EROSION AND SEDIMENT MODELING OF THE LAKE SIDNEY LANIER WATERSHED

by

JITENDRA BAL SHARMA

(Under the Direction of Marguerite Madden)

ABSTRACT

Lake Sidney Lanier is the primary source of water for the metropolitan Atlanta area. Its watershed is critical to the economic well being of the region and the State of Georgia as highlighted by the recent drought and the impact of the consequent water shortage. This project is a study of spatially distributed Universal Soil Loss Equation (USLE) based erosion and sedimentation in the Lake Lanier watershed. The non-point source erosion study was performed for 1984, 1991, 1992, 1999, 2001 and 2005, using Landsat imagery, State Soil Geographic (SSURGO) soil data, State Soil Geographic (STATSGO) soil data, the National Land Cover Data (NLCD) and 30-m U.S. Geologic Survey (USGS) Digital Elevation Models (DEMs). The sedimentation modeling was done for 1984, 1991, 1999 and 2005. The time period of this study has seen a major change in land cover in the watershed, which has important implications for water quality. This remote sensing and GIS based modeling was done for 30-m x 30-m grid cells, and shows the erosion 'hot-spots' in the watershed, their proximity to streams and their time evolution over the period of this study. The erosion modeling also identified the regions where the erosion exceeds the soil loss tolerances, highlighting these locations for soil conservation efforts. The spatially distributed sedimentation model is based on an empirically derived ‘drainage area vs. sediment delivery ratio (SDR)’ relationship. The erosion modeling provides the supply grid of eroded soil that is available to the sediment transport process. The sedimentation model provides a spatial distribution of the sediment deposition potential at every 30-m pixel, which is indicative of the highest upslope loading of sediment at that location. The querying of the sediment potential in the vicinity of the streams identifies the stream segments that are the most vulnerable to sediment input and associated pollutants. An index of impairment is proposed that helps determine the locations in the watershed most susceptible to sediment deposition. Viable comparisons of this spatially distributed erosion modeling with sediment discharge measurements of Faye et al. (1980) and Leigh (1998) lend confidence in the data and methods used in this study. Calibration of this model with more sediment discharge measurements can help in the effort to define and implement sediment Total Maximum Daily Loads (TMDL's). This study lays a foundation for more detailed spatially distributed erosion and sedimentation studies of the Lake Lanier watershed, conducted at higher spatial and temporal resolutions.

INDEX WORDS: Erosion, Soil Loss Rate, Sediment, Sedimentation, Sediment Yield Potential, Universal Soil Loss Equation (USLE), Digital Elevation Model (DEM), Non-Point Source

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A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial

Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2008

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May 2008

DEDICATION

This dissertation is dedicated to my parents Umesh and Shyama Sharma, whose love and support have always provided me inspiration to reach beyond my limits. This is dedicated to my wife Preeti and my sons, Neelkant and Chetanya, who have always been a great source of comfort and motivation in my endeavors. This is also dedicated to my mentors, teachers, professors, fellow students and friends, without whose encouragement I could not have completed this journey.

ACKNOWLEDGEMENTS

There are many individuals whose guidance and friendship has illuminated my path and shown me the way in this academic journey. Dr. Lewis Rogers was influential in introducing me to the area of remote sensing and erosion/sedimentation processes. Dr. Roy Welch has been a source of steadfast support and guidance, and was instrumental in getting me started in this particular spatially distributed erosion and sediment project. Dr. Marguerite Madden took over the role of a major professor upon Dr. Welch's retirement, and has been an exemplary guide who has always been there with advice and encouragement. Dr. David Leigh's work on measuring sediment discharge in the 1990's was one of the critical pieces that validated my research, and made me aware of how TMDLs relate to my research. Dr. Ernest Tollner was always generous with his time and introduced me to the idea of drainage area based SDR's, which became a very important part of my research. Dr. Adrian Thomas has been invaluable in acquainting me with the intricacies of the USLE and soil loss tolerances, and was always available for discussion when I needed it. I am grateful for all the interaction I have had with the professors on my committee, and how they have nurtured my intellectual development. Dr. Larry West has been very helpful to me in constructing the soil databases for this project. My colleagues Chris Semerjian, Dwight Lanier, Dr. Sudhanshu Panda have been the most helpful with technical advice that has been very useful to me in surmounting the challenges posed by my research project. A special mention is made of Dr. Jack Carlton, who planted my feet firmly on the academic path and has always been a role model.

TABLE OF CONTENTS

Page

CHAPTER

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

Lake Sidney Lanier, locally known as Lake Lanier, is the largest single water source for the metropolitan Atlanta area. It is fed primarily by the Chattahoochee River and its tributaries the Soque and the Chestatee Rivers. It is a major recreation area and is also the source of water for the Northeast Georgia region contiguous to the lake. The waters of the Lake Lanier watershed are also a critical resource for industry and populations downstream in the Chattahoochee River, which drains through the neighboring states of Alabama and Florida. The Lake Lanier watershed contains the headwaters of the Chattahoochee River, which upon joining the Flint River becomes the Apalachicola River and drains into the Gulf of Mexico. The Lake Lanier watershed is therefore the uppermost subset of a larger drainage watershed known as the Apalachicola-Chattahoochee-Flint (ACF) River Basin. The current drought conditions have precipitated a crisis highlighting the severe demand on the waters of this watershed by a growing downstream population. The current inability of the Lake Lanier watershed to supply the demands of the Atlanta region and the neighboring downstream states presents a major challenge for the future management of this resource.

The rapid urbanizing of the 2693 km^2 (1040 $mile^2$) Lake Lanier watershed has significant implications for both the quality and quantity of water available to support the growing population dependent on this resource. One of the greatest threats to the long-term well being of Lake Lanier, and other lakes in Georgia, is sedimentation caused by non-point source soil erosion in the watershed. Soil erosion from off-site locations in the watershed is the most prevalent environmental problem (USACE, 1999). Not only does sediment reduce the water capacity of the Lake, it also brings with it non-point source pollutants such as herbicides, pesticides, fertilizer, insecticides and other chemicals associated with agriculture and human habitation. Over time, this increasing non-point source pollution can accumulate in Lake Lanier and severely impact the water quality. Sedimentation also increases peak elevations of floods and decreases the water capacity of reservoirs. Therefore, the inevitability of development and land cover change must be guided by management practices that minimize erosion.

The identification of the areas that are the most vulnerable to erosion and sediment delivery must guide the placement of best management practices (BMP's) alleviating erosion and sedimentation to the maximum extent possible. The greatest environmental problem facing Georgia is the increasing shortage of water making the management of water resources an imperative. The aim of this project is to use geospatial tools such as remote sensing, geographic information systems (GIS) and spatial modeling techniques to study and quantify the spatial distribution of erosion and sedimentation in the Lake Lanier watershed.

The specific objectives of this project are:

a) Develop a spatially distributed soil erosion model for the entire Lake Lanier watershed that is based on the Universal Soil Loss Equation (USLE). This model will look at the change in soil loss rate over a twenty-one year time period, for the years of 1984, 1991, 1992, 1999, 2001 and 2005.
b) Develop a spatially distributed sediment yield potential model for the Lake Lanier watershed for 1984, 1991, 1999 and 2005. This explicates the spatial pattern of the

deposition of the eroded soil that is transported down-slope by surface runoff and deposited on the down-slope terrain. This model will be based on an empirically based upslope drainage area dependent sediment delivery ratio (SDR).

c) Estimate the sediment delivered to Lake Lanier over the period of this study. Some of the transported sediment reaches the stream network and is ultimately deposited in the Lake. The application of the sediment modeling to total maximum daily loads (TMDL's) and formulation of environmental law will be discussed. An analysis of the watershed erosion and sediment potential histograms will highlight the utility of statistical distributions as indicators of the susceptibility of the stream network to sediment and other non-point source pollution.

d) Compare the results of this erosion and sediment modeling with the USLE erosion modeling and sediment measurements in a landmark United States Geological Survey (USGS) study by Faye et al. (1980). In this study, Faye et al. modeled the USLE erosion and measured sediment outflow in the three upper Lake Lanier sub-watersheds of the Upper Chattahoochee, Chestatee and Soque Rivers. Faye et al. also estimated the net sediment inflow into Lake Lanier in the early 1980's. The results from this current spatially distributed erosion and sediment modeling will be compared to both the USLE based erosion modeling and sediment delivery measurements of Faye et al. and Leigh (1998) to establish the viability of this approach. This lends greater credence to the spatially distributed erosion and sedimentation modeling for future years, as is done in this study.

Study Area

Lake Lanier lies about 70 km (44 miles) northeast of downtown Atlanta (Figure 1). Nested in the foothills of the Southern Appalachians, the lake is a significant resource for recreation and the source of water for the Atlanta area and townships in its watershed. A man-made reservoir created in 1958 on the Chattahoochee and Chestatee River watersheds, Lake Lanier is maintained by the U.S. Army Corps of Engineers and is the largest water body in the state of Georgia (Table 1).

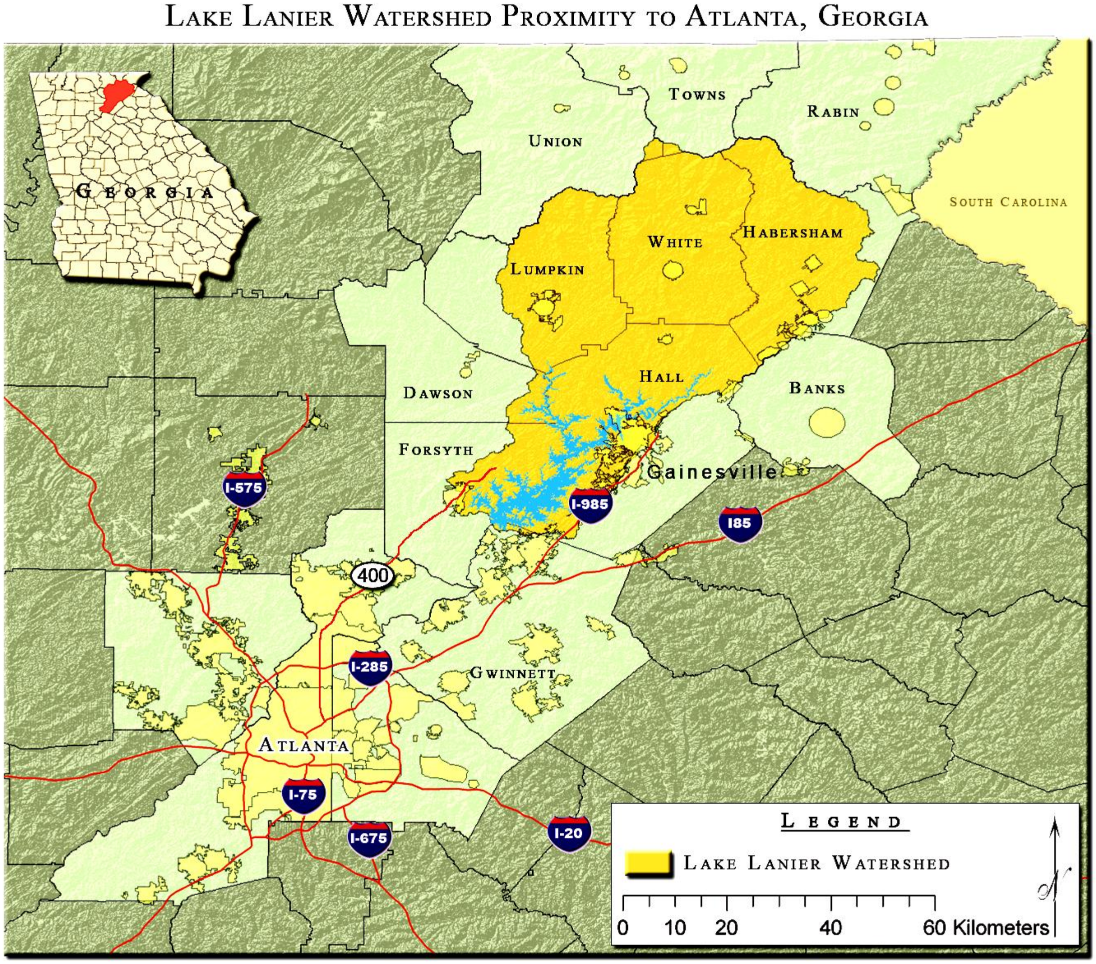
Table 1: Physical Characteristics of Lake Lanier, USACE (2004)

Full Pool Surface Area – 156 km^2 (60.2 $miles^2$ or 38542 acres)
Maximum Pool Elevation – 326 meters (1071 ft)
Area of Watershed – 2693 km^2 (1040 square miles)
Length of Shoreline – 869 km (540 miles)
Volume of Lake – 2.37×10^9 $meter^3$ (1,917,000 acre ft)
Primary Average Annual Inflow – Chattahoochee River (45%)
26.5 m^3/sec (934 ft^3/s)
Chestatee River (28%) 16.1 m^3/sec (568 ft^3/s)*
Average Annual Outflow – 58.7 m^3/sec (2071 ft^3/s)

* Remaining inflow is from streams that are not in the Upper Chattahoochee and Chestatee watersheds

It is the most visited lake that the Corps maintains nationwide with about 8 million annual visitors. It has an annual recreation economic impact of 5.5 billion dollars from recreational boating, fishing and tourism (Lake Lanier Association 2007). The Atlanta area has grown from 0.5 million inhabitants in the 1950's to more than 5 million at the present. In 2007, the Atlanta area was the fastest growing metropolitan area in the nation, with a population growth of 20.5

Figure 1: Proximity of the Lake Lanier Watershed to the Atlanta Area



Courtesy Dwight Lanier

percent from 2000 to 2006 (Demographica 2007). Not only does this increased urbanization require additional water supplies, it also increases the wastewater discharges to the rivers and water bodies. In some reaches of this basin, the rivers have reached their assimilative capacities (Georgakakos et al. 2000).

As described by, The Lake Lanier watershed occupies an area of 2690 km^2 and is in the Southern Piedmont Geologic Province (Fenneman 1938). This watershed contains the headwaters of the Chattahoochee River and its major tributaries, the Chestatee and the Soque

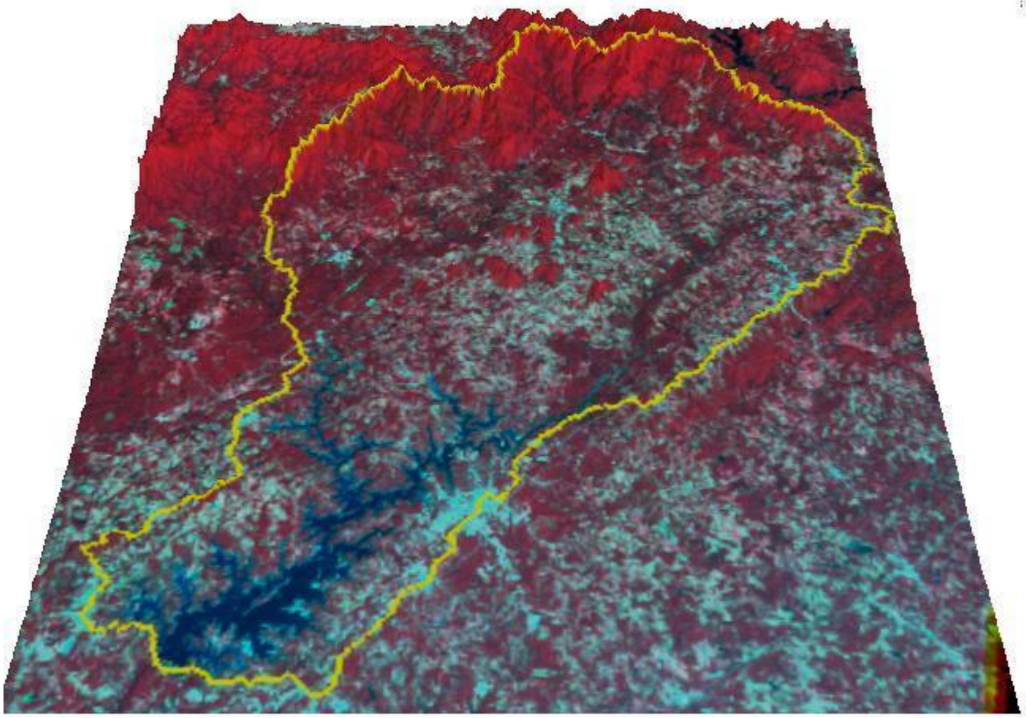
Rivers. This watershed includes the counties of Union, Towns, Lumpkin, White, Habersham, Dawson, Hall, Forsyth and Gwinnett. The northern portion of the watershed is characterized by steep mountains rising up to more than 1000 meters (3300 ft) in elevation and is still relatively forested and undeveloped. In the South, bottomlands of this basin are not as steep and are amenable to the rapid urbanization that is occurring.

