of better than 0.5. The results for the Calibration and Validation period are shown in Table 4.

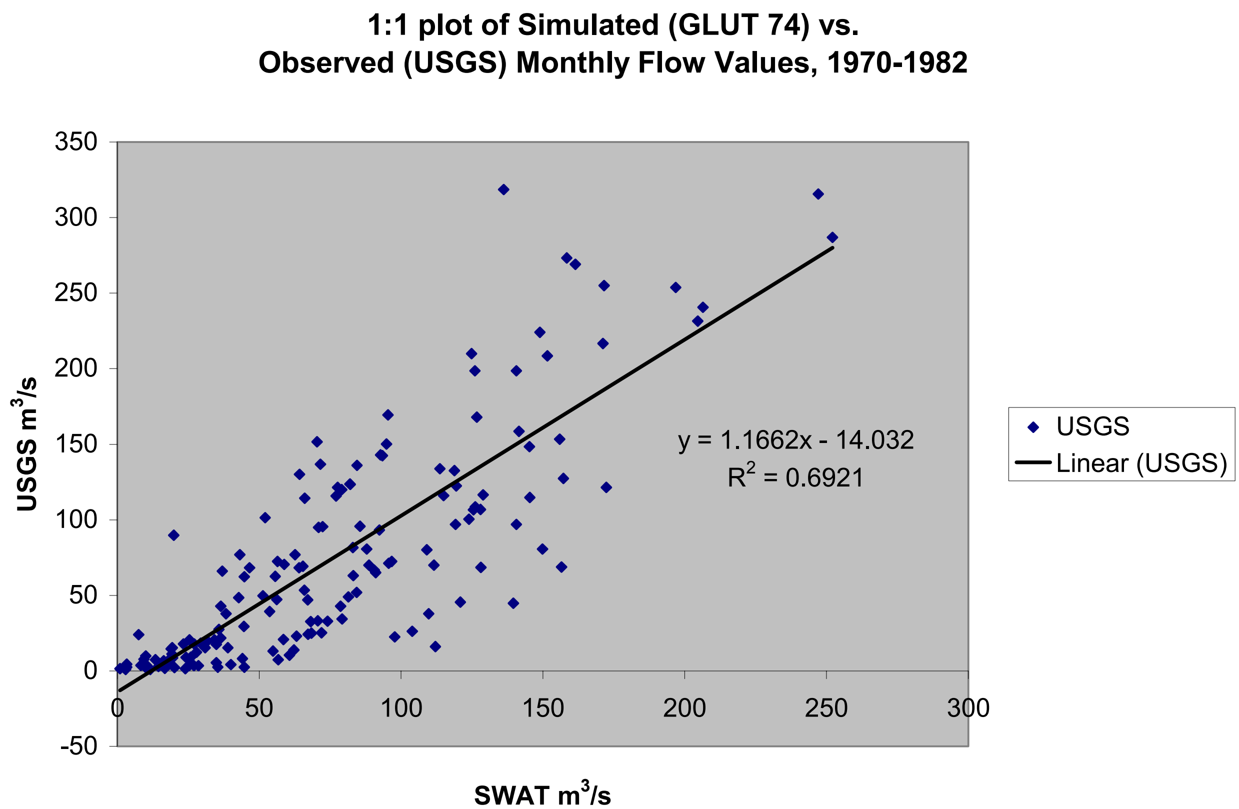
Table 4: RMSE and NSE for the calibration (1970-1976) and Validation (1977-1982) Periods.

	NSE	RMSE
Calibration	0.642	44.358
Validation	0.701	40.968
All Years	0.678	41.838

The overall NSE for the combined calibration and validation period of 1/1/1970 to 12/31/1982 was 0.678, and the RMSE was 41.838. This value for NSE compares favorably with the literature values summarized in Table 2.

Figure 1 shows the simulated monthly mean flow data plotted against the measured monthly data. Plotted in this manner, the data points of a perfect simulation would all fall on the 1:1 line. Thus, the slope and r^2 of a linear curve fit to these data provide another measure of the accuracy of the model predictions. Overall, the r2 of the 1:1 line is .69. Thus the model does well at predicting monthly flows using measured precipitation. The model is slightly under-predicting the highest flows, but is over-predicting the lower flows, thus creating negative intercept while maintaining a slope greater than 1:1.

Figure 1: Simulated vs. Observed Monthly Mean Flows for the Calibration Period.



Question #1 Comparison of simulations using GLUT 74 and Later Land Use Data

To assess the question of the SWAT model's sensitivity to variation in the land cover input layer, I examined the outputs of the simulations using 1985 and 1998 GLUT land cover input data over the time period used for calibration and validation of the model using the 1974 land cover. All input parameters and coefficients were held constant, so the only difference between these model runs was the land cover information.

Clearly, the model is sensitive to the changes that occurred in the land use inputs on the scale of two decades. Total water yield increased by 4.3% between the 1974 and the 1998 simulation, the groundwater yield increased by 10%, and the Baseflow Fraction shifted from 0.56 to 0.59. A summary of these model outputs can be found in Table 5.

Table 5: Summary outputs for simulations using the GLUT74, GLUT85, and GLUT98 land cover maps for the period of 1970-1979.

Land-cover	Surface Yield (mm)	Ground-water Yield (mm)	Total Yield (mm)	Base-flow Fract.	Per-colation from Soil (mm)	ET/ Precip.
GLUT74	158	192	346	0.56	427	0.51
GLUT85	160	200	355	0.56	436	0.50
GLUT98	154	211	361	0.59	440	0.50

Question #2: Comparison of the simulations using 1974, 1985, and 1998 land cover

Table 6 summarizes the model fit statistics for simulations using the GLUT74, GLUT85 and GLUT98 maps over three decades of measured precipitation inputs. The NSE of simulations using all three land cover maps does not improve with each simulated decade and the results for all three are essentially equivalent, regardless of the time period simulated. As shown above, the models using the 1974 and 1985 land covers score well during the period of the 1970s, with NSEs of .637 and .642. In the decade of the 1980s, all three models perform at just over 0.70, although the RMSE of each peaks in this decade, as well.

Table 6: NSE and RMSE for the USGS observed dataset versus the 1974 GLUT, the 1985 GLUT data, and the 1998 GLUT data.

NSE of Model Fit to Observed Flows			
Time Period of Flow/Precip.	Landcover Map		
	GLUT74	GLUT85	GLUT98
1970-1979	0.637	0.642	0.641
1981-1990	0.705	0.707	0.705
1994-2002	0.676	0.657	0.642
RMSE of Model Fit to Observed Flows			
Time Period of Flow/Precip.	Landcover Map		
	GLUT74	GLUT85	GLUT98
1970-1979	44.5	44.1	44.2
1981-1990	50.2	50.0	50.2
1994-2002	46.4	47.7	48.7

Surprisingly, the model using the 1974 GLUT landcover outperformed the other two slightly during final decade of the simulation. Thus, the models using contemporary precipitation and land cover do not outperform those using land cover data that are mismatched in time to the precipitation. Furthermore, as Table 7 shows, the three simulations are extremely efficient at predicting the outputs of other simulations, on any precipitation series, with an NSE of greater than 0.99 for all 9 comparisons. However, the RMSE for the pairwise comparisons involving the 1974 land cover dataset increases with each passing decade of simulation, from 3.13 to 3.97 against the 1985 GLUT land use and from 4.57 to 5.24 against the 1998 dataset. The errors increase in the time period between the landcover datasets, as well, with the RMSE of 3.13 for the 74-85 comparison rising to 4.57 for the 74-98 comparisons using the 1970s precipitation. Thus, while there is no overall increase in the predictive efficiency of the model, over time, it does appear that there is an effect of time on the model, as errors accumulate between the predictions of the 1974 model and the other two.

Table 7: Nash-Sutcliffe E for pairwise comparisons between simulations using the 1974 GLUT, the 1985 GLUT, and the 1998 GLUT landcover data.

NSE, Simulation to Simulation			
	Comparison		
Simulated Flow Period.	GLUT74-GLUT85	GLUT74-GLUT98	GLUT85-GLUT98
1970-1979	0.996	0.992	0.997
1981-1990	0.998	0.995	0.998
1994-2002	0.996	0.993	0.998
RMSE, Simulation to Simulation			
	Comparison		
Simulated Flow Period.	GLUT74-GLUT85	GLUT74-GLUT98	GLUT85-GLUT98
1970-1979	3.13	4.57	2.59
1981-1990	3.19	4.71	2.55
1994-2002	3.97	5.24	2.45

Question #3: Summaries of past and future runs

Appendix H shows a summary of the Reforested landscape simulation in tabular form. Returning the watershed to an entirely forested cover sharply affected the water yield and balance between baseflow and stormflow. Total water yield was reduced 13%, due to a reduction of surface yield by 33% and groundwater yield by 6%, resulting in a change in the baseflow ratio from 0.59 under the 1998 land cover to 0.65 under the Reforested landcover.

The second item in Appendix H is a plot of the flows for the 35-year simulation period, by month, intended to demonstrate the seasonality of water delivery under the two simulations. While the winter flows are nearly equivalent between the Reforested and GLUT98 simulations, the flows from August to December are noticeably higher for the GLUT98 simulation. This is due, in part, to the use of irrigation and the pumping of water from the deep aquifer for municipal use in the GLUT98 simulation, but is also a result of higher surface runoff from fall storms due to the lower baseflow ration of the GLUT98 simulation. Thus, the spring peak flows are higher, relative to the summer low flows, under the Reforested land use scenario.