The southernmost counties in this watershed are Gwinnett and Forsyth, which are the northeastern portions of the metropolitan Atlanta region (Figure 1). The middle portions of the watershed comprising mainly of Hall and Dawson Counties, are rapidly becoming suburbanized. This rapid change in land cover increases erosion and sedimentation impacting water quality and stresses the native ecosystems. The entire watershed has an underlayment of metamorphosed acid-crystalline rock. Consequently, the soils here are predominantly based on this material and tend to have thin loamy topsoil.

The city of Gainesville, with a population of 34000 in 2006, is located on the eastern shores of Lake Lanier and is the largest township directly adjacent to the lake. The I-985 and I-400 corridors running along the eastern and western shorelines on the lake have provided the infrastructure for rapid economic development in the Lake Lanier watershed. The southern end of the watershed is primarily urban and the northern end is rural.

The terrain of the study area is depicted as a three dimensional (3D) rendition of the Lake Lanier watershed (Figure 2). A false color Landsat Thematic Mapper (TM) image acquired on September 10, 1999 was used for this 3D depiction. The northern and mountainous sections of the watershed are largely forested and rural as evidenced by the predominance of the red color due to the high infrared reflectance of vegetation. The urban areas are light blue and are located towards the southern portion of the lake. The vertical exaggeration in the 3D perspective view is eight times. This view was created using the ‘Virtual GIS’ feature of ERDAS Imagine.

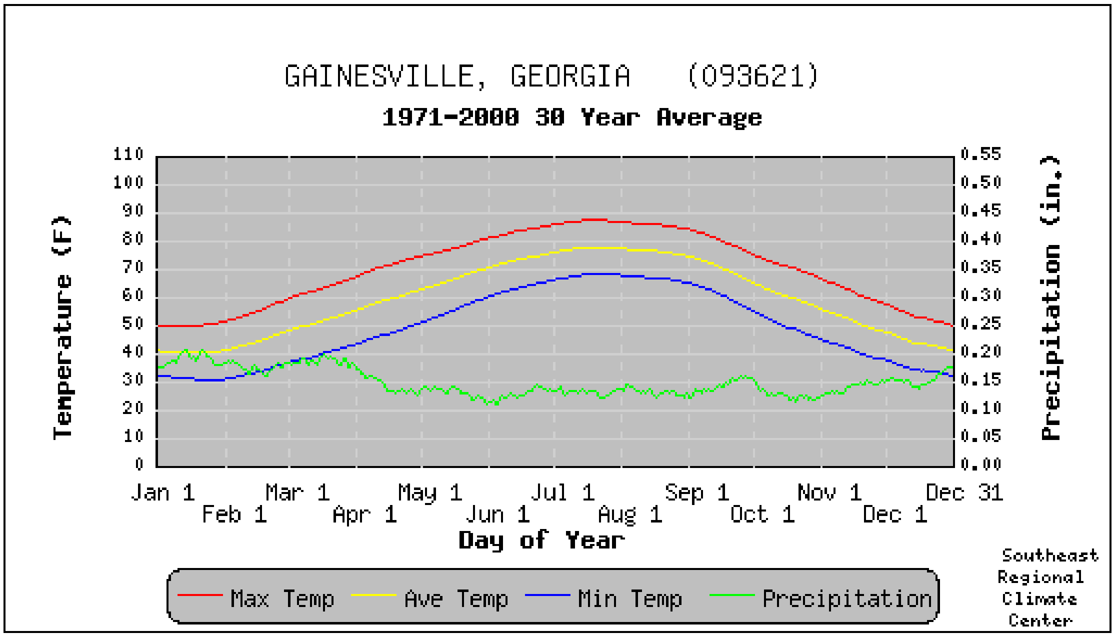
Figure 2: A 3-Dimensional Rendition of Lake Lanier Watershed Area Using a DEM and a 1991 Landsat TM Image



The climate of this area is governed by the mountainous terrain at the northern boundary of the watershed and its proximity of about 500 km (310 miles) to both the Atlantic Ocean and the Gulf of Mexico. Temperatures are moderate throughout the year. The mountains inhibit the southerly passage of polar winds from the north in the winter thus moderating cold temperatures. November is generally the first month of freezing temperatures and March the last month of freezing (Figure 3). The coldest daytime temperatures are in December through February and seldom are more than 12.8°C (55° F). Subfreezing temperatures occur often, but temperatures below -17.8° C (0° F) are rare. The summers are generally warm, but are moderated by the average elevation of about 340 m (1115 ft). The temperatures in the summer rarely exceed 37.8°C (100° F) with night-time temperatures seldom below 15.6°C (60° F).

The precipitation in this area exceeds 1524 mm (60 in.) per year and promotes the growth of natural vegetation and agricultural crops. The average yearly precipitation is 1328 mm (52.3 in.) with most thundershower activity in July. The monthly rainfall ranges from 86.4 mm (3.4 in.) in October to 175.3 mm (6.9 in.) in March. The dry periods are mainly in late summer to early fall. Average yearly snowfall is about 76 mm (3 in.) with snow of more than 102 mm (4 in.) more than every five years. Severe ice storms occur roughly every ten years causing travel hazards and disruption of utilities (www. lakelanier.com/ghgen.html).

Figure 3: GAINESVILLE, GEORGIA 1971 - 2000 Average Monthly Temperature and Precipitation (SERCC 2005)



Note: data are smoothed using a 29 day running average.

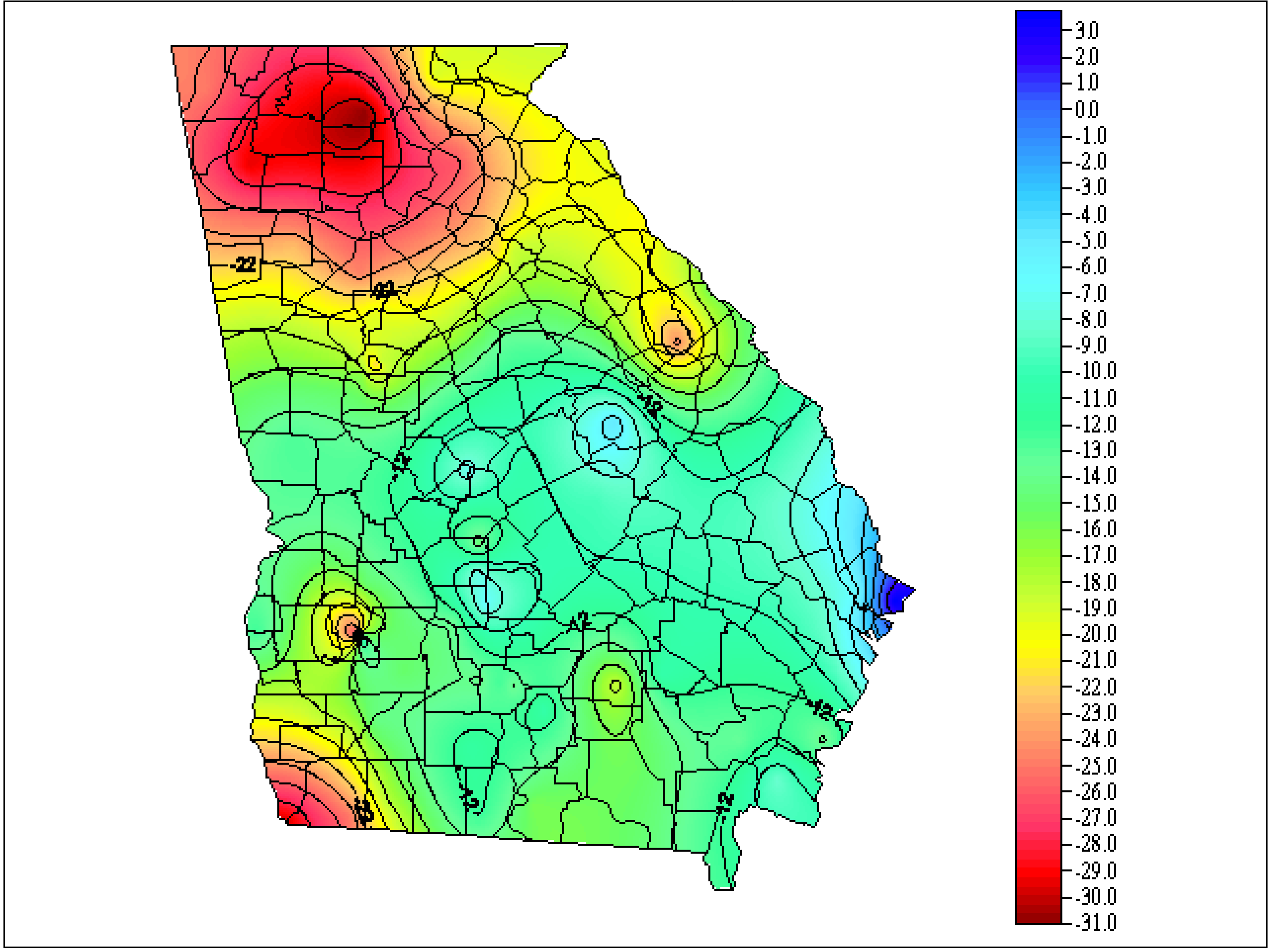
The Current Drought and the Water Demand on Lake Lanier Watershed

The current prolonged drought in North Georgia has lowered the lake levels to a historic low of 321 meters (1052 ft) above sea level in late November 2007. The drought has developed slowly over the years due to decreasing net rainfall and the deviation from the average annual precipitation in Georgia from 1971 to 2000. The reduced precipitation for 2007 show that the Lake Lanier watershed was severely impacted (Figure 4 and Figure 5).

The ACF Basin, with an area of about 52,000 km^2 (20,000 $mile^2$), has four reservoirs to control the flow of water of the Chattahoochee-Apalachicola Rivers, which are Lake Lanier, Lake West Point, Lake George and Lake Seminole. These reservoirs control the flow of water in the ACF Basin and Lake Lanier contains 65 percent of the storage in the Chattahoochee River system. Therefore in dry spells, there is an inordinate demand for water release from Lake Lanier to meet the needs of the users downstream that are dependent on particular minimum water flow rates. This puts a large demand on this study area comprising 5 percent ACF Basin to support the dry weather needs of 95 percent of the basin.

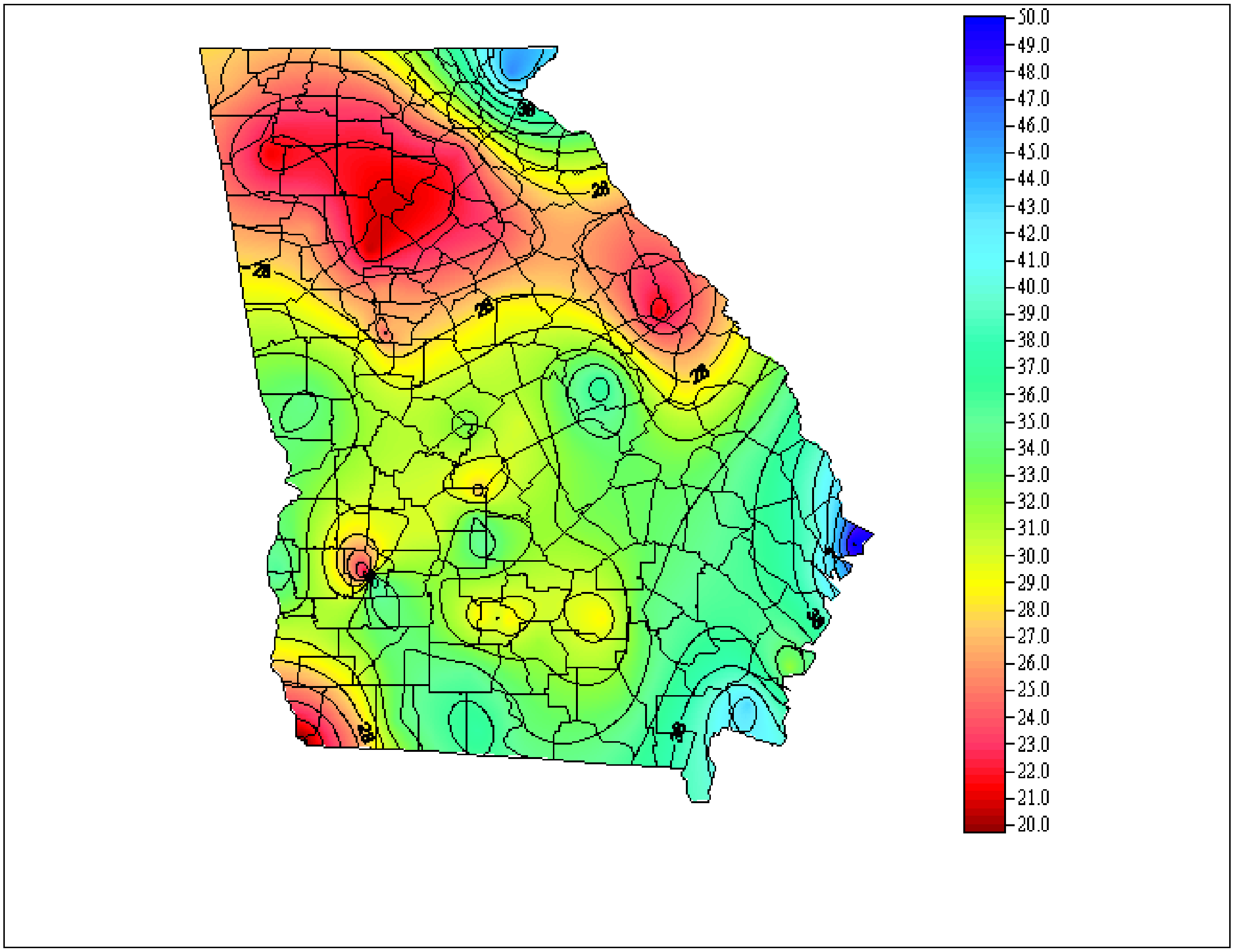
Furthermore, since Lake Allatoona in North Georgia, also a large water source to the Atlanta Area, has 25 percent of the capacity of Lake Lanier with a watershed of about the same size, Lake Lanier is slower to fill up in comparison with the same rainfall in the area. The ratio of the watershed surface area to the lake surface area for the Lake Lanier watershed is 14:1, whereas for adjacent Lake Alatoona Watershed it is 58:1. For the Lake West Point Watershed which is further down in the ACF Basin, this ratio is 85:1. Therefore the Lake Lanier watershed needs more frequent rainfall than other watersheds in Georgia to be able to maintain its water levels (Figure 6). A good discussion of the impact of Lake Lanier water level for the rest of Georgia is given by the Lake Lanier Association (2007).

Figure 4: Georgia Deviation from Normal Precipitation in Inches: 1971-2000 (GAEMN 2008)



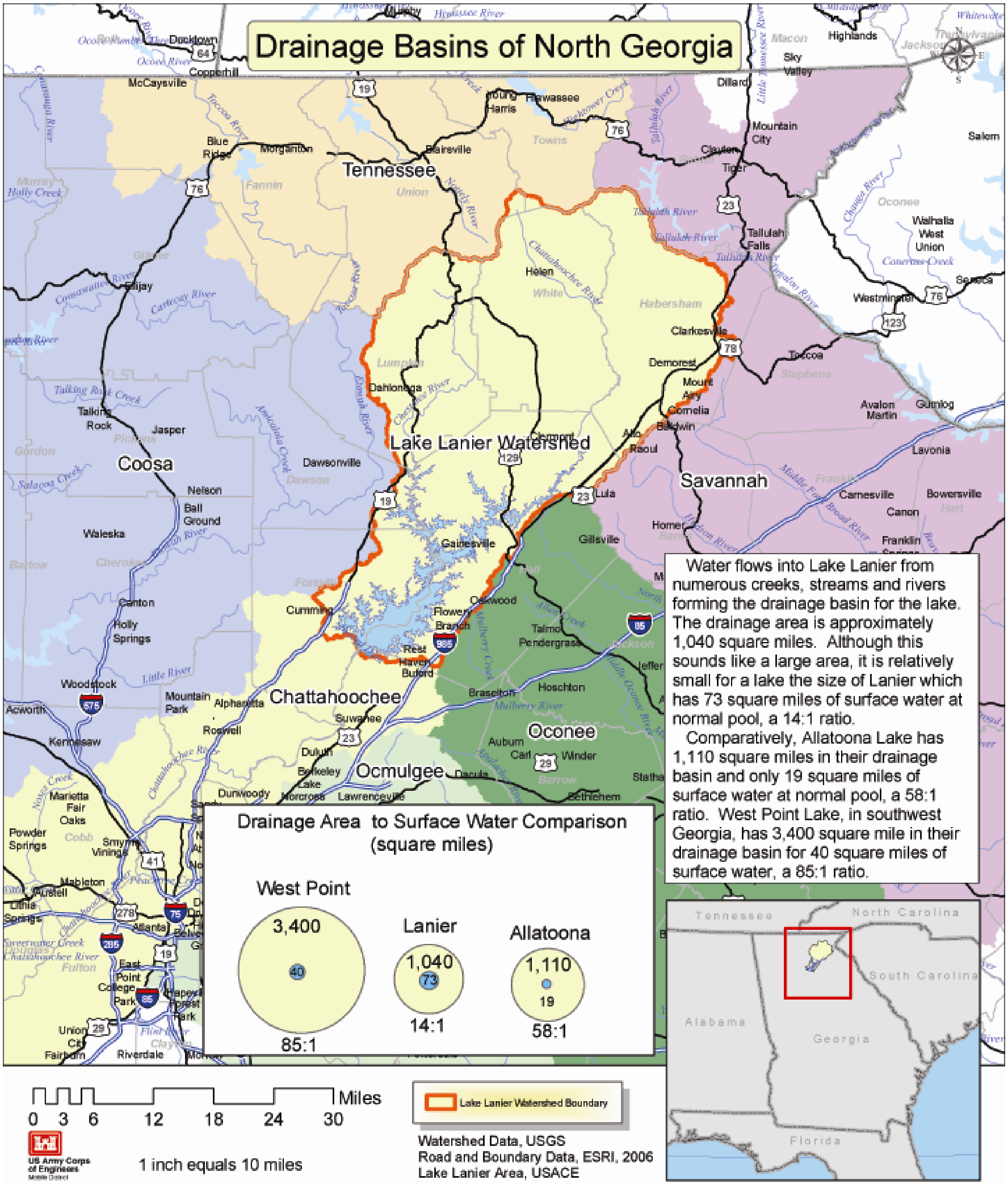
The consequence of the both lowered rainfall in the watershed and increasing usage of the waters downstream of the ACF basin has caused the water level of Lake Lanier to plummet to critically low levels (Figure 7). The waters of the ACF basin have been a subject of legal dispute by Georgia, Alabama and Florida, labeled as 'Tri-State Water Wars' (SELC, 2007).

Figure 5: Rainfall Totals in 2007 for Georgia in Inches (GAEMN 2008)



Georgia would like to have enough water to keep the Atlanta area growing, whereas Alabama and Florida need the water for their own economic well being. The current water crisis in the region inevitably provides the impetus for more effective water resources planning, allocation and conservation. This highlights the importance of understanding the watershed level processes such as erosion and sediment deposition in receiving reservoirs. These are very important for understanding and managing both water quality and quantity issues.

Figure 6: Drainage Basins of North Georgia and Watershed Area to Lake Surface Area Comparisons (USACE 2003)

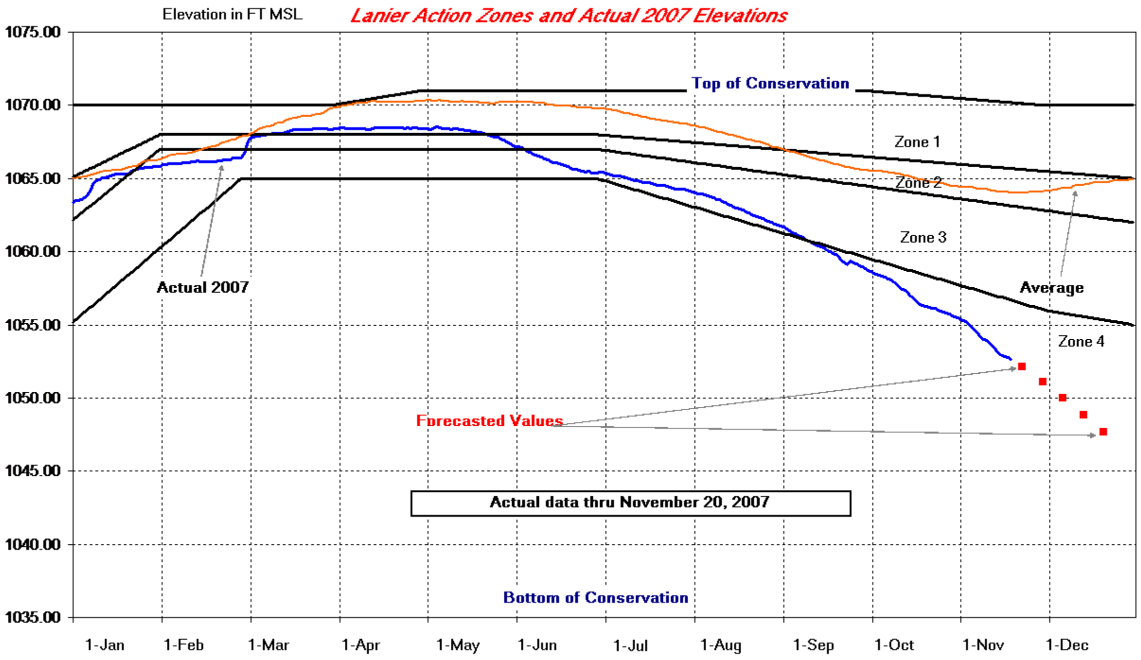


Water flows into Lake Lanier from numerous creeks, streams and rivers forming the drainage basin for the lake. The drainage area is approximately 1,040 square miles. Although this sounds like a large area, it is relatively small for a lake the size of Lanier which has 73 square miles of surface water at normal pool, a 14:1 ratio.

Comparatively, Allatoona Lake has 1,110 square miles in their drainage basin and only 19 square miles of surface water at normal pool, a 58:1 ratio. West Point Lake, in southwest Georgia, has 3,400 square mile in their drainage basin for 40 square miles of surface water, a 85:1 ratio.

Watershed Data, USGS
Road and Boundary Data, ESRI, 2006
Lake Lanier Area, USACE

Figure 7: Water Levels at Lake Lanier (USACE 2007)



* Zones indicate standard management practices for different water levels in Lake Lanier

Literature Review

The Clean Water Act (CWA 1972) is the legal bedrock that provides protection for the surface waters of the United States. The CWA deals only with water quality issues and does not apply to groundwater or water quantity issues. The statute aims to reduce and eliminate pollution discharges into waterways with the goal of "protection and propagation of fish, shellfish, and wildlife and recreation in and on the water" (CWA 1972). To this end of maintaining the integrity of the Nations surface waters, the health of surface waters is predicated upon biological, chemical, and physical metrics. Biological metrics are based on the health of the invertebrate and fish populations in the river and stream systems of a basin as they are the most sensitive to degradation of their habitats due to chemical pollutants and sediments. Physical metrics of water quality are a measure of non-point source runoff of eroded soils and the subsequent soil deposition in the floodplains and the receiving water bodies. The water runoff brings with it both soils and other nutrients and chemical pollutants which impact the water quality of the lake.

All three of these markers of stream and surface water health are related to each other as well. An increase in sedimentation in an aquatic ecosystem can stress the invertebrate and fish populations. England and Rosemond (2004) have shown that small reductions in forest cover in the headwater streams of the Upper Chattahoochee have an impact on weakening the food webs for crayfish and insectivorous fish. Newcombe et al. (1991) have developed a stress index of aquatic ecosystems based on the concentration of sediments and the duration of exposure.
The two significant ways by which pollutants reach water bodies are from point and non-point sources. Point sources of pollutants are from specific geographic locations such as industrial wastes or municipal sewage discharge and are quantifiable. Non-point pollutant sources are more diffuse and geospatially distributed. They may originate from agricultural fields, animal waste, chemicals from human activities and transported to water bodies due to runoff from the rain. Until the early 1980's, the CWA focused on point source pollution mainly because it was more easily quantifiable and a regulatory framework was built to control it.

In a Congressional Report Service summary of the Clean Water Act, Copeland (2002) describes the change in focus in 1987 of the legislation towards controlling non-point source pollution;

> “ Prior to the 1987 amendments, programs in the Clean Water Act were primarily directed at point source pollution, wastes discharged from discrete and identifiable sources, such as pipes and other outfalls. In contrast, except for general planning activities, little attention had been given to nonpoint source pollution (stormwater runoff from agricultural lands, forests, construction sites, and urban areas), despite estimates that it represents more than 50 percent of the nation’s remaining water pollution problems. As it travels across land surface towards rivers and streams, rainfall and snowmelt runoff picks up pollutants, including sediments, toxic materials, and conventional wastes (e.g., nutrients) that can degrade water quality. “

The quantification of non-point source pollution is a daunting problem due to its inherent complexity. With the recent convergence of powerful geospatial tools, detailed soil maps and satellite data, it is now possible to model the transport of spatially distributed non-point source pollutants due to rainfall runoff. Most non-point source pollutants are transported along with the eroded soil and are deposited as sediment along the surface runoff pathway or in a water body. Therefore, the understanding of spatially distributed erosion and sedimentation is central to the quantification of transport and deposition of the associated non-point source pollutants.

Definitions of Terminology

There are several terms that are central to this study and need to be defined to ensure clarity in the discussion of this watershed scale erosion and sedimentation modeling study.

Hydrology is the scientific study of the movement, distribution and storage of water within the confines of the Earth system (Singh, 1989). This includes the study of water under the ground, on Earth surface and in the atmosphere. This study is constrained to erosion and sedimentation which are primarily surface hydrological processes.

Runoff is defined as the flow of water on a terrain due to rainfall, snowmelt or irrigation (USGS 2005). This is a complex process and is dependent on the type of soil, landover and terrain slope.

Soil erosion by water is defined as the detachment and transport of soil particles by rainfall and the subsequent runoff (Ellison 1946). Hydrologically these processes can be classified as soil erosion due to sheet or upland surface flow and due to stream or channel flow (Novotny et al. 1994). This study is restricted to modeling soil erosion, transport and deposition due to surface flow over the terrain, before the transported soil reaches streams or lakes.

Soil loss rate is defined as the mass of eroded soil per unit area per unit time. This is typically represented in the units of tons/acre/year in the United States. When applied to small plots, soil erosion rate is also referred to as s*oil loss* (Mutchler et al. 1988). The term *soil erosion* is quantified by the *soil loss rate.*

Soil loss tolerance is defined as the maximum rate of soil erosion that will permit a high level of crop productivity that can be sustained economically and indefinitely (USDA 1978).

Sediment is the detached eroded soil that is transported due to runoff and deposited either on the land or in a water body such as a stream or a lake. *Sedimentation* refers to the process of soil erosion, transport and eventual deposition as sediment.

Sediment yield is the quantity of sediment arriving and depositing at a particular location. This location may be one where there is deposition of sediment along the surface flow path, or eventual deposition in a stream or a lake. The Bureau of Land Management (1999) defines *sediment yield* as 'The amount of sediment removed from a watershed over a specified period, usually expressed as tons, acre-ft, or cubic yards of sediment per unit of drainage area per year'. Mutchler et al. (1988) define *sediment yield* as the mass of sediment that passes a location at the outflow end of a plot, field, channel or watershed. In this non-point modeling project, *sediment yield* is the average annual sediment arriving at a grid cell of 30-meter spatial resolution. Since the *sediment yield* is based on the USLE, which is not an absolute but a relative measure of sediment deposition, it will be referred to as the *sediment yield potential* in this modeling project. If the *sediment yield potential* at a 30 m x 30 m grid cell is twice as much at one location compared to another, this implies that the ratio of the actual value of the *sediment yields* at the two locations is approximately two as well. This highlights the need for actual *sediment yield* measurements based on fieldwork to calibrate erosion and sedimentation modeling.

Sediment discharge occurs when eroded soil is transported to and deposited in a stream or lake in the drainage network and is measured in units of tons per year.

Sediment delivery ratio (SDR) of a particular (e.g. 30 m x 30 m) grid cell is the ratio of the *sediment yield* at that cell to the total soil erosion in the contiguous upslope drainage area.

Erosion and sedimentation are physical metrics that are difficult and time consuming to measure in the field. The spatial distribution of erosion and sediment deposition patterns is directly related to the understanding of the spatial distribution of non-point source chemical transport. This is as most often, the chemical movement occurs due to the water runoff, in conjunction with soil transport. Several types of models have been developed to estimate erosion and sediment loads over landscapes and within entire watersheds.

Watershed Scale Soil Erosion Models using GIS and Remote Sensing with Spatially Distributed Environmental Parameters

Merritt et al. (2003) have performed a comprehensive review of erosion and sediment transport models. They categorize all erosion and sedimentation models into three main categories; empirical, conceptual, or physics based. The empirical soil erosion models such as the USLE are based on field measurements of erosion as a function of the variables that it is most dependent on, such as soil type, rainfall, land cover and topography. Empirical models have a relative ease of use but the modeler must have a clear knowledge of the constraints within which the observationally derived relations are tenable. They are generally very useful for first estimates and identification of regions of high erosion and sedimentation. Conceptual models integrate both empirical data and sequences of physical processes. Examples of conceptual models are the Agricultural Non-Point Source (AGNPS) model developed by Young et al.

(1989) and the Source Water Assessment Tool (SWAT) developed by Arnold et al. (1998), which are well known models used to calculate spatially distributed erosion, sediment and nutrient transport in watersheds. Physics based models, also known as process based models, such as the Water Erosion Prediction Project (WEPP) by Flanagan et al. (1995) are not sufficiently developed as yet for applications to large watersheds such as the Lake Lanier watershed (Nearing et al. 1995, Nearing et al. 1998). The differences between these model types are not always very clearly defined and many times models can be classified as hybrids of these three categories. Furthermore, these models are then categorized in order of the size of the watershed for which they can model erosion and sedimentation. Currently, only the SWAT model and its variants can perform non-point modeling for watersheds larger than 200 km^2. Watersheds of this size are also known as mesoscale watersheds, which have linear dimensions to the order of a few hundred kilometers.