Appendix I contains a summary table comparing the outputs of the GLUT98 and Sprawl simulations for the projected period of 2005-2030. Continuing the trend displayed in the Reforested simulation, increasing the percentage of urban land uses in the watershed had the effect of increasing the total water yield by 7%, though this affected the surface flows disproportionately, increasing surface yield by 19%, while groundwater flow actually declined, slightly. This further shifted the baseflow ratio from 0.62 under the GLUT98 land cover ma to 0.57 under the Sprawl land cover simulation.

Appendix I also contains a plot of the projected flows, by month that demonstrates the seasonality of water delivery under the GLUT98 and Sprawl simulations. June and July flows are somewhat higher under the Sprawl scenario, as are December, January, and February flows. The overall effect of these shifts is that the spring peak appears to occur as much as a month earlier under the Sprawl scenario and the relative difference between this peak and the summer low flows is further reduced.

Appendix J contains a table comparing the results of the three scenarios over the period of 2005-2030, using the same simulated precipitation data for all three simulations. Total water yield under the Sprawl scenario is 25% higher than under the Reforested scenario, and the baseflow ration declines from 0.69 under the Reforested scenario to 0.57 under the Sprawl scenario. The GLUT98 simulation shows intermediate values for all model outputs. Finally, this table shows that uncalibrated sediment loading increases with development, by 5,820% between the Reforested and GLUT98 scenarios and by a staggering 10,940% between the Reforested and Sprawl scenarios.

4. Discussion

Overall, the SWAT model performed above expectations in simulating this watershed. Anticipating substantial seemingly random variability due to the poor coverage of the precipitation gages and relative scarcity of flow gages within the watershed, I set an NSE threshold of 0.50 for a successful calibration, yet several of the simulations performed at better than 0.70, and even the least efficient models bested the 0.50 threshold. Using freely-available datasets as model input, this model is able to simulate the runoff behavior of a 7044 km^2 watershed to within 20mm, about +/- 7%, of measured annual water yield.

Given the apparent success of the calibration, the relative lack of differences between the outputs of the model using different Land Cover inputs is puzzling. Several factors may be contributing to this situation, among them unusual precipitation patterns, specious calibration effects, and confounding effects of the various land uses.

Both of the later simulation decades were characterized by lower precipitation than the calibration period. The water years of 1985-1989 saw a drought with a recurrence interval of 10-25 years in central Georgia, though effects farther to the south and east were substantially less. During the late 1990s, however, the state of Georgia suffered a severe drought, and flows on the Altamaha and Ogeechee rivers, adjacent to the Satilla River watershed, reached 50-year lows (Barber and Stamey 2001). This situation impacted both the hydrology of the Satilla River system and the expected performance of the model significantly. During drought conditions, shallow groundwater processes are almost non-existent simply because there is so little water in the soil. Thus, the entire groundwater component of the SWAT model was not in use for much of this period, and any variability that may have resulted from errors or estimation in the parameters of this sub-model would have disappeared from the model output. Essentially, the drought simplified the simulation problem, not only was there less rain to run off, but much of the runoff was handled by the well-validated SCS curve routing method.

Confounding the apparent simulation benefit of this drought, however, is the fact that the model was not calibrated for drought conditions, since the calibration period of 1968-1976 did not contain any drought years. Ideally, the calibration period would contain the entire expected range of environmental conditions, as attempting to simulate conditions beyond the calibration envelope typically leads to unpredictable results. Although this does not appear to be the case, here, the apparent quality of the simulation could reflect as much luck as calibration accuracy.

Despite the changes in the precipitation regime, it is surprising that there are so few obvious differences in the simulations resulting from use of the three different GLUT land use maps. Indeed, it is likely not the case that the various land uses have no effect on the runoff behavior of the watershed but, rather, that at the current level of disturbance, the effects of different land uses substantially offset one another. For example, increased runoff within a subbasin from a bedded pine plantation may be swamped by the artificial maintenance of soil moisture and increased percolation from an irrigation management operation in an adjacent HRU. While these effects appear to be in balance, currently, there may be a threshold response to increasing change, beyond which additional land use change will have seemingly disproportionate effects. The significant shift in the baseflow ratio between the GLUT98 coverage and the Sprawl scenario seems to be a result of this sort of threshold response to increasing impervious surface coverage.

It may also be the case that the model is predicting runoff in spite of the land use inputs. Given the relative lack of detail in the STATSGO soils coverage and the agricultural classes of the GLUT classification scheme, a number of parameters were adjusted, perhaps unreasonably so, in the calibration process. I performed no ground-truthing on the values for many of the groundwater and crop-management parameters, any of which might have been unrealistically affecting the water balance, and introducing "error" that actually improved the model performance. While the model could certainly be "right for the wrong reasons," the evapotranspiration values predicted by the model are well within the range of values measured by Bosch, et. al., (2004) for a nearby agricultural watershed, so the biological components of the model, at least, are functioning in a realistic manner.

Despite the unsophisticated approach to the construction of the simulated land cover maps, the implications of the Reforested and Sprawl scenarios are profound. If the Reforested simulation is taken as a proxy for the pre-development land cover, then human impacts on the hydrology of this system are already measurable, both in terms of the amount and timing of freshwater delivery to the estuary. The results of the Sprawl simulation demonstrate how quickly these effects could become severe, if current trends in development within the watershed continue. The erosion and sediment loading calculations are especially noteworthy. Although these values were uncalibrated, the relative effects of development between the scenarios should be consistent, and an increase of three orders of magnitude is disturbing, indeed.

The more subtle effects of the shift in the baseflow fraction between the scenarios and the alteration in the relative height of the spring flow peak may also begin to explain the declines in the crab fishery in the Satilla River Estuary. The simulations consistently demonstrated a shift away from baseflow and toward storm flow delivery of runoff with increasing development. This implies that runoff is increasingly being delivered to the estuary in large pulses as that the steady inflow of groundwater is attenuated. Blanton, Seim et al. (2003), report that there is a steady landward flux of salt in the estuary during neap tide as a result of gravitational circulation. Thus, an increase in surface water input could lead to a larger proportion of freshwater being exported from the estuary over this salt wedge, raising the average salinity of the estuary during low-flow periods. Increases in the proportional input of warm surface water could lead to corresponding increase in the temperature of the estuary, as well. Lee and Frischer (2004) cite a relationship between increased temperature and salinity and infection of blue crabs with the parasite *Hematodinium*, and demonstrate parasite-induced crab mortality after exposure to increased salinity for as little as 72 hours. The relationship of estuarine salinity to blue crab populations may be more subtle, however, as Brachyuran crabs may delay metamorphosis in response to extreme salinity (Forward, Tankersley et al. 2001), and salinity and turbulence appear to regulate the post-settlement secondary dispersal of blue crab megalopae (Welch and Forward Jr 2001).

Future Directions for the use of SWAT in the Satilla River Watershed

There are a number of obvious directions to explore in an attempt to improve the accuracy and generality of SWAT simulations for the Satilla River Watershed. The detailed input scheme used by Bosch, et al, (2004) used both the more detailed empirical

SSURGO soils data and land use data that were specific down to the crop planted. AVSWAT has the ability to incorporate these datasets with no more effort than was required for STATSGO and GLUT, model accuracy might easily be improved through the use of more detailed inputs. While SSURGO soil surveys for the Satilla River watershed are still pending, the GLUT project has released the 1998 land cover using a 44-class land use scheme. Unfortunately, the additional detail in this classification scheme is not in the agricultural uses, but rather in resolving mixed-forest community types and fine levels of detail regarding the plants visible in the urban land use categories. Since SWAT's urban module is unable to parameterize this detail, and the physiological differences between the published values for the plant community types are small, the improvement that may be gained through incorporating the 44-class land cover dataset may be minimal.

Even with the reservations expressed above, the SWAT model shows real promise as a simulation tool for the Satilla River Watershed. The predictions it makes about the Sprawl scenario, *viz.*, a decrease in the baseflow ratio, a slight increase in runoff, and reduced aquifer recharge, are all reasonable and consistent with the results of observed in more urbanized catchments. The Satilla River watershed is still relatively unimpacted by development, even with the urban increased cover by 50%, as in the Sprawl scenario, the modeled portion of the watershed was less than 0.7% urban classes. Assuming an average of imperviousness of 40% among the urban classes, this places the Satilla at approximately 0.3% impervious, while the recent Pew coastal sprawl report sets 10% imperviousness as the upper bound to maintain a functioning coastal ecosystem (Beach 2003). (It is true that only the upland portion of the Satilla River watershed was modeled, while the majority of the current urban cover and likely development pressure will be in the regions of the watershed downstream of the Atkinson gage. However, the low topographic relief of these areas and lack of gauging stations in the coastal drainage networks made simulating these systems impractical on the scale of this project.) Thus, decision makers in the Satilla River watershed have the room to experiment with management options, but experimenting without a method and a plan would amount to a squandering of their resources at this scale. Based on the results presented here, the SWAT model should be included in the formulation of these management hypotheses and, potentially, used to assess the results.

The most obvious deficiency in this calibration is the lack of urban landcover for simulation. The model could easily be used in the Savannah River Basin, where the development in Chatham County would provide ample impervious surface to model. Given its proximity to the Satilla, calibration parameters obtained there ought to be portable with little modification.

A second extension of the modeling effort would be toward better simulation of the daily hydrograph. While this calibration is well suited for monthly and annual trend extraction, it does not adequately capture extreme events, and these may be important both biologically, from the standpoint of flushing materials through and scouring of the aquatic habitat, and physically, from the perspective of erosion and flood control. While SWAT is not well suited to modeling daily data, an newly-developed extension of SWAT, called AGWA, the Automated Geospatial Watershed Assessment, uses a single user interface to drive both SWAT and an event-based model, KINEROS, which simulates storm peaks (Miller, Semmens et al. 2002). While the AGWA user interface is not as advanced, or stable, as AVSWAT2004, it appears to be in more active development and may shortly become a viable alternative modeling platform. The incorporation of better storm simulations would allow the Swat model to be more finely calibrated on a daily time step could reduce the “flashy” aspects of the daily hydrograph. However, it may also be that the thunderstorms that characterize this area are not well captured y the existing climatological network (Bosch, Sheridan et al. 1999). If so, the inevitable error in the precipitation data will limit the potential to calibrate and model on a daily time step.

I have focused on modeling hydrologic response and freshwater delivery, but the SWAT model is capable of simulating chemical transport (Nitrogen and Phosphorous), Sediment, and bacterial pollution, as well. While I did not have the resources to acquire the necessary input data for these calibrations, a hydrologic calibration is a necessary first step in any simulation of the other factors, and this model could be extended to each.

Finally, the primary deficiency of SWAT as a scenario-planning tool is in the model architecture, itself. While it is quite flexible with regard to “scenarios,” these consist of management activities, even to the extent of defining multi-year management scripts for crop rotation, pesticide application and the like. SWAT is unable to accommodate other kinds of changes during a simulation, such as an increase in municipal water extraction during a hot year, or the conversion of land form one type to another. However, because SWAT reads and writes structured plain text files, it would be possible to couple a second model to SWAT that would adjust the inputs during the transition from one year to the next. Indeed, this is the mechanism of the upcoming Auto-calibration Tool which pauses the model, reads the outputs, then shuffles the input parameters, and passes them back to the model engine. If given the ability to realistically simulate a changing landscape, the SWAT model would be a powerful planning tool, indeed.

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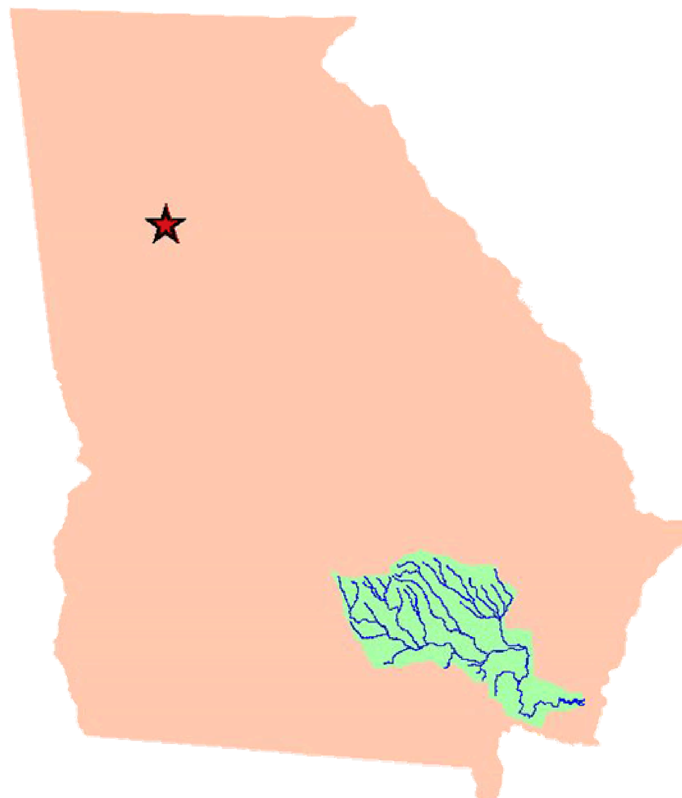
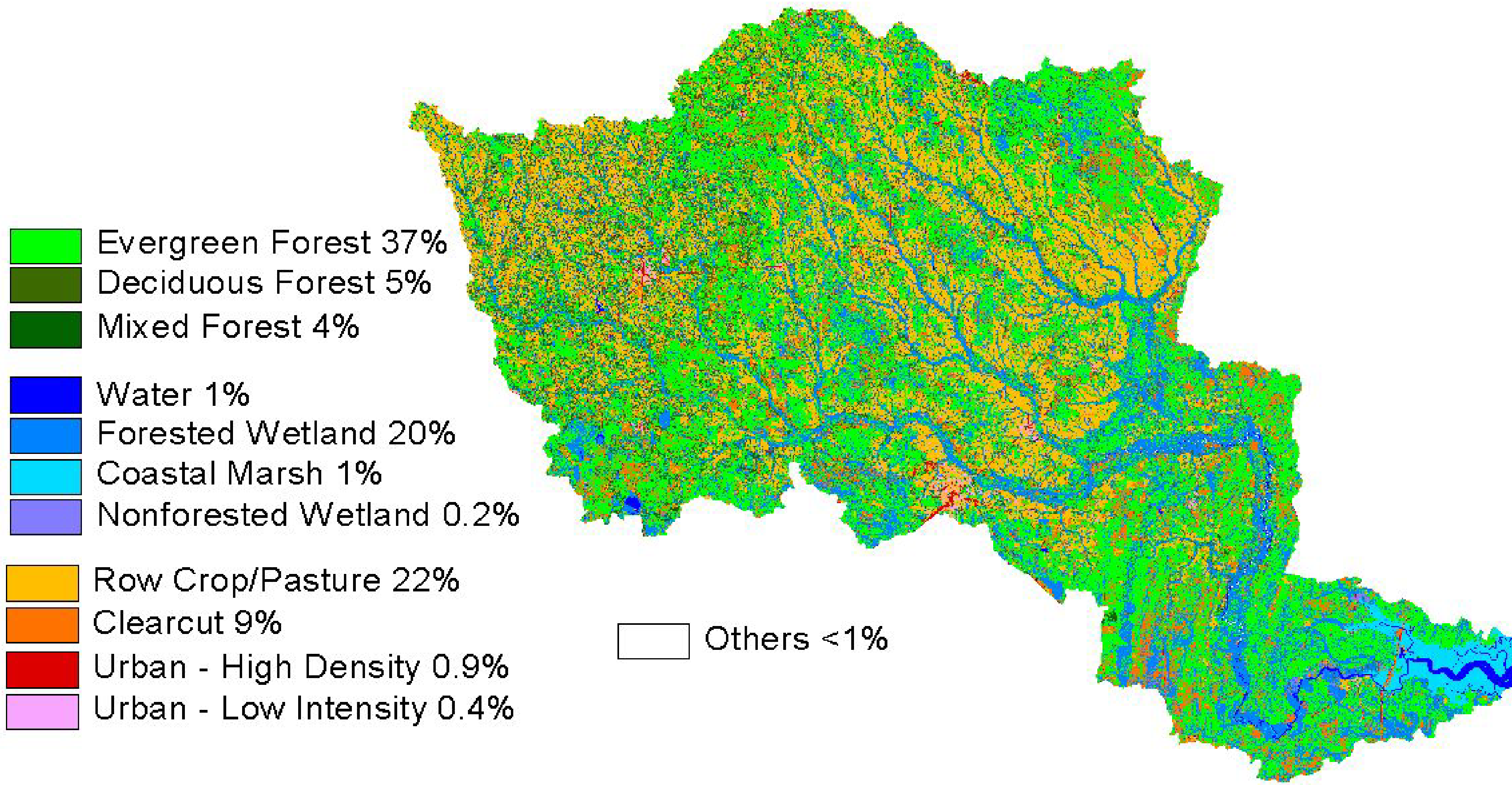
Appendix A: Location of the Satilla River Watershed