In a more recent review of models of erosion and sediment transport models by Krysanova et al. (2002) also summarize erosion and sedimentation models into three similar types as follows:

> "Erosion processes are very complex, and there are a number of modeling tools developed for different spatial scales and using different concepts. Three model categories are used for the assessment of water erosion:
> (a) fully empirical models such as USLE (Wischmeier and Smith, 1978) and RUSLE (Renard et al., 1991);
> (b) models largely based on mathematical descriptions of physical processes like WEPP (Nearing et al., 1989) and EUROSEM (Morgan et al., 1992); and
> (c) intermediate models combining mathematical process description with some empirical relationships like ANSWERS (Beasley et al., 1980), EPIC (Williams, 1984), GLEAMS (Leonard et al., 1987) and AGNPS (Young et al., 1989).

> Most of these models can be used only at the field scale or in small homogeneous watersheds. The water erosion models usually include a hydrological module, except the fully empirical ones, which can calculate sediment yield using some rainfall or runoff factor.
>
> The availability of GIS (Geographic Information System) tools and more powerful computing facilities makes it possible to overcome many difficulties and limitations and to develop distributed continuous time basin-scale models, based on available regional information. Recent development provides a few models, which allow evaluation of erosion processes at the basin scale, among them SWRRB (Arnold et al., 1990), SWAT (Arnold et al.,1993 and 1994), and SWIM (Krysanova et al., 1996 and 1998a). Usually, the basin-scale model includes a version of a field-scale model as a module, plus a parametrization of the routing processes."

Currently, the Agricultural Non-Point Source Model (AGNPS) and the Source Water Assessment Tool (SWAT) are the most well developed and used non-point source erosion and sedimentation models in the United States. The AGNPS model, however, is constrained to watersheds of 200 km^2 or less (Young et al. 1989), which renders it unsuitable for the Lake Lanier watershed, which is about 2500 km^2 in area. The SWAT model, however, is capable of modeling non-point source erosion and sedimentation on large mesoscale watersheds. A comprehensive review of the SWAT model, its history, applications and its future directions is given by Gassman et al. (2007). The SWAT model has been available as an extension in Arc View 3.0 and in mid-2007 SWAT became available as an extension in ArcGIS 9.1. The SWAT model breaks up the watershed into smaller sub-watersheds called 'hydrological response units', with uniform land-cover, soil type and management practice. The SWAT model is capable modeling of erosion, sediment, nutrient and bacterial transport from both point and non-point sources, on a time step ranging from daily to annually. The recent availability of this modeling tool within a contemporary software platform such as ArcGIS 9.1 will undoubtedly result in a whole range of spatially distributed erosion and sediment transport studies worldwide.

The model developed in this study is based on both empirical and conceptual approaches to modeling erosion and the subsequent sediment transport. In this watershed of interest, erosion is primarily the detachment of soil due to energy supplied by rain. Soil erosion due to rain is predicated upon many different forces and is very difficult to model based on fundamental physical principles. In intractable physical problems of this type the engineering approach can lend very useful results. Engineers develop empirical relations between variables governing the phenomena of interest called 'engineering correlations'. These empirical relations have very specifically defined limits within which the model describes the phenomena in an acceptable manner. The USLE is an example of such an engineering correlation. This is an empirical relation that predicts the soil erosion in tons/acre/year if the soil types, land-cover, topography, average rainfall and crop management practice are known.

This sediment modeling has been done using an empirically-based upslope area dependent sediment delivery ratio (SDR). Each grid cell is taken to be an outlet for an upslope drainage area, with the SDR for the eroded soil in this upslope drainage area determined by the empirical SDR vs. drainage area relationship (Roehl 1962, Boyce 1965). The eroded soil supply grid is provided by the USLE calculation. Another approach to sediment modeling would be to use a sediment delivery ratio that is based on the physical attributes of the individual cell as done by Vieth (2002) which factored in the cell slope, land cover and cell size. The U.S. Forest Service (1980) Stiff Diagram involves a more detailed determination of the SDR based on several grid cell attributes. It involves the knowledge of seven cell parameters which are sediment delivery, surface runoff, delivery distance, surface roughness, slope gradient, soil texture, percent ground cover and slope shape. The formulation of a spatially distributed SDR based on the Stiff Diagram is expounded upon with examples by Tollner (2002), and will be explored using GIS tools in a future research project. This cell attribute based SDR approach for non-point erosion and sedimentation has also been developed by Fraser et al. (1998) and Fraser (1999) as the SEDMOD model.

The satellite and terrain data processing are based on physical and mathematical principles. This approach is useful for rapid identification of erosion and sedimentation ‘hot-spots’ and for estimating the sediment yield and discharge to water bodies. This model can be used for any size watershed where the relationship between the sediment delivery ratio and drainage area is known. This project will also explore the attendant challenges and opportunities of non-point source erosion and sedimentation characterization of large mesoscale watersheds, with areas larger than 2500 km^2 (~1000 square miles) via geospatial modeling.

Soil Erosion Modeling Using the United States Department of Agriculture (USDA) Universal Soil Loss Equation (USLE)

The USLE has been one of the most successful and widely applied erosion prediction tool for purposes of soil conservation. Originally created by the Agricultural Research Service (ARS) of the USDA by Wischmeier and Smith (1965), the USLE was further modified in 1978 (Wischmeier and Smith 1978) to better model the soil erosion data. The USLE was developed at the National Runoff and Soil Loss Data Center primarily to model soil erosion potential in the agricultural lands in the United States, east of the Rocky Mountains. The USLE predicts the long-term average annual rate of erosion on a field slope based on rainfall, soil type, topography, land cover and management practice. The USLE predicts soil loss due to sheet and rill erosion on a single slope and does not account for erosion due to other practices such as gully, wind or tillage erosion. Results of the USLE are reported in the in the British System of units and the equation is represented as follows

$$\mathbf{A = R \times K \times LS \times C \times P} \qquad \text{Equation 1}$$

A is the potential long-term average annual soil loss in tons per acre per year. This value is then compared to the ‘tolerable soil loss limits’, as defined by the soil management agencies in the particular study area.

R is the rainfall factor, also known as the Erosivity or the Energy Intensity factor. It reflects the fact that soil erosion is greatly influenced by both the average intensity and the duration of rain in the study area. The R factor is a product of the rainfall energy and maximum

30-minute intensity of the rainfall divided by hundred, averaged over the whole year. The R factor for the Lake Lanier watershed area is 340 (Wischmeier and Smith 1978, p7).

K is the soil erodibility factor. It is the average soil loss in tons/acre per area for a specific type of soil in cultivated or entirely fallow land with a 'standard' length of 72.6 ft and a slope steepness of 9 percent. This factor is a measure of how susceptible soil particles are to detachment and transport due to rainfall and runoff. Soil texture is a primary factor affecting K, but organic matter and permeability also are contributing factors.

LS is the length-slope gradient factor. This factor represents the ratio of soil loss under given conditions to that of a site with the 'standard 'length of 72.6 ft and slope of 9 percent. The steeper and longer the slope is, the greater the soil erosion.

C is the crop/vegetation and management factor. It determines the efficacy with which specific soil and crop management systems prevent soil loss. The C-factor is a ratio between soil loss from land under a specific soil or crop management system to soil loss from continuously fallow and tilled land. The C factor can be determined by land cover type. In this study the land cover was extracted by supervised classification of Landsat TM and MSS imagery.

P is the support practice factor. It represents the effects of practices that reduce water runoff and hence reduce soil erosion. The P factor is the ratio of soil loss by a support practice to that of straight row farming up and down the slope.

There are numerous representative examples of USLE-based erosion studies in the United States. One of the first USLE-based erosion studies was by Morgan and Nalepa (1982) who used aerial photos to derive land-cover and constructed a GIS database to do the calculations identifying areas of greatest erosion. Soileau et al. (1990) studied the soil erosion patterns in a

3.8 ha research watershed in the Limestone Valley of Northern Alabama by comparing USLE based predictions with spatial patterns of fallout Cesium-137. Price (1993) modeled the soil erosion within the pinyon-juniper woodlands in Utah. In a well known study, Renwick et al. (2004) applied the USLE to study the role of impoundments in the sediment budget of the Coterminous United States. Jackson et al. (2005) have used the USLE to model surface erosion in a rural Southeastern Piedmont watershed, to study the legacy of the sediment deposits from the days of the cotton farming in the South. Fernandes and Welch (1994) constructed an innovative non-point source USLE based erosion and sedimentation model for the Lake Allatoona watershed, North of Metro Atlanta. Field and photogrammetric based erosion studies related to the USLE have been performed by Welch et al. (1983), Thomas et al. (1983), Welch et al.(1984), Thomas et al. (1988).

Subsequently, the USLE has been used to model soil erosion and subsequent sedimentation potential in agricultural areas and river basins all over the world. This equation that was developed to describe erosion of the soils east of the Rocky Mountains has been used in erosion control efforts, helping preserve valuable farmland and provide sustainable nutrition to populations on a global scale. It has a major impact on soil conservation efforts and agriculture worldwide. There are numerous examples of international applications of the USLE. Mati et al. (2001) did a comparative study of the application of USLE to the African Savannahs in both the East and West of the continent. Basic et al. (2004) studied the impact of tillage and crop management on soil erosion in central Croatia. Cohen et al. (2005) modify the USLE for soil risk erosion study of a small watershed in Kenya. Lin et al. (2002) outline the experience of applying USLE to assessing soil erosion in Taiwan.

The Revised Universal Soil Loss Equation (RUSLE) was developed as an improvement of the USLE (Renard et al., 1991, 1997). The RUSLE includes more precise rainfall factor R values and a modified length-slope LS factor based on the ratio of rill to interrill erosion and accommodating more complex slopes (Renard et al., 1994). The key difference in the land cover C factor between the two models is that the RUSLE allows for change in the C factor over a 15-day interval. However, Rapp et al. (2001) have shown that the RUSLE does not seem to show any improvement in soil loss estimates relative to the USLE. The RUSLE may estimate erosion better if very detailed land cover classes are used, which is not the case in this study. Therefore the USLE erosion estimates should suffice in modeling the soil erosion and sedimentation in this study, which is based on four major land cover classes of Urban/Rocks/Soils, Forest, Pasture/Agriculture and Water.

A comprehensive non-point source modeling of erosion and sedimentation of the Lake Lanier watershed has not yet been accomplished and has only become possible in the past few years with the recent availability of remotely sensed image data and powerful GIS analysis tools. The first study of erosion and sedimentation of the Lake Lanier watershed area was performed by Faye et al. (1980) with the scope of this study culminating in the late 70's. This study encompassed the entire Upper Chattahoochee river basin from its uppermost reaches in North Georgia, Lake Lanier and all the way to the end of the West Point Lake in west Georgia. It cataloged and measured the sediment discharge, hydrography and stream morphology in its study area. The tools and techniques used in fluvial sediment measurements have been cataloged in detail by Kondolf et al. (2003). Faye et al. (1980) also estimated USLE-based soil erosion averaged over the sub-watersheds of the Upper Chattahoochee River Basin. The USLE erosion modeling was done by segmenting the study area into sections with relatively homogeneous terrain characteristics like land cover and slope. This study included data from the United States Geological Survey (USGS) monitoring stations in the watershed which was used to estimate the sediment discharge into Lake Lanier.

Previous erosion studies of the Lake Lanier watershed investigated particular aspects of erosion and or sediment/nutrient delivery, but there are no studies for spatially distributed non-point source erosion and sedimentation modeling for the entire watershed. Nearing et al. (1993) estimated daily nutrient fluxes into Lake Lanier from limited tributary data. The USGS (1995) did a study summarizing water quality research in the Apalachicola-Chattahoochee-Flint River basins impacting the states of Alabama, Georgia and Florida. Leigh (1998) has estimated the sediment input into Lake Lanier from the Chattahoochee and the Chestatee, using stream-flow data and suspended sediment samples. The Tennessee Valley Authority (TVA) (2000) conducted a study of non-point area sources and pollution load estimates in the Upper Chattahoochee River Area. The TVA study encompasses about 71 percent of the Lake Lanier watershed area and is based solely on inventories of non-point source pollution sources identified from aerial photographs. Zeng and Rasmussen (2001) measured sediment and phosphorus inputs into Lake Lanier by the Chattahoochee and Chestatee Rivers from 1996-97. The Upper Chattahoochee Basin Group has performed a series of demonstration projects to reduce non-point source pollution loadings from a variety of sources, including erosion (Rivers and Hawks, 2001). Gainesville College faculty Semerjian and Williams (2001) conducted a USLE based erosion study of the Soque River watershed for the Upper Chattahoochee Riverkeeper. The Soque River is a major tributary of the upper Chattahoochee River.

Several researchers have examined the public policy and management issues related to erosion and sedimentation in the Lake Lanier watershed. Kundell and Rasmussen (1995) examined the scientific and regulatory issues for the Georgia Board of Natural Resources. The environmental firm CH2MHILL (2000) prepared a watershed assessment and management plan for the part of the Lake Lanier watershed in Hall County, with this study focusing primarily on the biotic markers of water quality. The National Academy of Public Administration's Center for the Economy and the Environment (2001) completed a comprehensive report on the causes, costs and consequences of sedimentation in the Chattahoochee watershed. Tetra Tech, Inc., (2002) prepared a report for the U.S. Army Corps of Engineers which outlines an environmental impact related to the operation and maintenance of Lake Lanier.