Satilla River Watershed

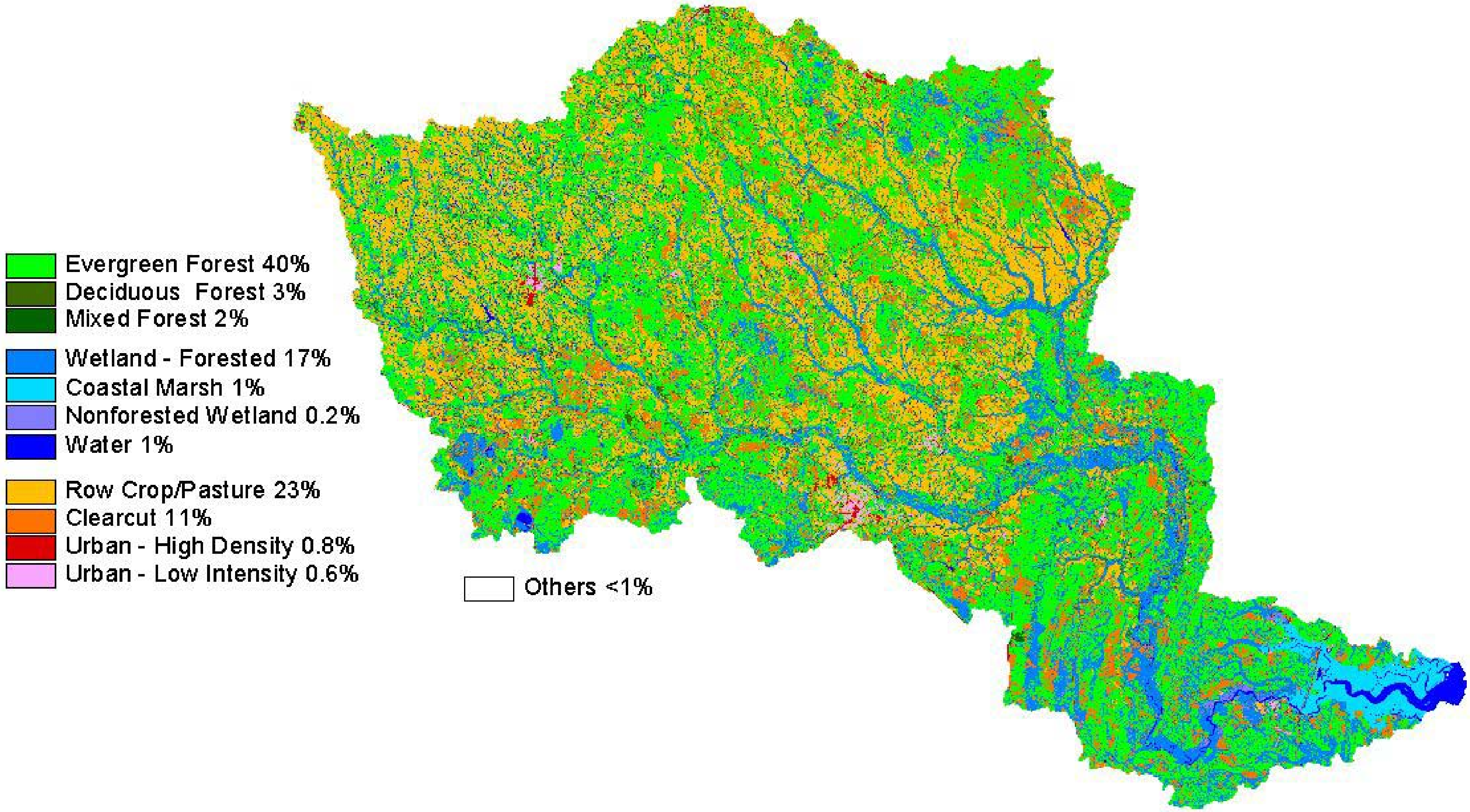


The Satilla River and Little Satilla River lie on the Georgia Coastal Plain.

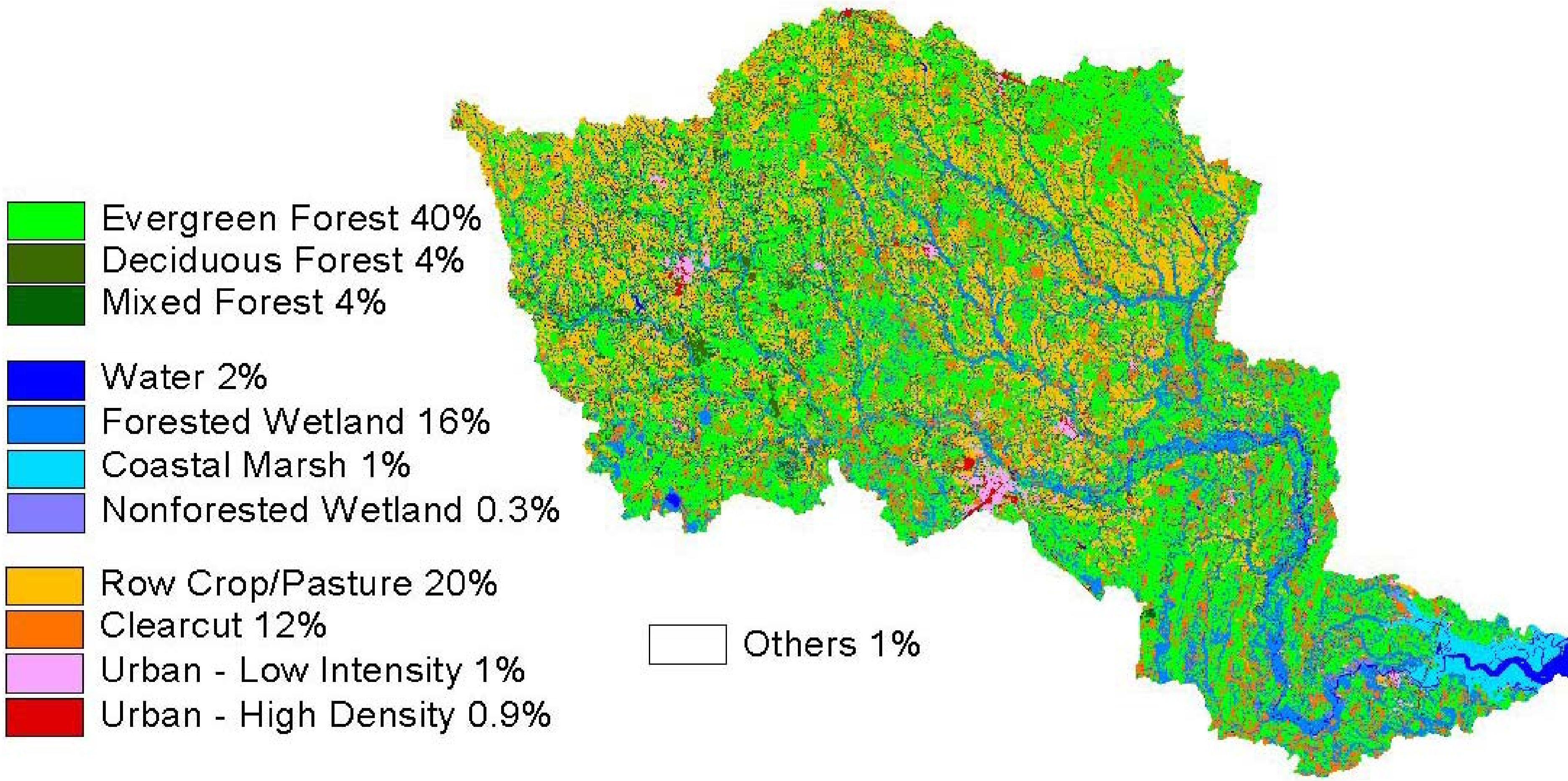
1974 GLUT Land Cover



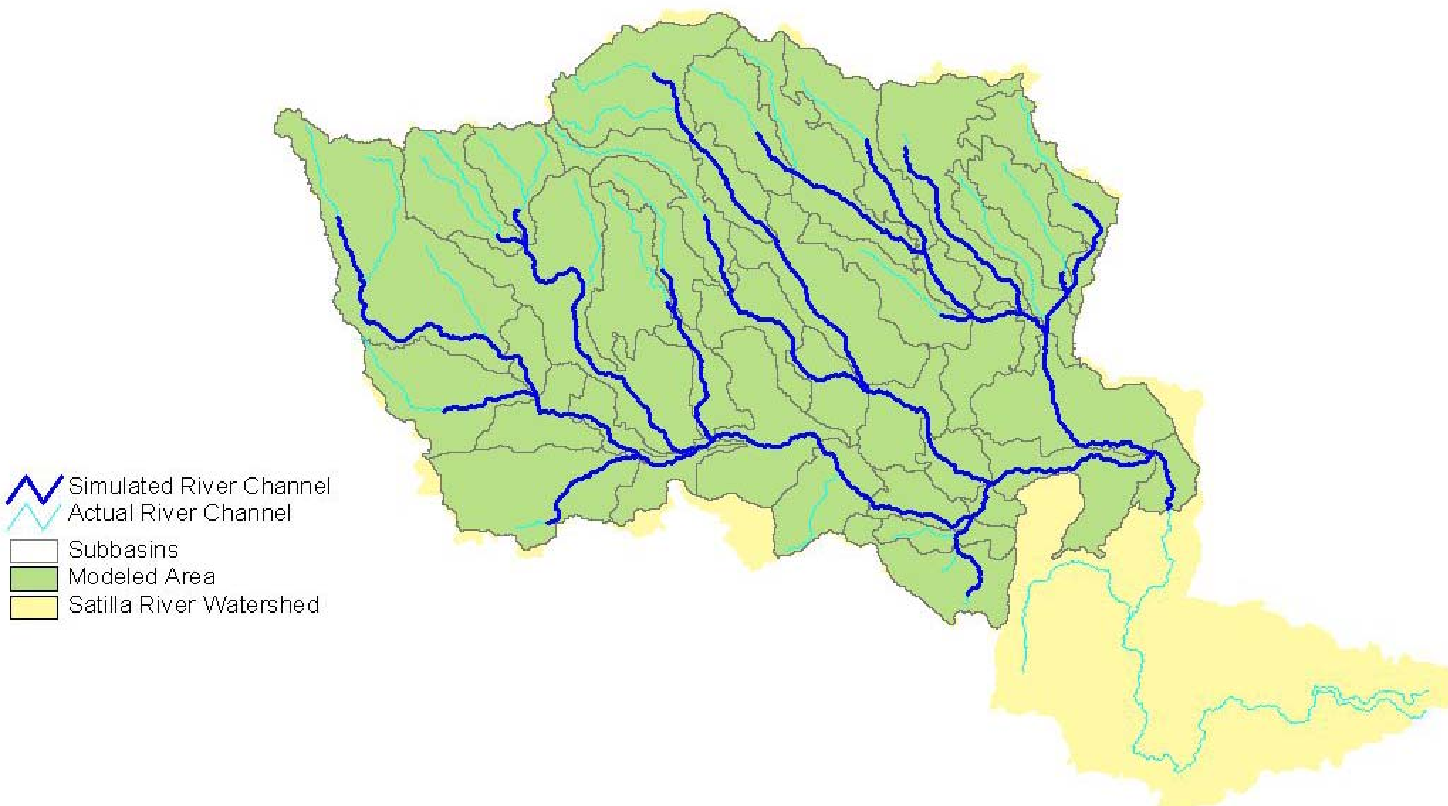
1985 GLUT Land Cover



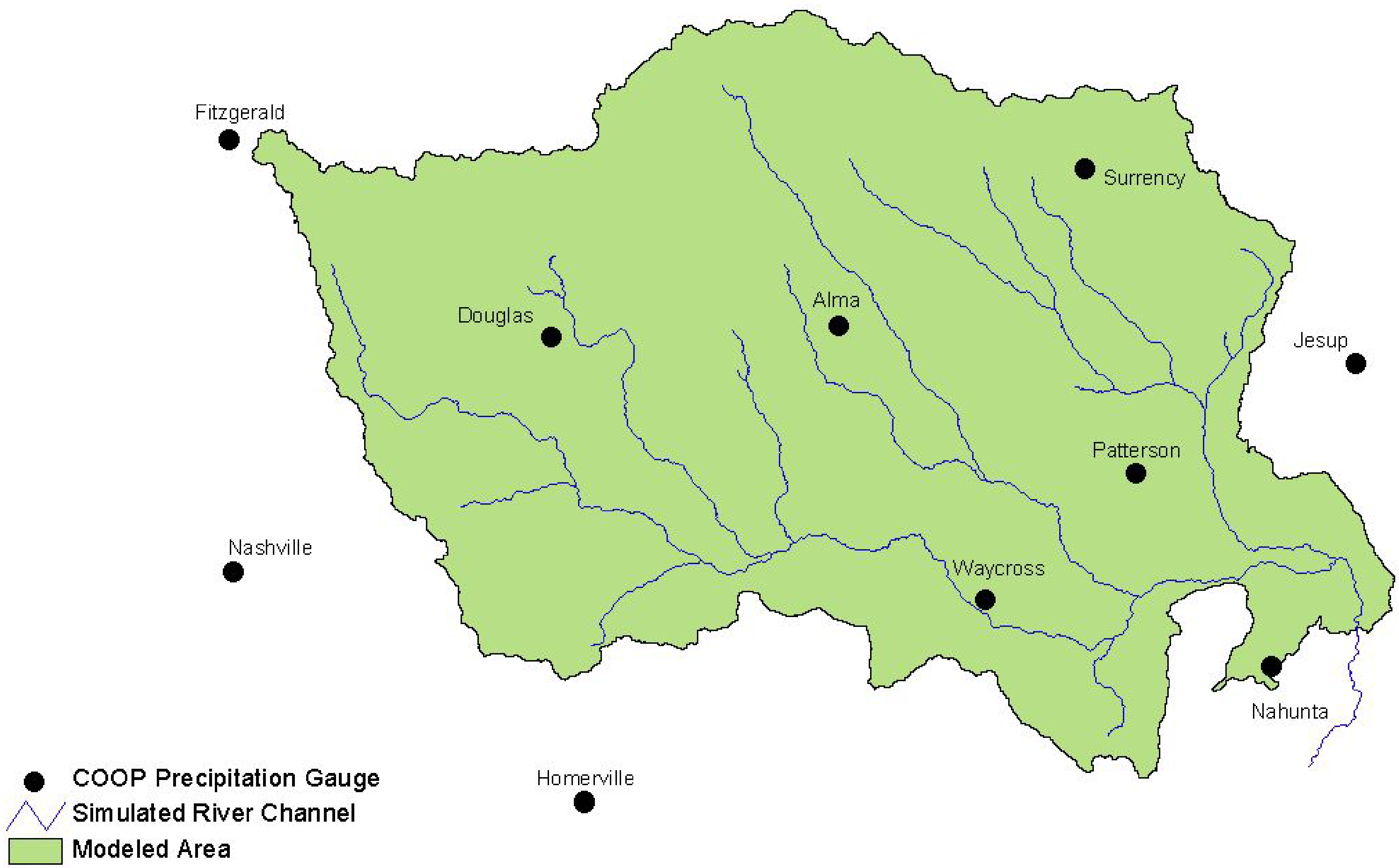
1998 GLUT Land Cover



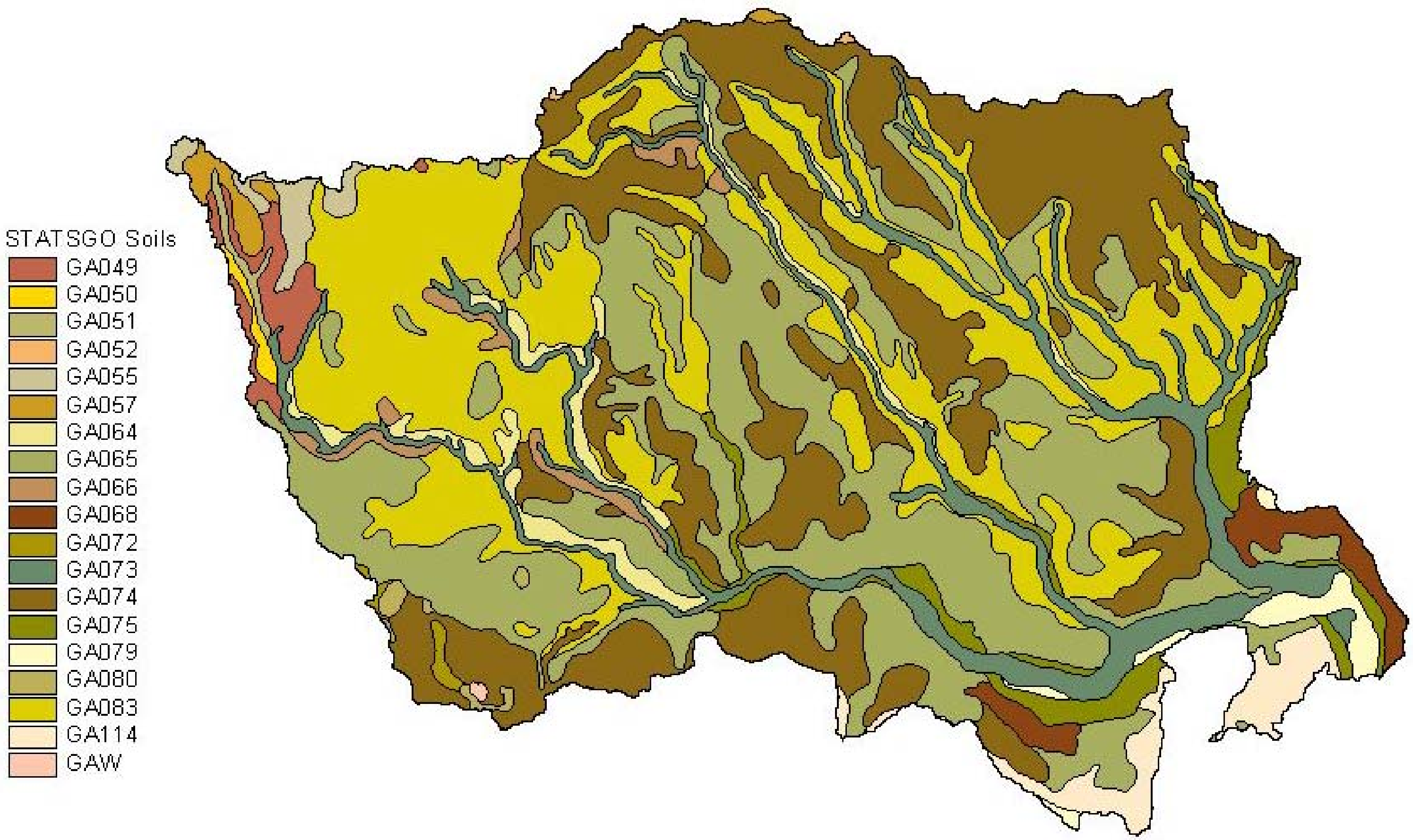