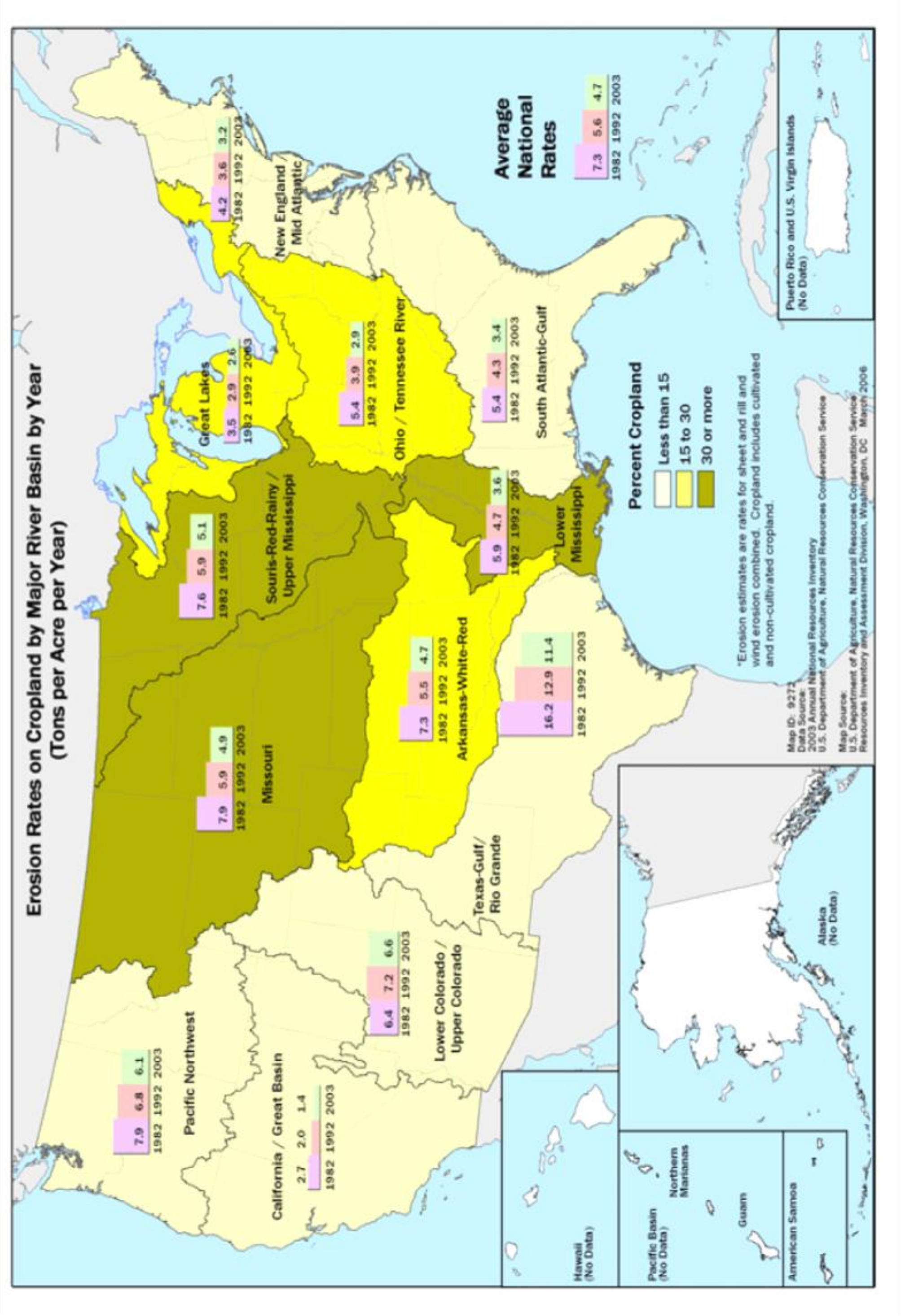
A USLE based erosion and sedimentation study similar to this one has been done for Lake Alatoona by Fernandes and Welch (1994). A cell size of five acres was used for this study and the streams in this watershed were manually digitized. The computing storage and processing available at this time was a major constraint for the erosion and sediment modeling, and the software development. A custom software package was developed to read in the GIS data layers and perform the calculations for erosion and sediment modeling. An extent of 128 x 128 cells could be processed at one time by this software, which made it necessary to break up the watershed into USGS topographic quadrangles. The model was applied to each quadrangle separately. This study used a sediment delivery ratio based on the ratios of slopes of the current cell with the upslope cell, along the flow path.

The study by Fernandes and Welch (1994) was the inspiration for this erosion and sedimentation study of the Lake Lanier watershed. The availability of powerful GIS software such as ArcGIS has made it possible to do erosion and sedimentation studies at varying scales and for large watersheds. The availability of large data storage capacities and rapid processing power in desktop computers has largely eliminated computing constraints. Since the model development was done on a standard software platform such as ArcGIS, it minimizes data format compatibility issues and makes the model available for use on other watersheds by other researchers. The model developed in this study can be used for non point source erosion and sedimentation modeling in mesoscale watersheds such as that of Lake Lanier.

Soil Loss Tolerances

Soil loss tolerance was a concept defined in the 1940's as the rate of soil loss that was permissible without diminishing the ability to support vegetation and agriculture indefinitely (USDA 1978). The soil surface is a dynamic phenomenon in which soil is produced by weathering of geologic matter, addition of organic matter and erosion by water and wind. The soil loss tolerance is therefore equivalent to the rate at which soil is produced at any one given location maintaining the viability of the region as a human and ecological habitat. Soil loss tolerance or the T-factor began to be used by the National Resource Conservation Service NRCS (formerly the Soil Conservation Service) in the mid-1960's for purposes of conservation planning (Schertz et al., 2006). The most recent compendium of the soil erosion tolerances for cropland in the United States is the National Resources Inventory (NRI 2003) which is compiled by the NRCS. The NRI also tabulates the erosion soil loss rates on croplands in the major river basins in the United States (Figure 8). The soil loss rate due to erosion in Georgia's croplands is 4.7 +- 0.4 tons/acre/year (NRI 2003).

Figure 8: Average Erosion in Cropland by Major River Basin (NRI 2003)



CHAPTER 2

DATA SOURCES AND EROSION MODELING

This study was performed at a 30 m x 30 m spatial resolution corresponding to the spatial resolution of the digital elevation model (DEM) and Landsat imagery used to model sediment erosion and deposition. The following sections will elaborate on the input data layers and the mathematical details of the methodology employed in the non-point source erosion modeling part of this study. The spatially distributed soil loss rate provides the sediment supply grid that is subsequently used in the sediment yield modeling elaborated upon in Chapter 3.

Lake Lanier Watershed Soils

There are two soil databases of interest for the Lake Lanier watershed. The State Soil Geographic (STATSGO, 1991) and the Soil Survey Geographic (SSURGO, 2006) soil databases were used for modeling erosion and sedimentation for this watershed. Both of these soil databases have been compiled by the National Resource Conservation Service (NRCS) and are downloadable at their website (www.nrcs.usda.gov). The older STATSGO soil database has a smaller scale of 1:250,000 and has been available since 1991. The more recent SSURGO soil database, which is scheduled to be completed in 2008, is of a larger scale, generally ranging from 1:12,000 to 1:63,000.

The spatially distributed soil tolerance T-factor layer for the Lake Lanier watershed was derived from the SSURGO soil database (Figure 9). The k-factor and the T-factor GIS layers were generated by performing a spatial attribute join with the 'component' table in the SSURGO geo-database. The T-factor in the study area varies from 1 to 5 tons/acre/year. The modeled non-point source USLE soil erosion for the time period of this study was compared to the spatially explicit T-factor in the analysis of results in Chapter 5.

The older STATSGO (1991) soil data were used only for the 1984 USLE non-point source erosion modeling of the study area, for comparison with the USLE results of Faye et al. (1980), in which they had used soil erodibility k-factor data provided by the Georgia Soil and Water Conservation Service in 1977. The STATSGO erosion modeling results were also compared to the SSURGO based results. The STATSGO soil shapefile for the Lake Lanier watershed was subset from a larger STATSGO soil map of the entire state of Georgia. The STATSGO shapefile clipped to the watershed extent was then converted to an ESRI Grid file with a 30 m x 30 m spatial resolution, with the soil erodibility k-factors assigned to each grid cell (Figure 10).

The more recent and spatially detailed SSURGO (2006) data was used for the soil erodibilty k-factor layer in the non-point source USLE modeling of the Lake Lanier watershed for 1984, 1991, 1992, 1999, 2001 and 2005 (Figure 11). This vector (shapefile) to raster (ESRI Grid) conversion is necessary for purposes of performing the raster algebra for the USLE erosion modeling. The SSURGO soil data is more spatially detailed and voluminous, and is available for download by individual counties from the NRCS website.

Figure 9: SSURGO Soil Erosion Tolerance T-Factor Map for the Lake Lanier Watershed

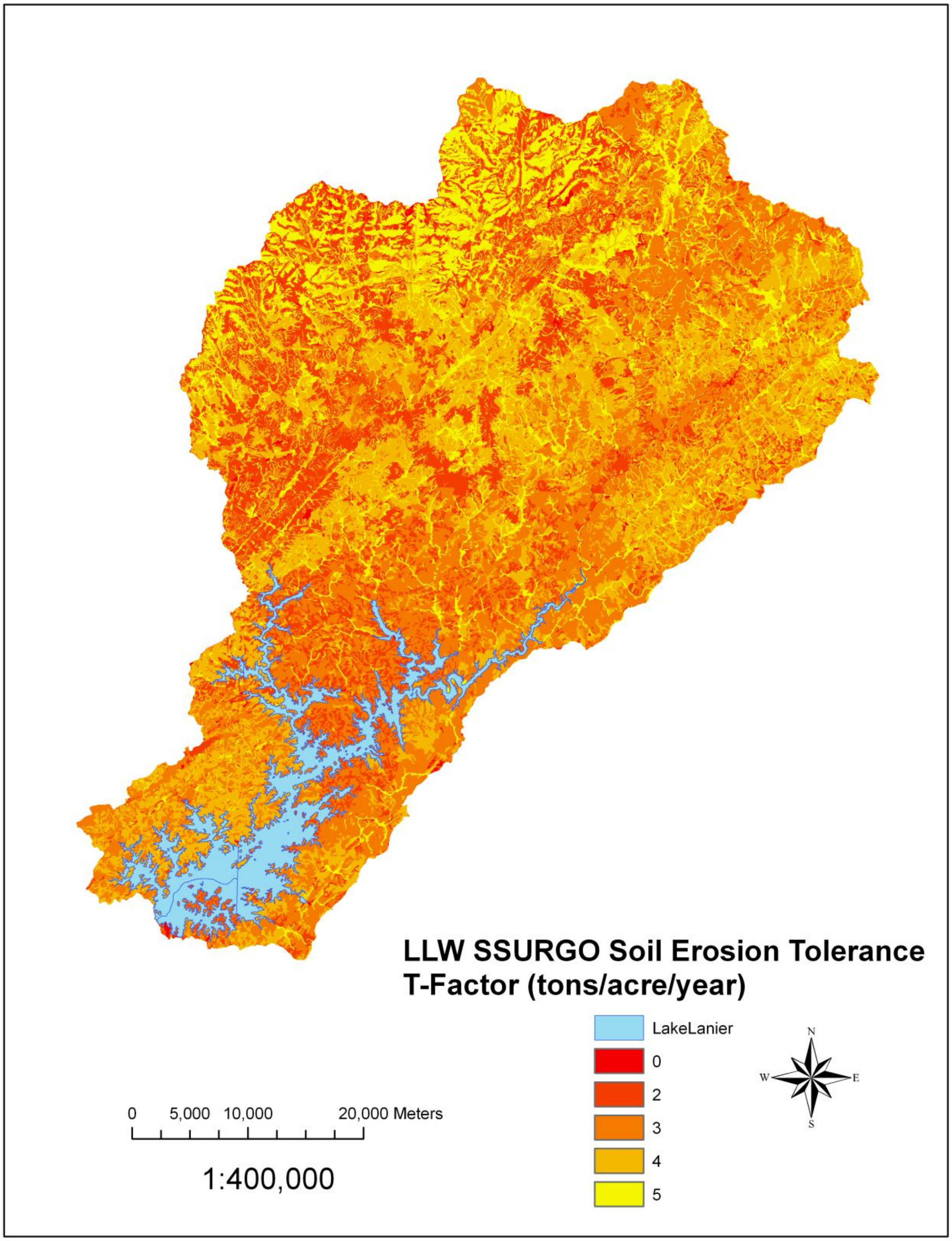


Figure 10: STATSGO Soil Erodibility k-Factor

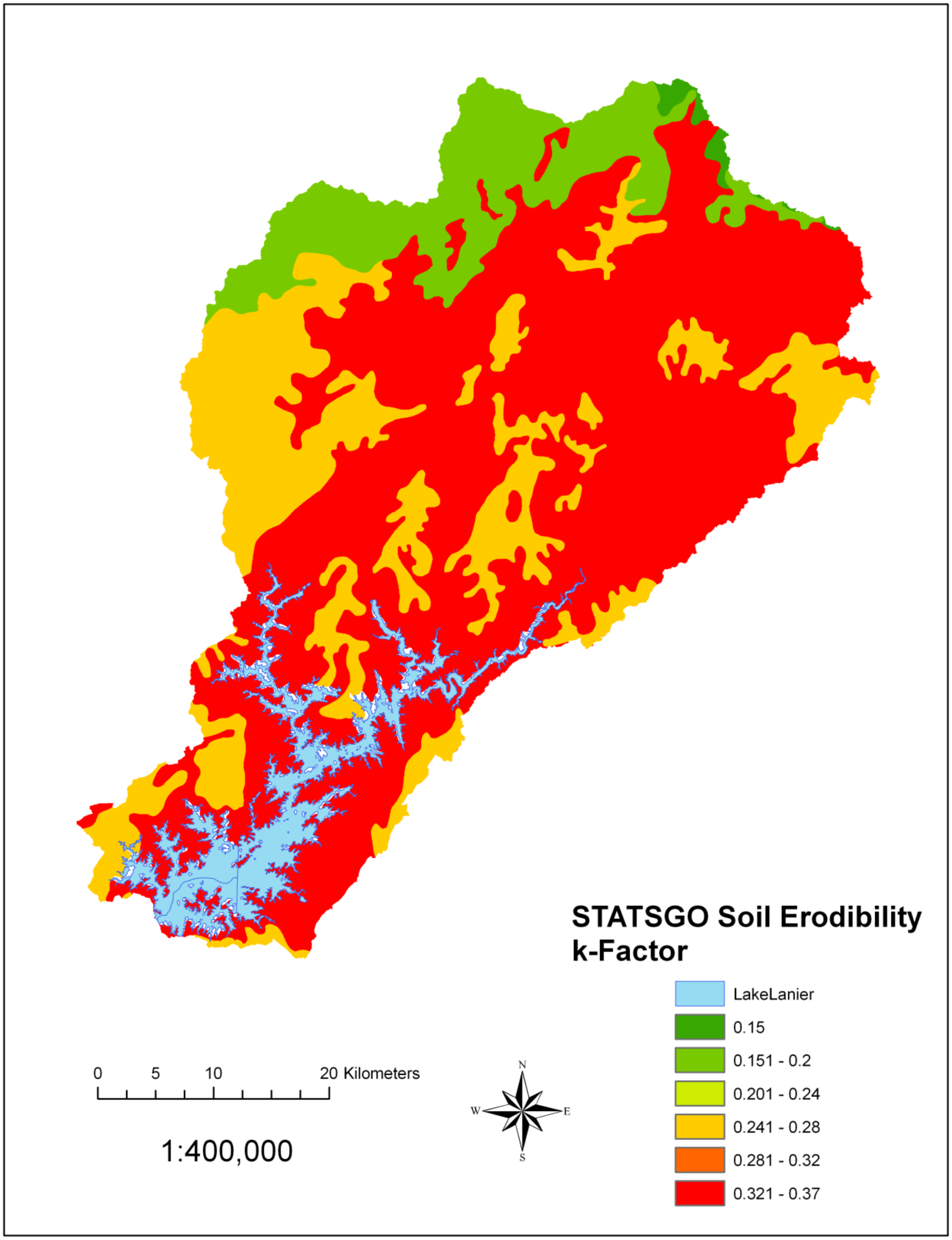
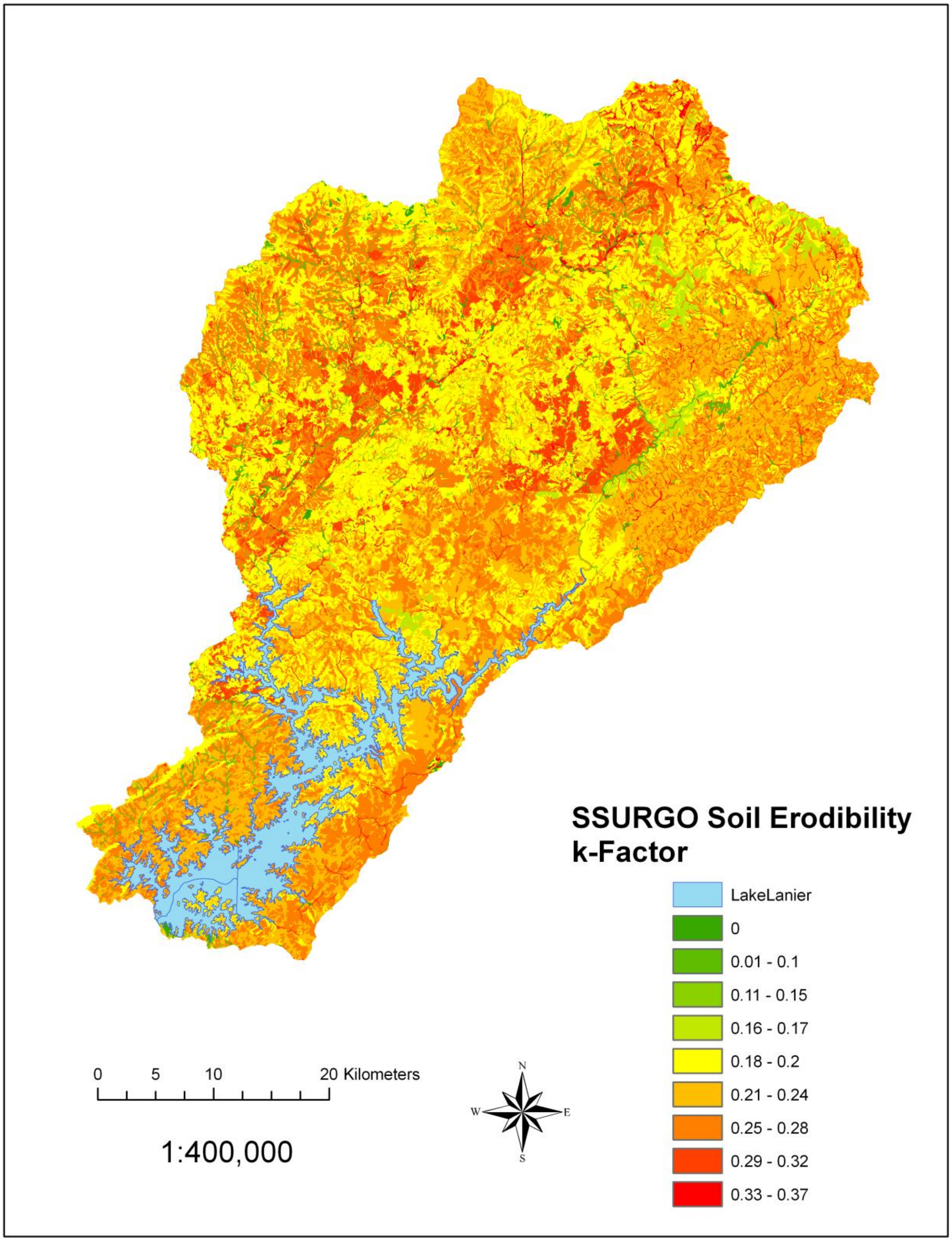