Modeled Area



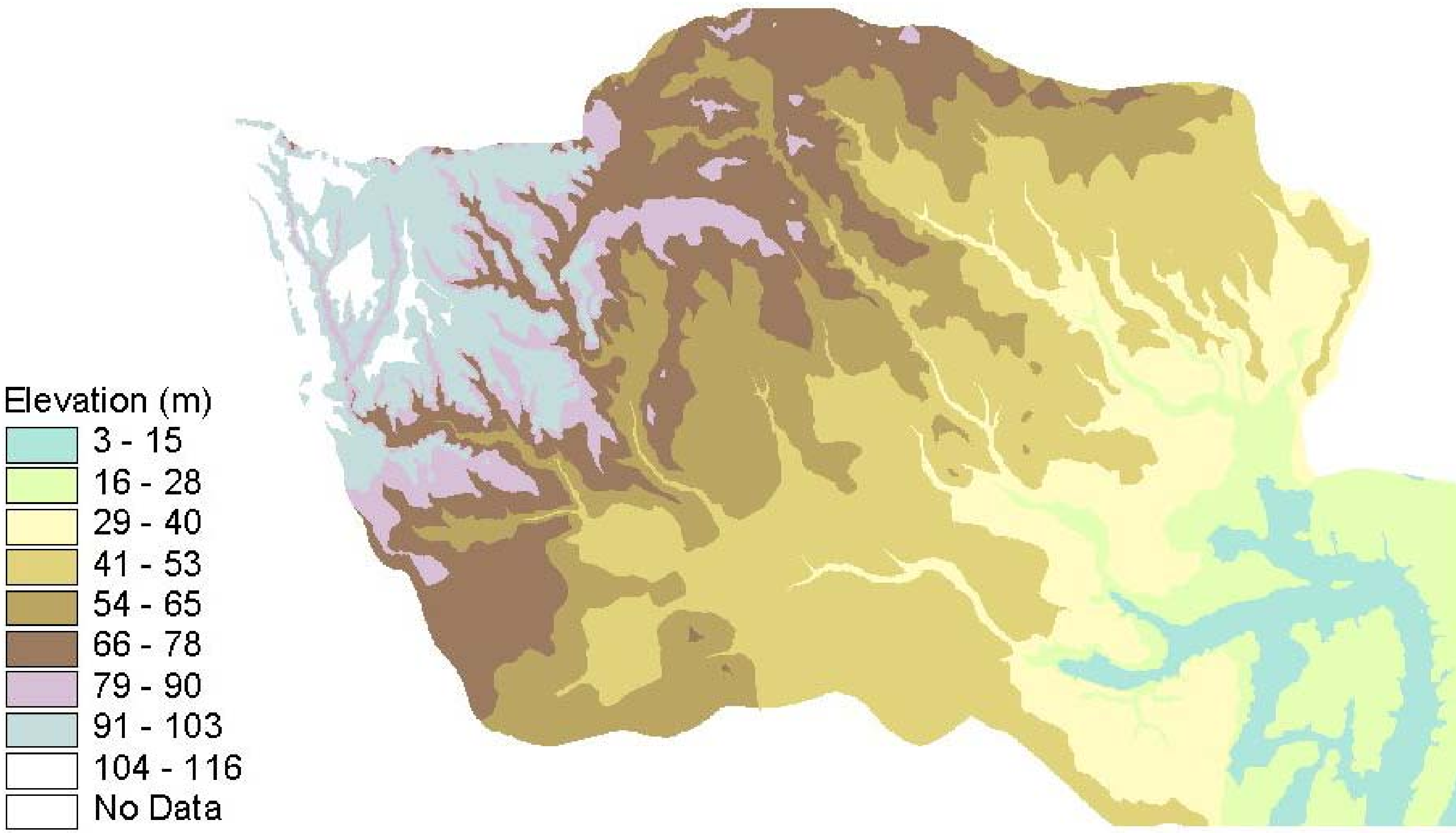
Precipitation Gauges



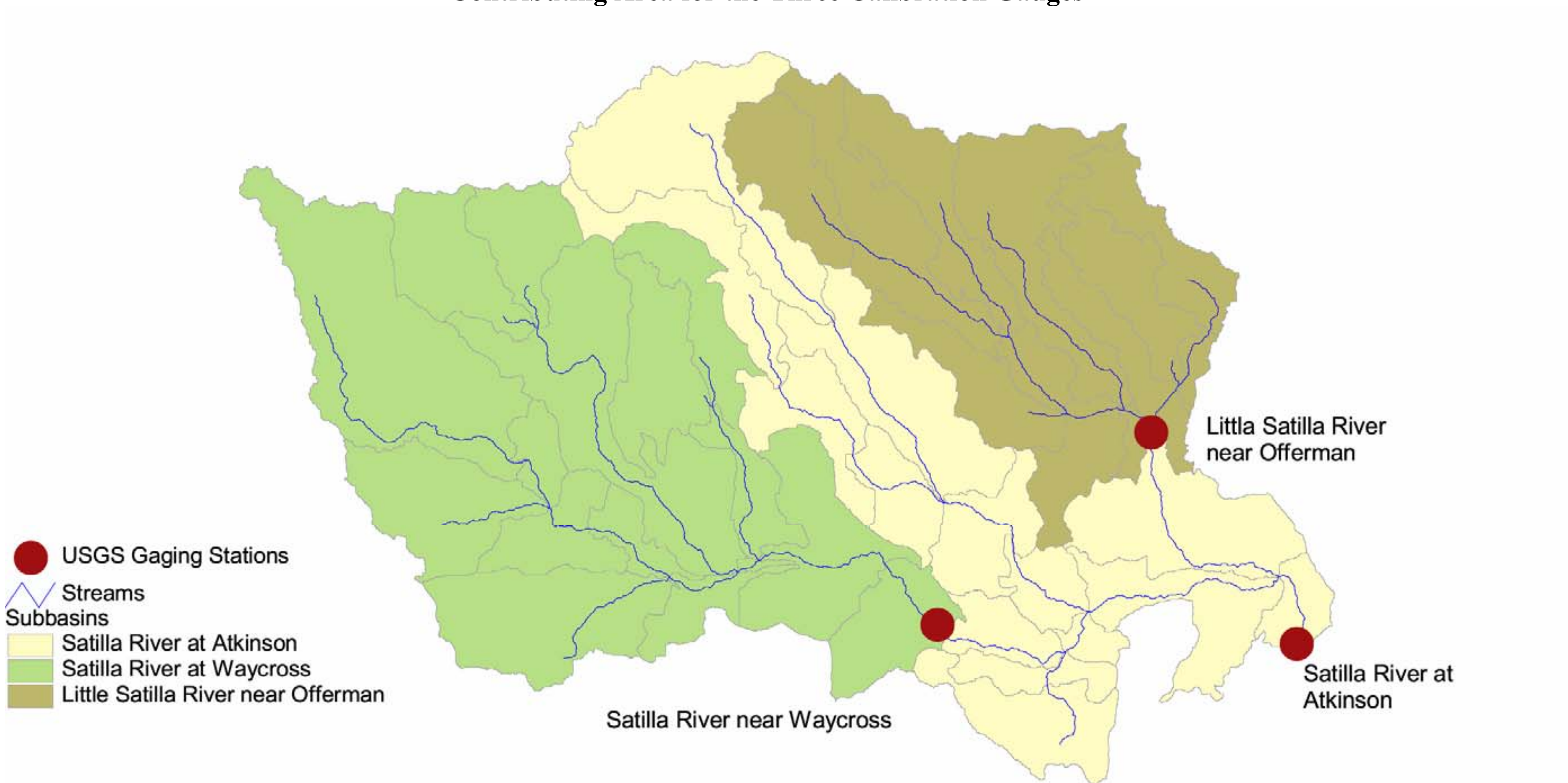
STATSGO Soils



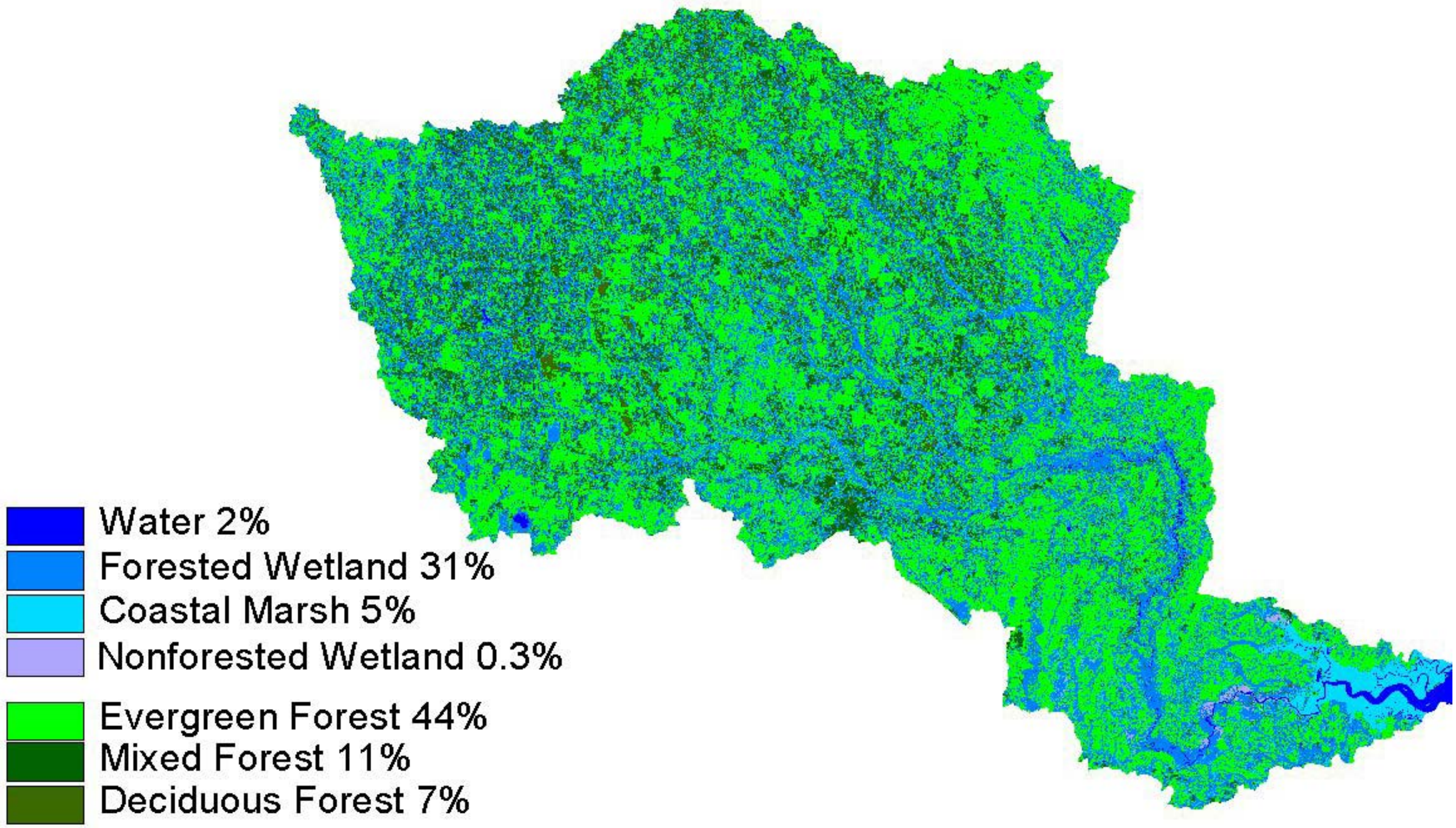
Elevation (DEM)