Figure 11: SSURGO Soil Erodibility k-Factor

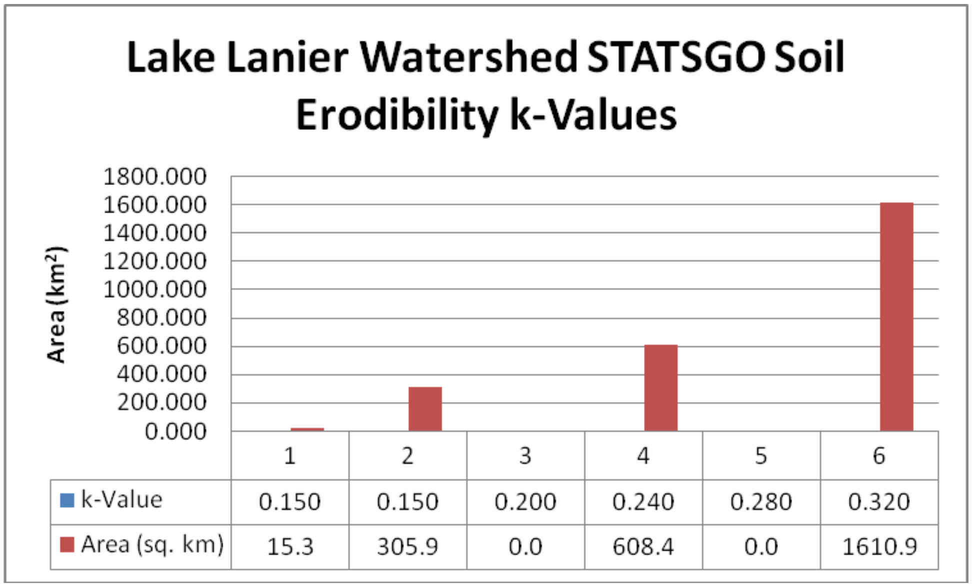


The soils of the Lake Lanier watershed are a part of nine counties in northeast Georgia and have specific SSURGO NRCS code designations (Table 2). The SSURGO soil map shapefiles for each one of these counties were downloaded from the NRCS website, mosaiced into one coverage and then subset to the Lake Lanier watershed boundary. The subsequent shapefile was then converted to an ERSI Grid file with a spatial resolution of 30 m x 30 m, with the grid cell value being the SSURGO soil erodibility k-factor The k-factor attribute had to be queried from the SSURGO database by performing a relational join with the 'component' table. Histograms of the Area vs. STATSGO and SSURGO soil erodibilities show the areal extend of each erodibility class (Figure 12 and Figure 13).

Table 2: Counties Included in the Lake Lanier Watershed and their NRCS SSURGO Soil Designations

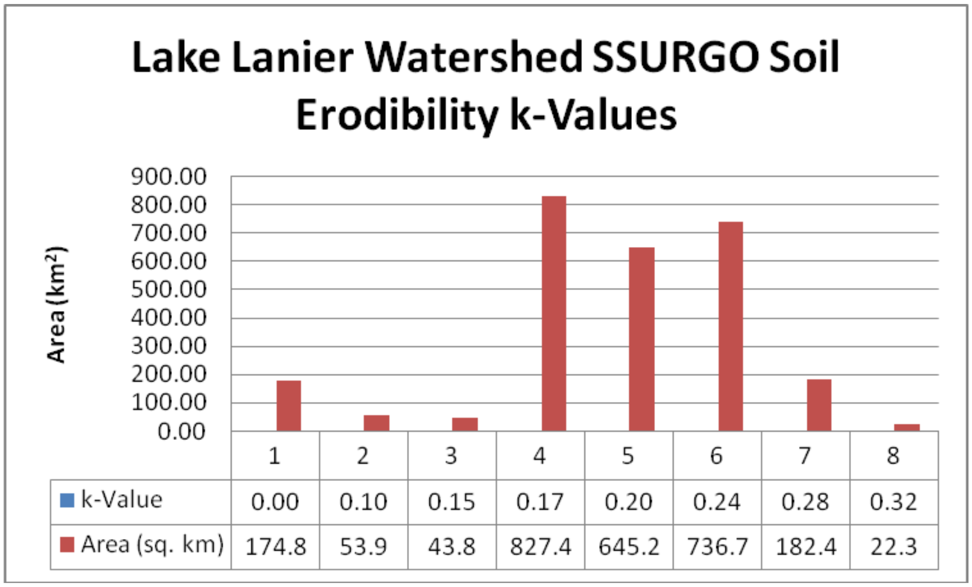
	County	NRCS Designation
1	Hall	GA139
2	Gwinnett	GA135
3	Forsyth	GA117
4	Dawson	GA085
5	White	GA311
6	Union	GA291
7	Towns	GA281
8	Lumpkin	GA187
9	Habersham	GA137

Figure 12: Area vs. STATSGO Soil Erodibility Histogram



	1	2	3	4	5	6
🟦 k-Value	0.150	0.150	0.200	0.240	0.280	0.320
🟥 Area (sq. km)	15.3	305.9	0.0	608.4	0.0	1610.9

Figure 13: Area vs. SSURGO Soil Erodibility Histogram



	1	2	3	4	5	6	7	8
🟦 k-Value	0.00	0.10	0.15	0.17	0.20	0.24	0.28	0.32
🟥 Area (sq. km)	174.8	53.9	43.8	827.4	645.2	736.7	182.4	22.3

Landuse/Land Cover (LULC) of the Lake Lanier Watershed

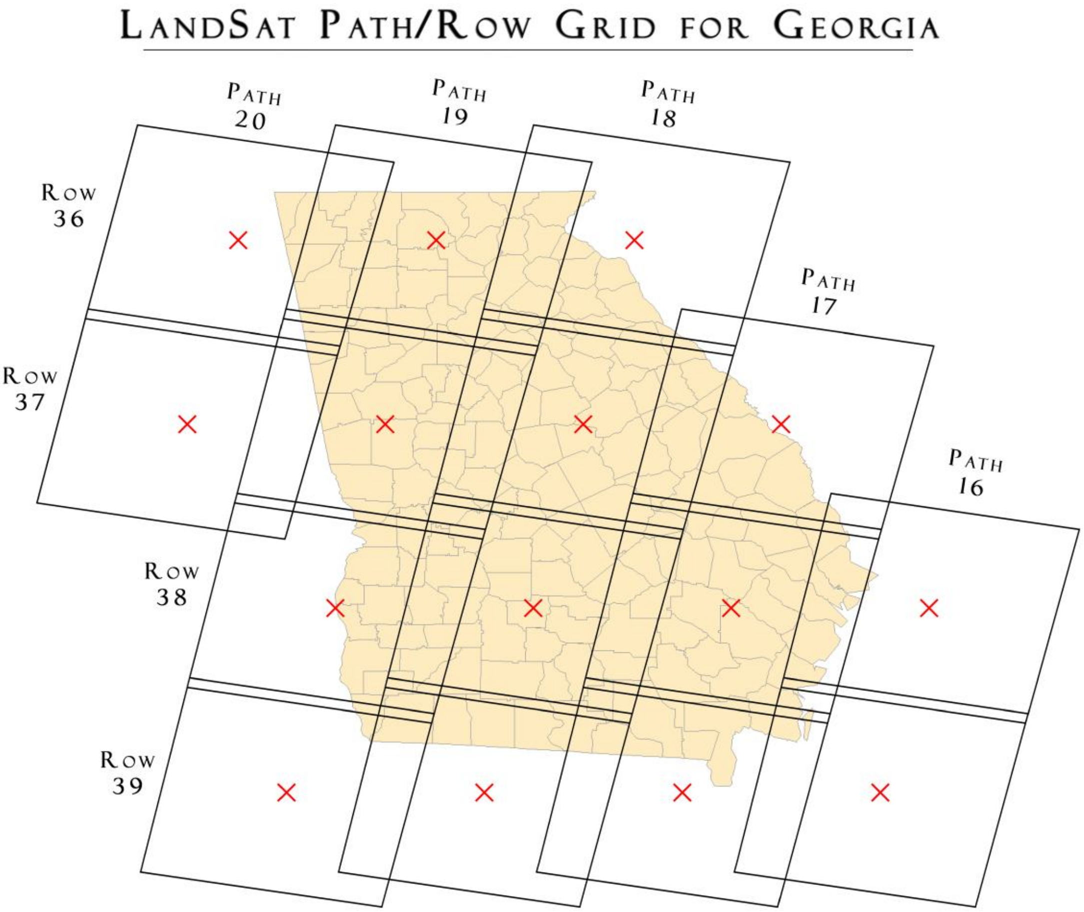
It was necessary to perform this modeling for the early 1980's to compare results with erosion modeling sediment measurements performed by Faye et al. (1980). Soil loss rate due to erosion has a quadratic dependence on terrain slope in the USLE, and a linear dependence on land cover type. In the absence of land cover maps for the time period from early 1980's to when this project began in 2005, the only viable option was to classify the available cloud free Landsat multispectral imagery of the Lake Lanier watershed to obtain a time series of Landuse/Land Cover (LULC). The four major land cover classes of Water, Forest, Pasture/Agriculture and Urban/Rocks/Soils, of a mesoscale watershed at 30-m x 30-m spatial resolution, can be derived using spectral image segmentation and classification methods. Therefore, LULC derived from Landsat multispectral imagery with the same image processing methodology is viable input into the USLE modeling.

The availability of archived Landsat imagery allowed a reconstruction of the LULC all the way back to the early 1980's. The USGS Global Visualization Viewer (GLOVIS) was browsed on the web for all the available Landsat imagery from the late 1970's to 2005. Cloud free imagery for the study area was available for the month of September in 1984, 1991, 1999 and 2005, and these years became the foci for this study. Since the weather in September is usually cool with low humidity, there is a greater likelihood of cloud free conditions in the study area.

All of the Landsat imagery was provided by the USGS resampled to 30 meter spatial resolution. In order to co-register all the images to a root-mean-square error (RMSE) of one pixel (i.e. +/- 30 m), the 2005 Landsat image was re-rectified using ground control from the 1-meter resolution 2005 USDA National Agriculture Imagery Program (NAIP) airphotos. NAIP imagery has a horizontal accuracy that is within 5-meters of reference ortho-imagery. The reference ortho-imagery is mosaiced digital ortho quarter quads (DOQQs) used to digitize USDA Farm Service Agency (FSA) common land unit (CLU) boundaries (USDA 2006). The NAIP 2005 imagery is available for download from the USDA NRCS geospatial data gateway website (USDA 2008). Subsequently all of the Landsat image subsets for the watershed were registered to the 2005 Landsat imagery as a reference image. This resulted in a set of cloud free imagery of the watershed in geographic registration that would be used for the extraction of the land cover data sets. The four images spanned a 21-year time period and were all acquired in September. This is a relatively cloud free month with full leaf-on and peak foliage color conditions ideal for mapping the land cover and inferring landuse.

The study area is completely within the Landsat TM scene located at path 19 row 36 based on the World Reference System-2 (WRS-2) for the 1991, 1999 and 2005 imagery (Figure 14). The land cover maps used in this study were derived from Landsat Multispectral Scanner (MSS) imagery from September 1984 and Thematic Mapper (TM) imagery from September 1991, 1999 and 2005 (Figure 15 through Figure 18). The 1984 MSS imagery is based on the World Reference System-1 (WRS-1) path 18 row 36 and path 19 row 36, neither of which fully contain the watershed. Therefore, color balancing and mosaicing of two separate Landsat images acquired in September 1984 from adjacent paths, was required.

Figure 14: Landsat TM WRS-2 Coordinate System for Georgia



Note: The Study Area of the Lake Lanier watershed is in Path 19 Row 36 of the WRS-2 (Courtesy Dwight Lanier)

Figure 15: 1984 Landsat MSS Image Mosaic in False Color Rendition

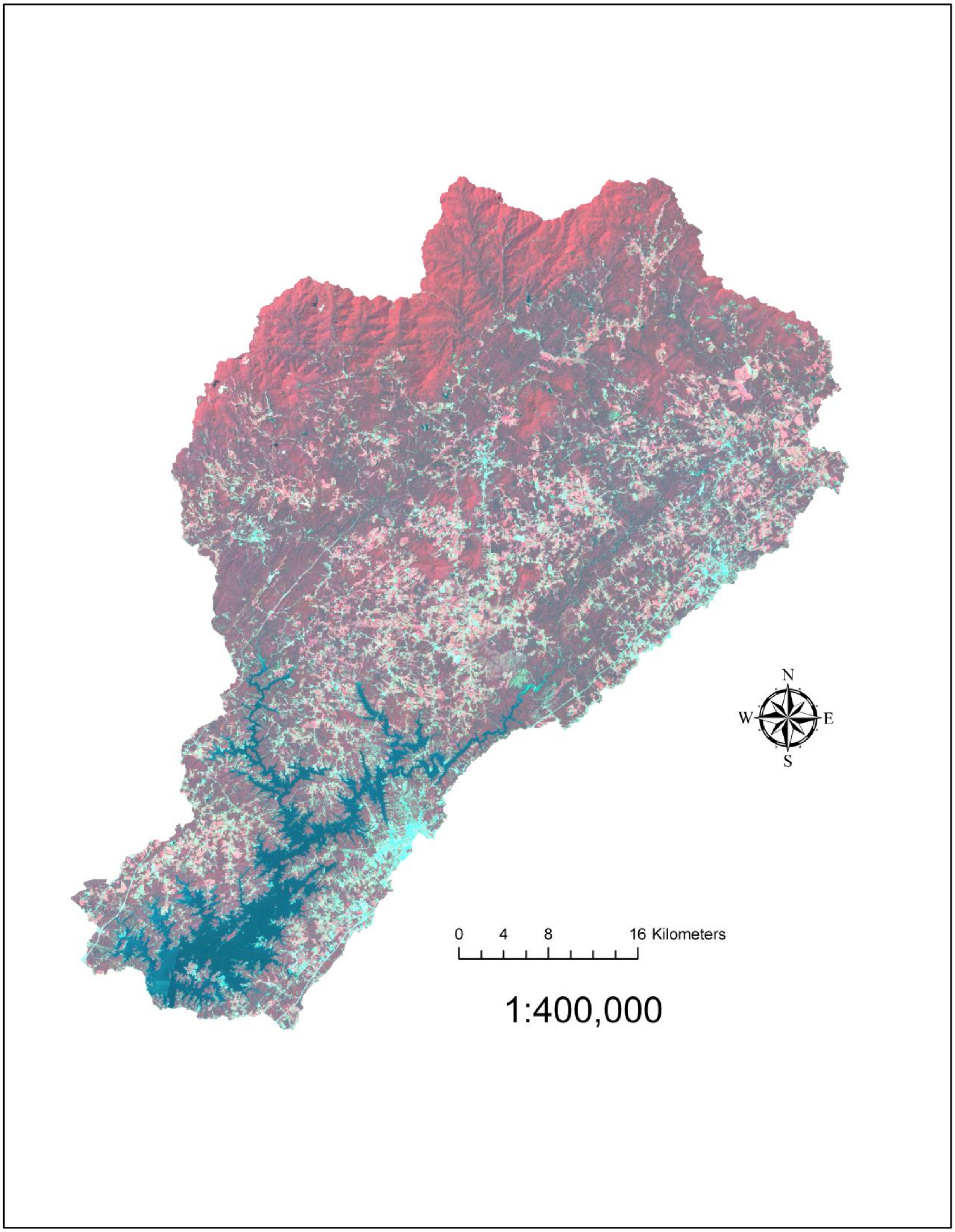


Figure 16: 1991 Landsat TM Image in False Color Rendition

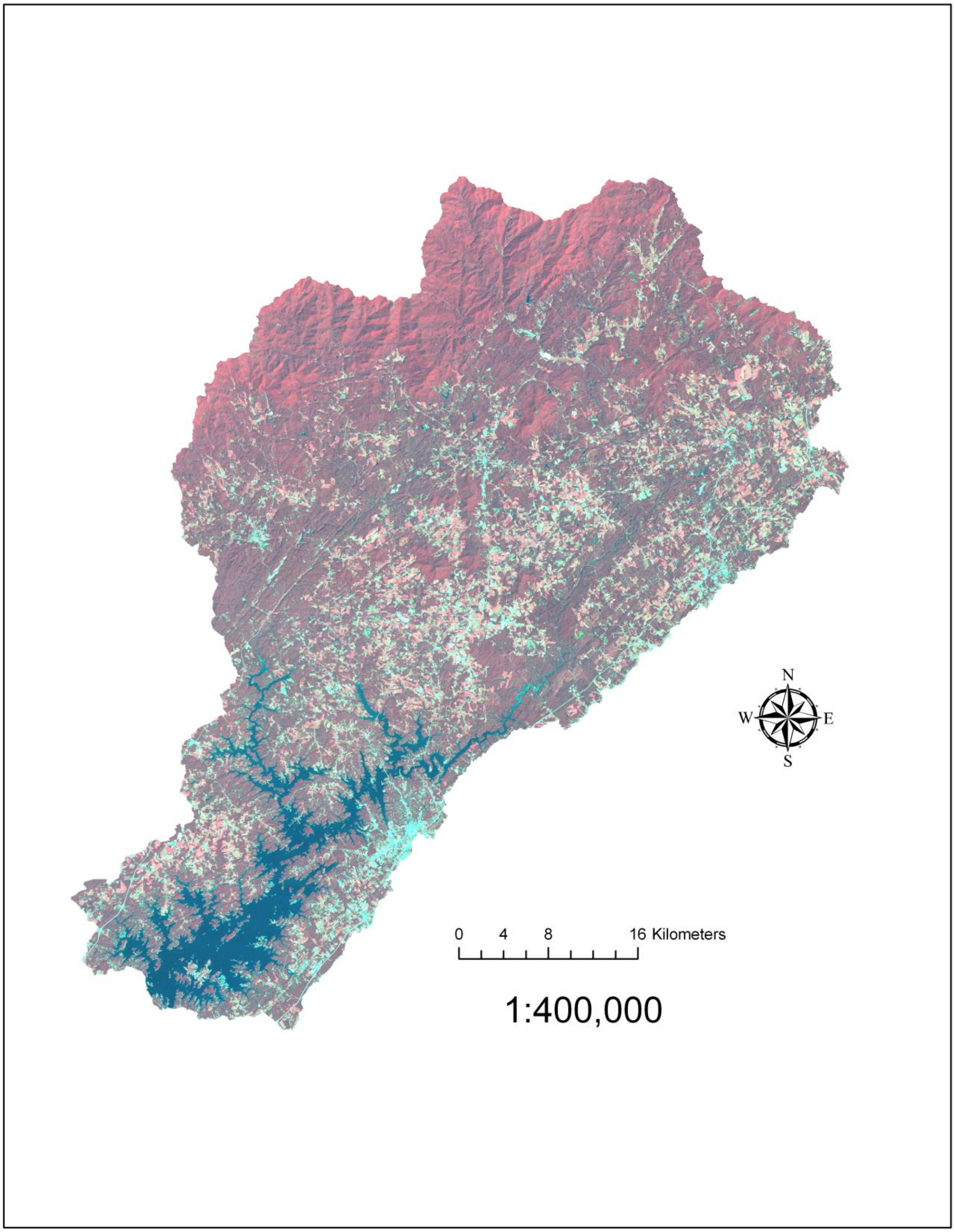


Figure 17: 1999 Landsat TM Image in False Color Rendition

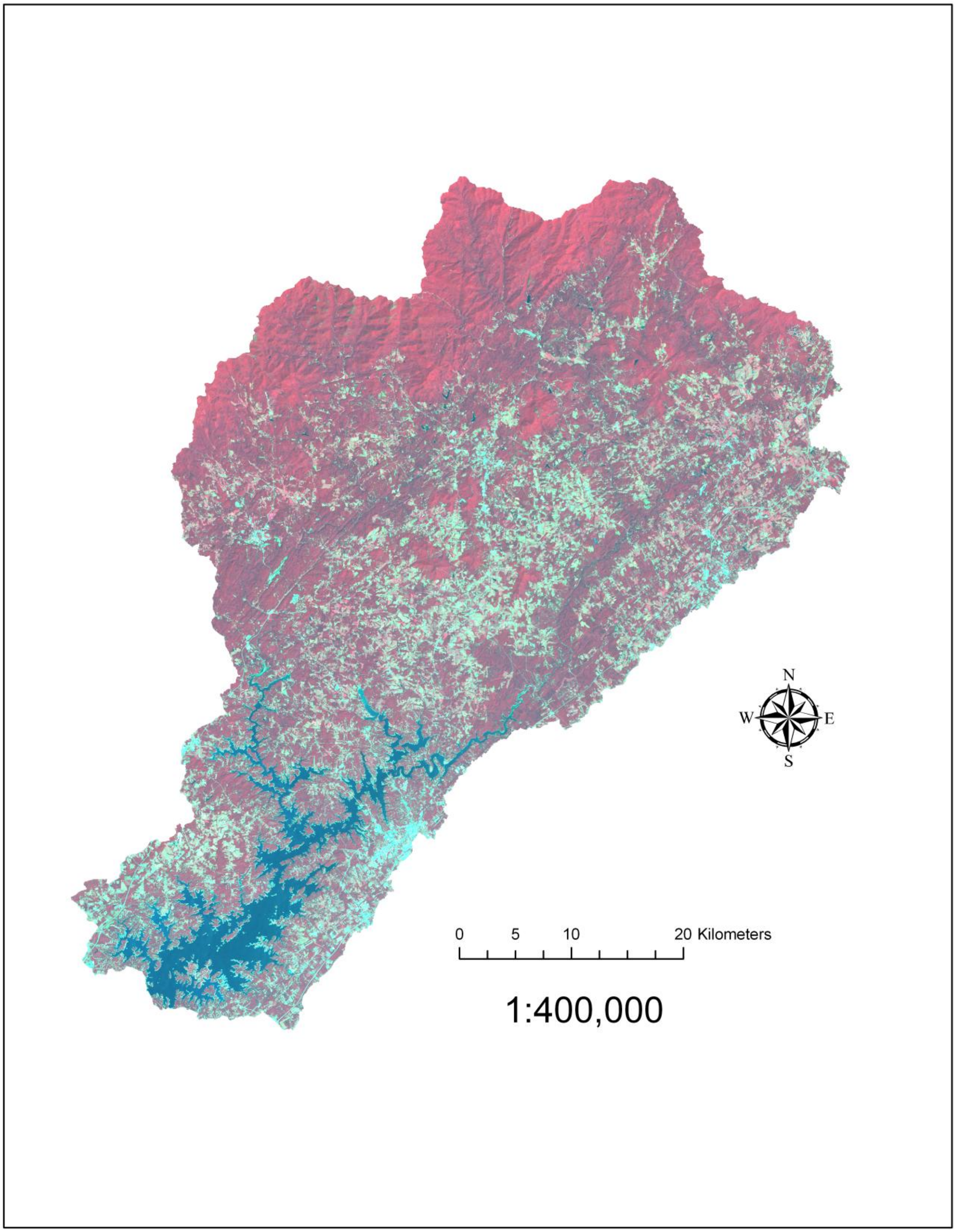
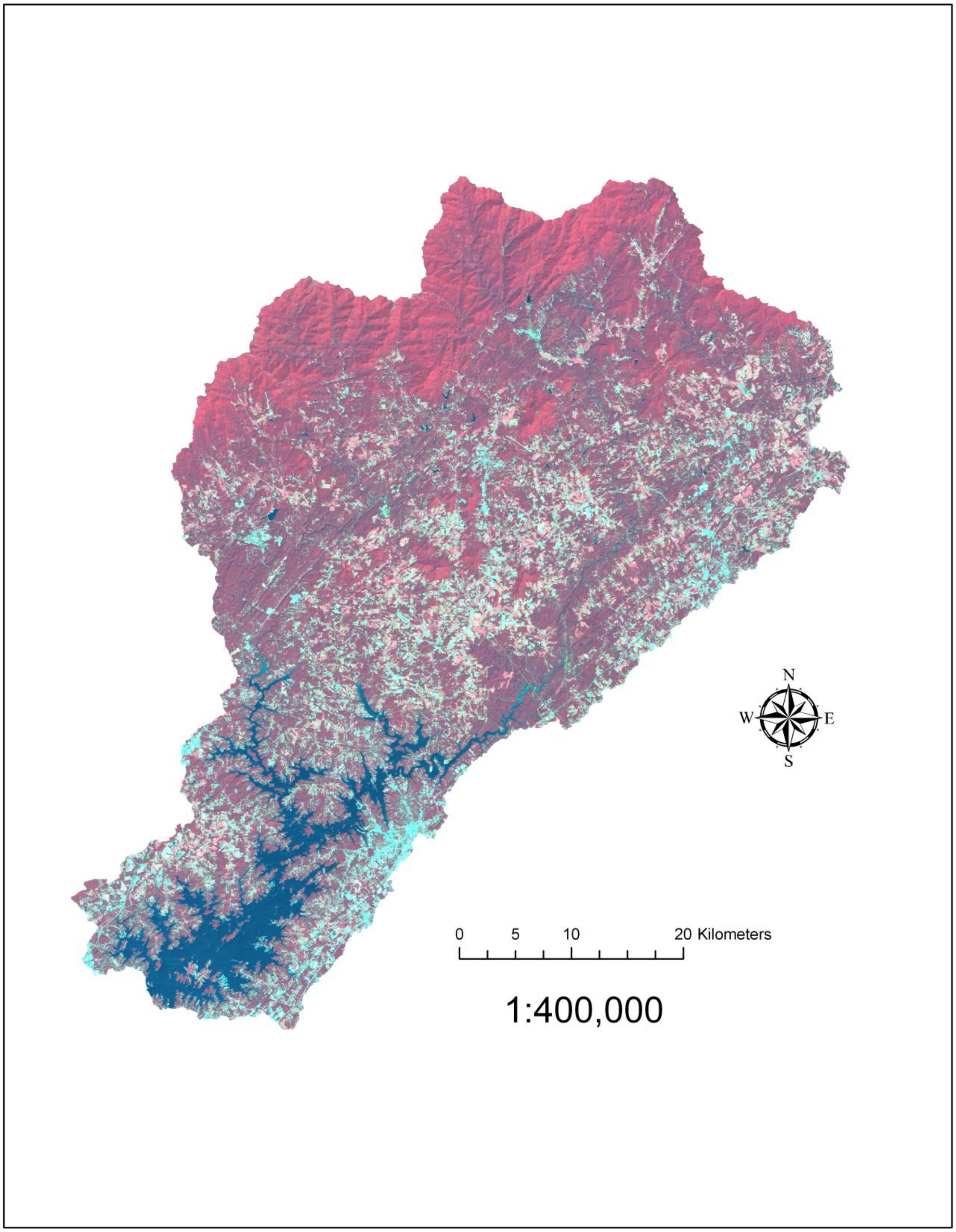


Figure18: 2005 Landsat TM Image in False Color Rendition



Lake Lanier Watershed Land Cover Classification from Satellite Images

The landuse/land cover (LULC) classification of the Landsat imagery was initially performed using supervised classification techniques of ERDAS Imagine software (Leica Geosystems, Inc.). Four major land cover classes that are readily identifiable in this watershed are urban/rocks/soils, water, forest and agriculture/pasture. Given that the size of the watershed is about 2700 km^2, the extraction of these fundamental land cover classes is reasonable. However, there was spectral mixing between the classes that seemed irresolvable with pixel-based supervised classification techniques available in ERDAS Imagine. The use of Definiens eCognition Ver. 4 software with its innovative image processing approach minimized this spectral confusion. Consequently the LULC maps of this watershed that were used in this project were extracted using eCognition software. This process is elaborated upon in the following paragraphs.

ERDAS Imagine 9.0 was initially used to do a supervised classification with training sets created by a visual interpretation of false color multispectral imagery. The region in the northern part of the watershed is very hilly, such that the lighting conditions and hence terrain radiance are not uniform, causing a spectral mixing of the pasture/agriculture classes with the forest classes and the urban/rocks/soils. This added a substantial ‘noise’ to the derived land cover such that every time a supervised classified was performed with a new signature set, there were variations in land-cover classification. A major factor for this mixing was the heterogeneity in the ground reflectance due to the mountainous terrain in the northern portion of the watershed. The spectral mixing in the training sets was confirmed by examining the signatures in feature space plots between band 3 (Red) and band 4 (NIR) of Landsat imagery.

The optimal solution to the problem with spectral mixing of the training sets was provided by the use of an object based image analysis (OBIA) capability of a relatively new image processing program called eCognition by Definiens. Definiens is an ‘image intelligence’ company that was founded by physics Nobel Laureate Gerd Binnig in 1986. Definiens developed this new object based approach to image analysis known as ‘multiresolution image segmentation’ (Blaschke et al., 2000) which is encoded in their eCognition image processing software. This image processing capability is rapidly evolving and eCognition was renamed to Definiens Professional 5.0 and then subsequently to Definiens Developer 7.0 (Definiens, 2007). Each iteration of this software has incorporated successively advanced image processing capability. Definiens is used for many diverse image processing applications ranging from medical imaging to geospatial applications. In this project, eCognition software was used for land cover classification from Landsat imagery.