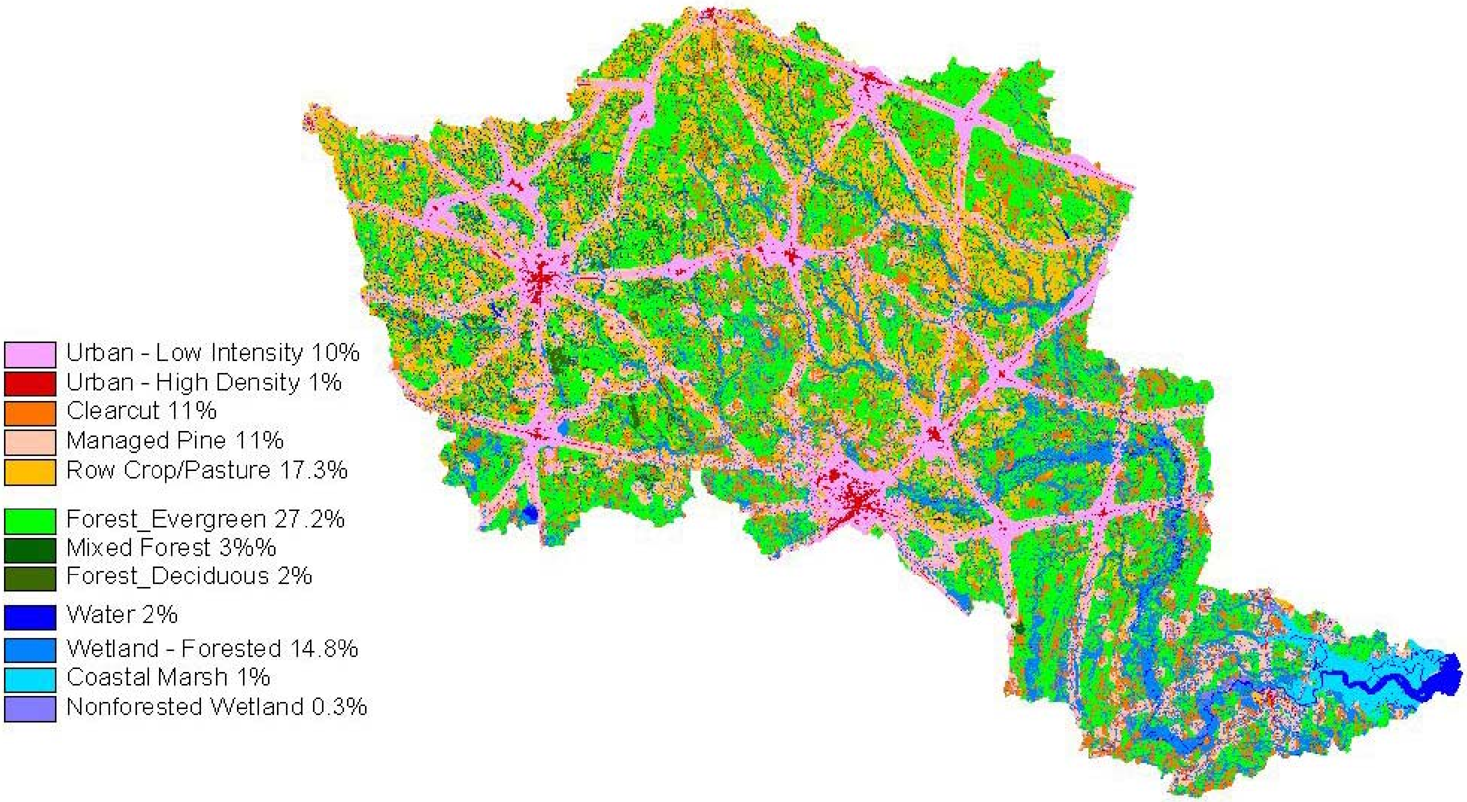
Contributing Area for the Three Calibration Gauges



Reforested Land Cover



Sprawl Land Cover



Appendix E: Yield and Water BalanceResults of Iterative Calibration Process

At Atkinson	Total Water Yield (mm)	Surface Yield (mm)	GroundwaterYield (mm)	Baseflow Ratio
Actual	304.02	142.89	161.13	0.53
sim35	565.35	234.74	332.66	0.59
sim36	558.56	152.29	406.27	0.73
sim37	511.99	152.29	359.7	0.70
sim38	444.81	152.29	294.32	0.66
sim39	415.19	152.35	264.64	0.64
sim40	320.37	152.45	169.73	0.53
sim41	296.67	151.87	146.59	0.49
sim45	298.01	151.34	148.48	0.50
sim47	299.23	151.45	149.76	0.50
sim47_noirr	293.99	150.36	145.43	0.49
sim49	293.00	149.83	144.97	0.49
sim52	301.71	168.76	135.38	0.45
sim57	325.43	168.76	159.11	0.49
sim58	325.44	168.76	159.11	0.49
sim60	343.52	169.87	176.1	0.51
sim61	334.88	168.14	169.18	0.51
sim62	337.59	168.11	171.92	0.51
sim63	337.62	168.11	171.95	0.51
sim64	347.02	169.97	179.51	0.52
sim65	334.81	169.23	168.02	0.50
sim66	329.65	168.24	163.85	0.50
sim67	352.62	169.23	185.82	0.53
sim71	352.63	169.22	187.14	0.53
sim75	343.29	163.38	184.21	0.54
sim76	309.32	155.57	157.52	0.51

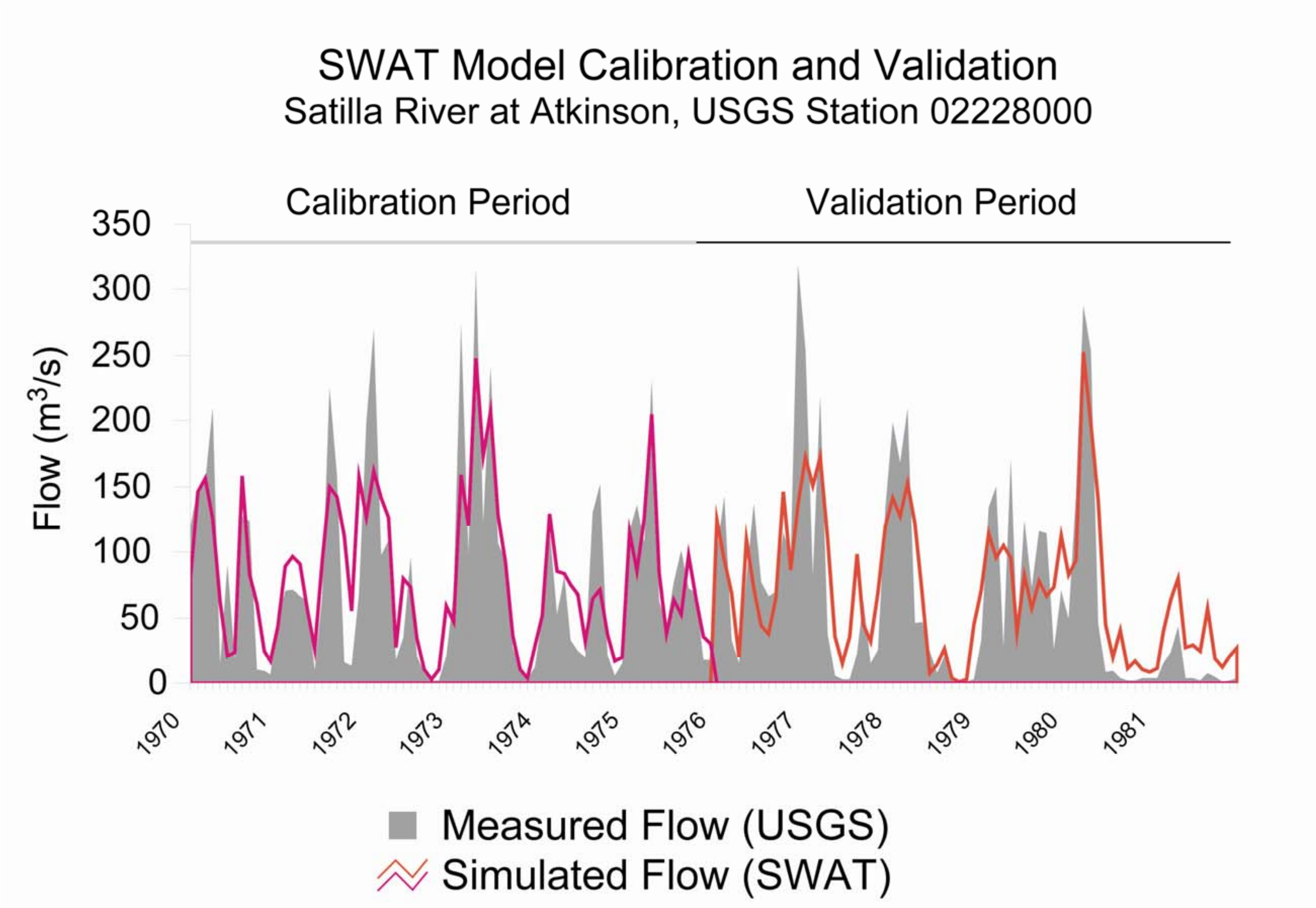
Selected results only. Initial .runs during model set-up (0-10), early calibration runs (11-24) and those for which the only change was the simulation period are not shown

Most sensitive parameters, based on initial sensitivity analysis.

Parameter	Rank
CN2	1
GWQMN	2
rchrg_dp	3
ESCO	4
SOL_AWC	5
GW_REVAP	6
canmx	7
sol_z	8
SLOPE	9
ALPHA_BF	10

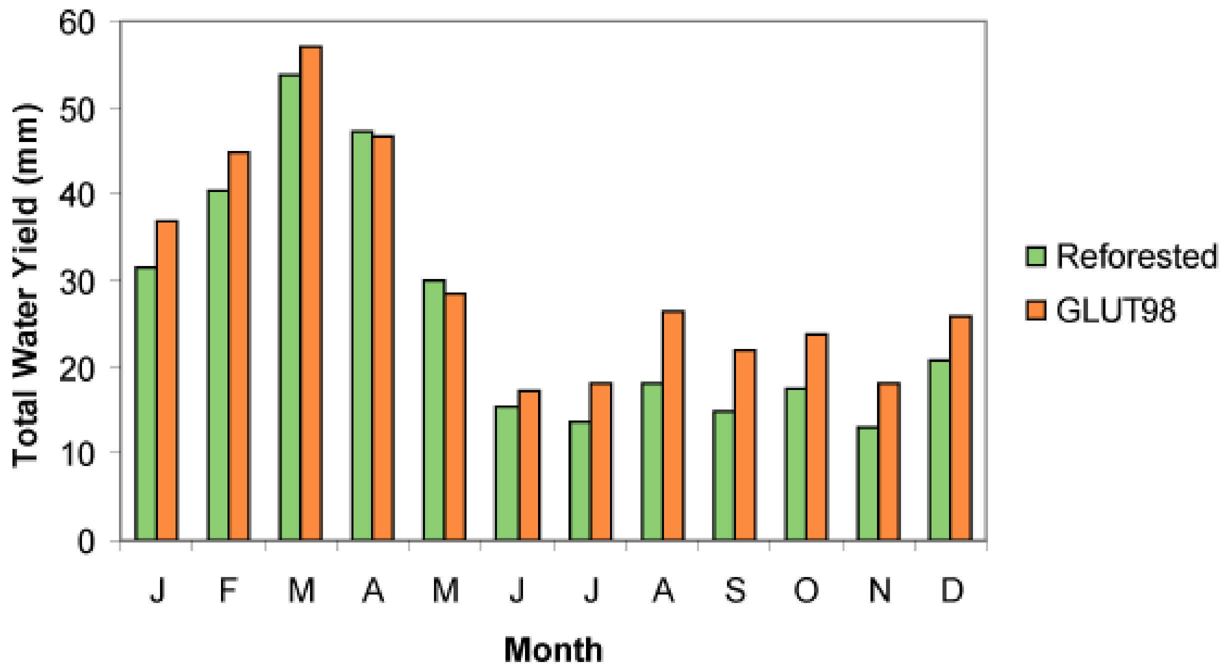
Parameters adjusted during calibration.

Parameter	Description	Default Value	Calibrated Value
Ch_n1	Manning's N for Tributaries	0.014	0.050
Ch_n2	Manning's N for Main Channel	0.014	0.035
ESCO	Soil Evaporation Compensation Factor	0.95	0.92
GW_revap	Groundwater Revap Coefficient	0.00	0.18
Sol_AWC	Available Water Content of soil layers 1-6	1.0x Soil Database	1.07x Soil Database
Revapmn	Fractional depth of water in the shallow aquifer for revap to occur	0.00	0.9
Rchrg_dp	Recharge fraction to deep aquifer	0.05	0.13
GWQMN	Threshold Depth of water (mm) in shallow aquifer for baseflow to occur.	0	125
CN2	SCS Curve number for runoff condition 2	1.0x soil/land cover specification	0.9x soil/land cover specification
Canmx	Canopy interception depth (mm)	Unspecified	3.0


SWAT Model Calibration and Validation
Satilla River at Atkinson, USGS Station 02228000
Calibration Period
Validation Period
Flow (m3/s)
350
300
250
200
150
100
50
0
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
Measured Flow (USGS)
Simulated Flow (SWAT)

Summary of Reforested Land Cover Scenario for the period of 1968-2002		
	GLUT98	Reforested
Surface Yield (mm)	154	115
Lateral Soil Yield (mm)	9	9
Groundwater (Shallow) Yield (mm)	205	194
Revap (Shallow-soil -> plants) (mm)	174	174
Deep Aquifer Recharge (mm)	56	55
Total Aquifer Recharge (mm)	434	421
Total Water Yield (mm)	364	315
Baseflow Ratio	0.59	0.65
Percolation out of Soil (mm)	437	423
ET (mm)	513	527
ET/Precipitation	0.48	0.49
Total Sediment Loading (T/ha)	0.367	0.007

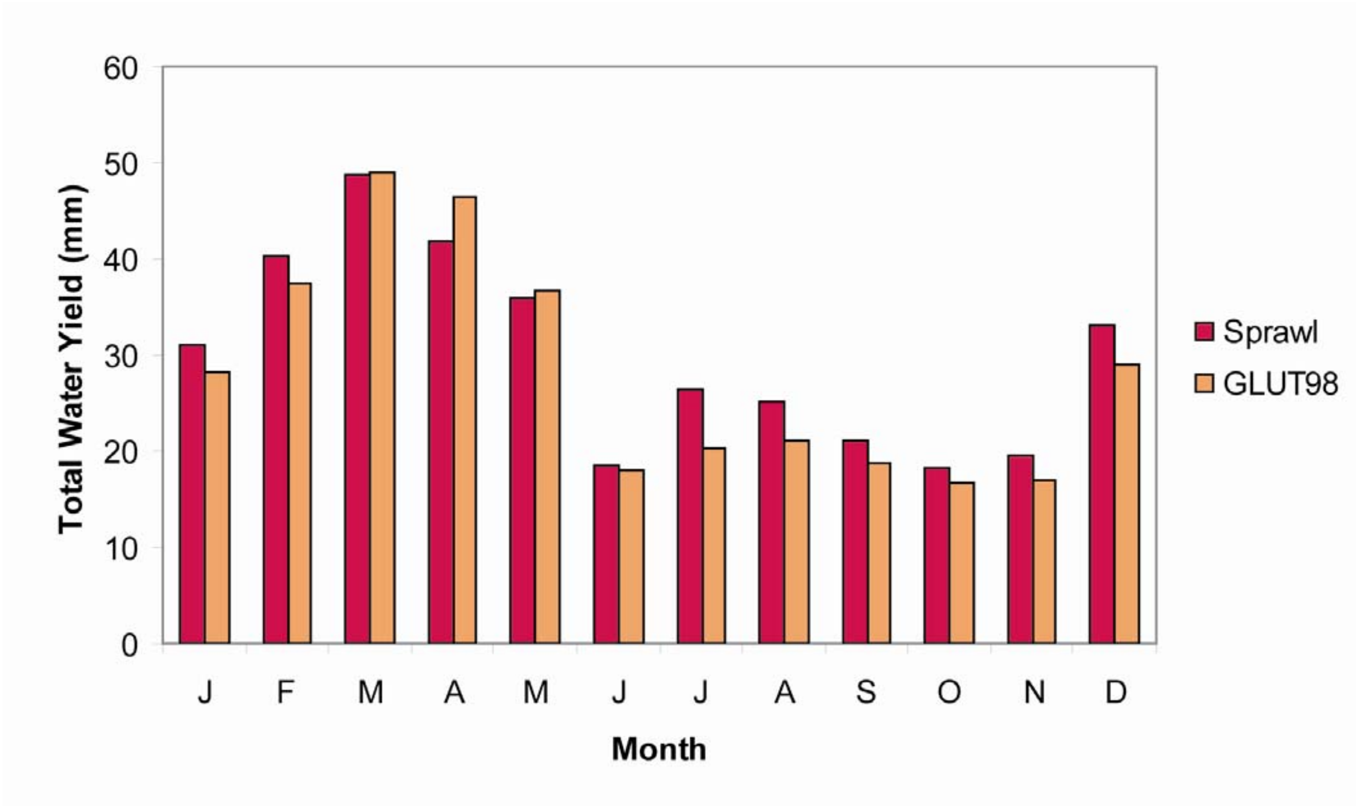
Seasonality of Flow for Reforested Scenario, 1968-2002



Appendix I: Sprawl Scenario Summaries

Summary of Sprawl Land Cover Scenario for the period of 2005-2030		
	GLUT98	Sprawl
Surface Yield (mm)	132.94	158.35
Lateral Soil Yield (mm)	9.82	9.62
Groundwater (Shallow) Yield (mm)	198.16	192.99
Revap (Shallow-soil -> plants) (mm)	211.64	211.61
Deep Aquifer Recharge (mm)	61.35	60.56
Total Aquifer Recharge (mm)	471.91	465.86
Total Water Yield (mm)	337.13	358.50
Baseflow Ratio	0.62	0.57
Percolation out of Soil (mm)	477.27	471.06
ET (mm)	606.00	583.10
ET/Precipitation	0.51	0.49
Total Sediment Loading (T/ha)	0.296	0.552

Seasonality of Flow for Sprawl Scenario, 2005-2030



Summary of all Land Use Scenarios, 2005-2030			
	Reforested	GLUT98	Sprawl
Total Water Yield (mm)	288	337	359
Surface Yield (mm)	93	133	158
Groundwater Yield (mm)	198	198	203
Baseflow Ratio	0.69	0.62	0.57
Total sediment loading (T/ha)	0.005	0.296	0.552

Seasonality of Flow for Reforested, GLUT98, and Sprawl Scenarios, 2005-2030