The initial multi-resolution segmentation performed by eCognition on the image parses it into segments that have similar surficial reflectance spectra and characteristics such as texture. This is very useful for the choice of training sets as it restricts the choice of area of interest (AOI) of the signatures to be spectrally homogeneous and thus minimizes the confusion between classes. The land cover maps were extracted with the OBIA approach and have a 30-m x 30-m spatial resolution (Figure 19 through Figure 23).

Figure 19: Lake Lanier Watershed LULC 1984

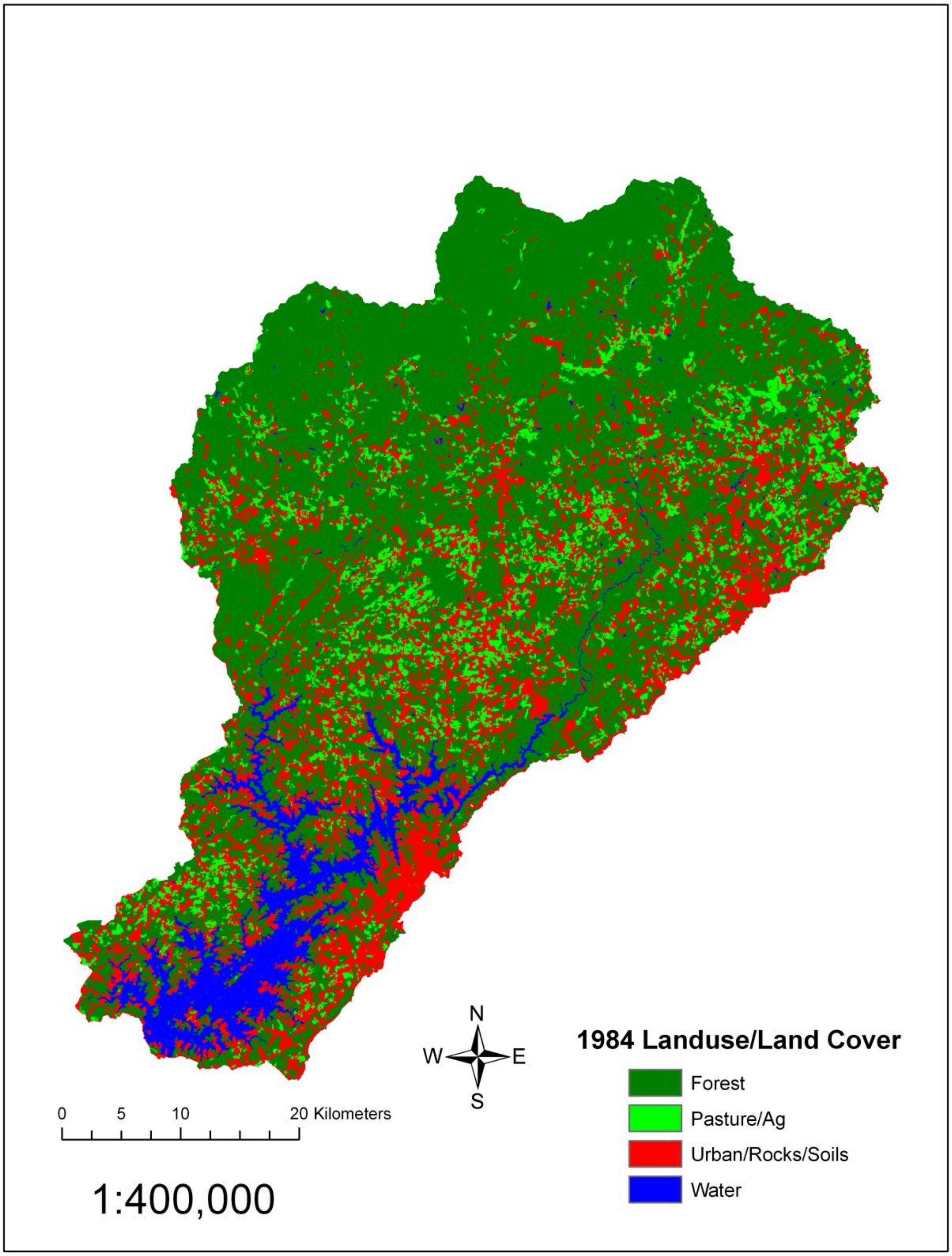


Figure 20: Lake Lanier Watershed LULC 1991

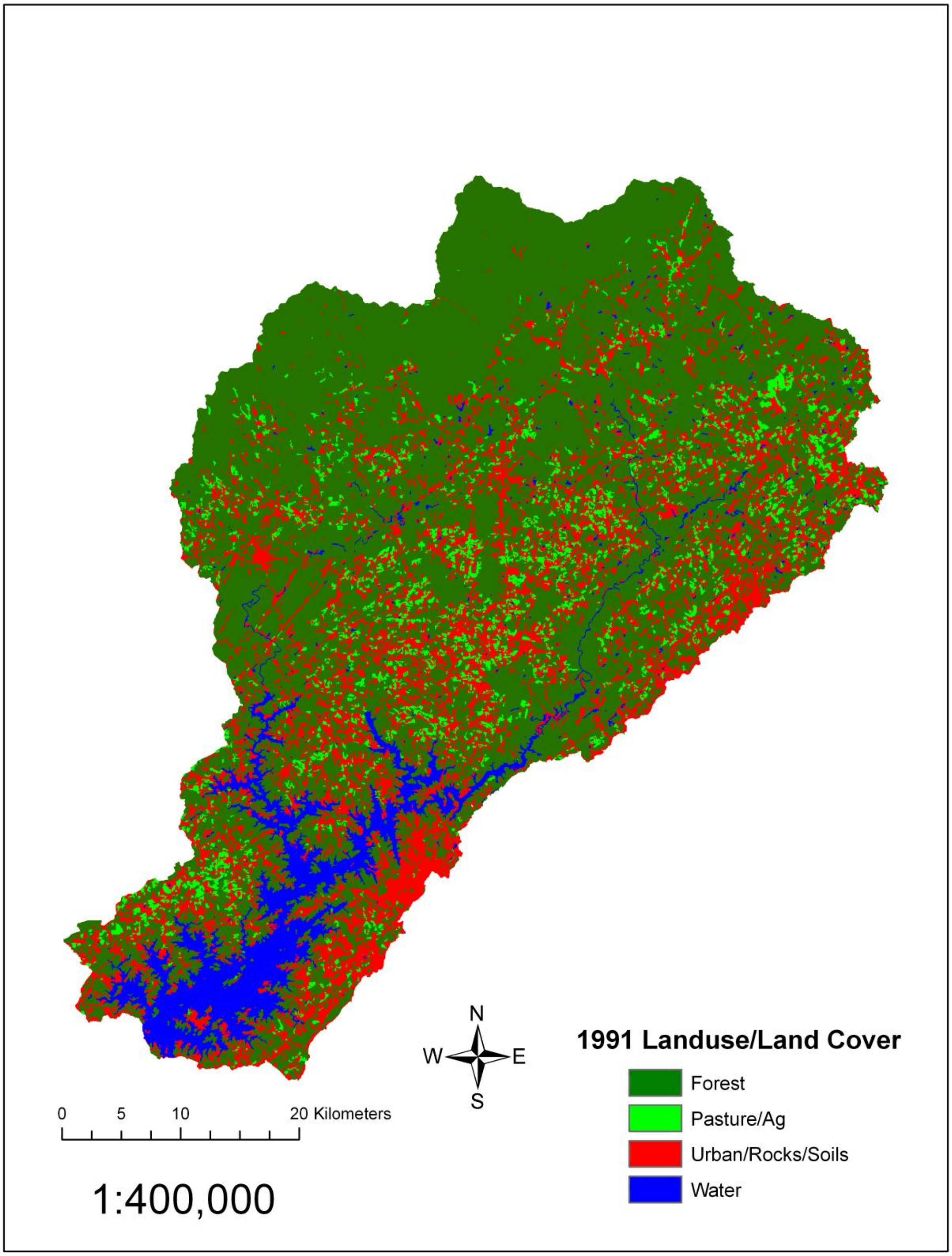


Figure 21: Lake Lanier Watershed LULC 1999

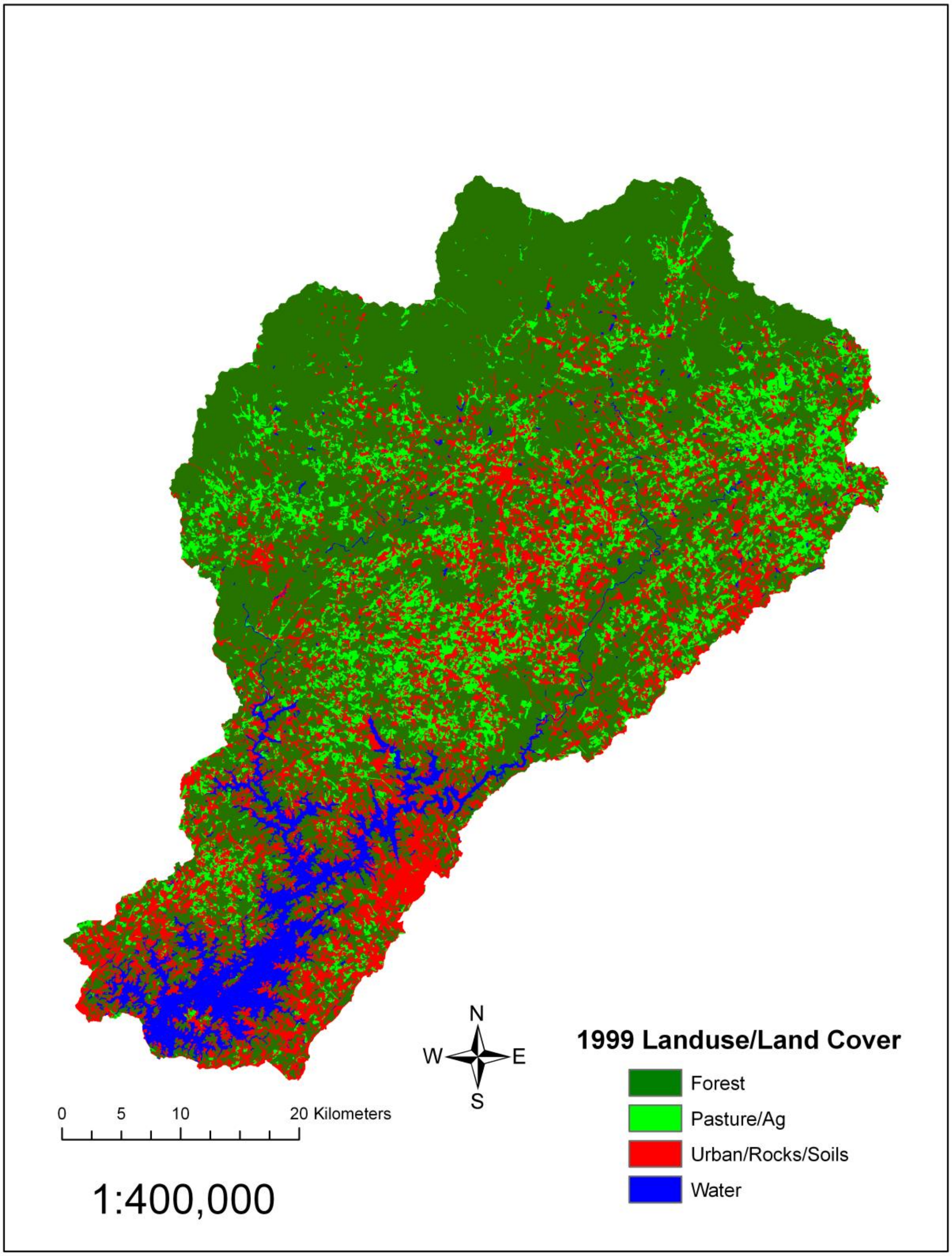
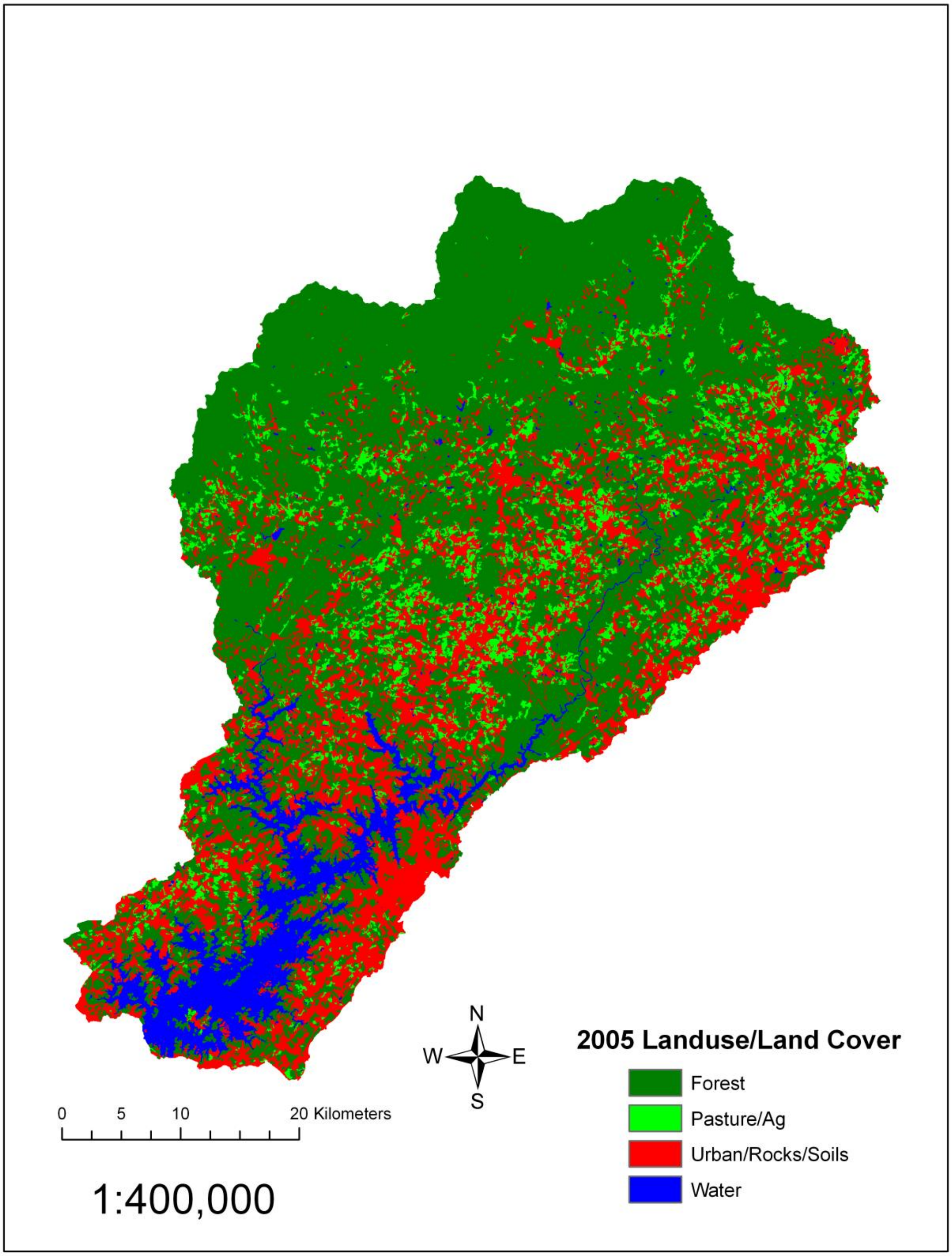
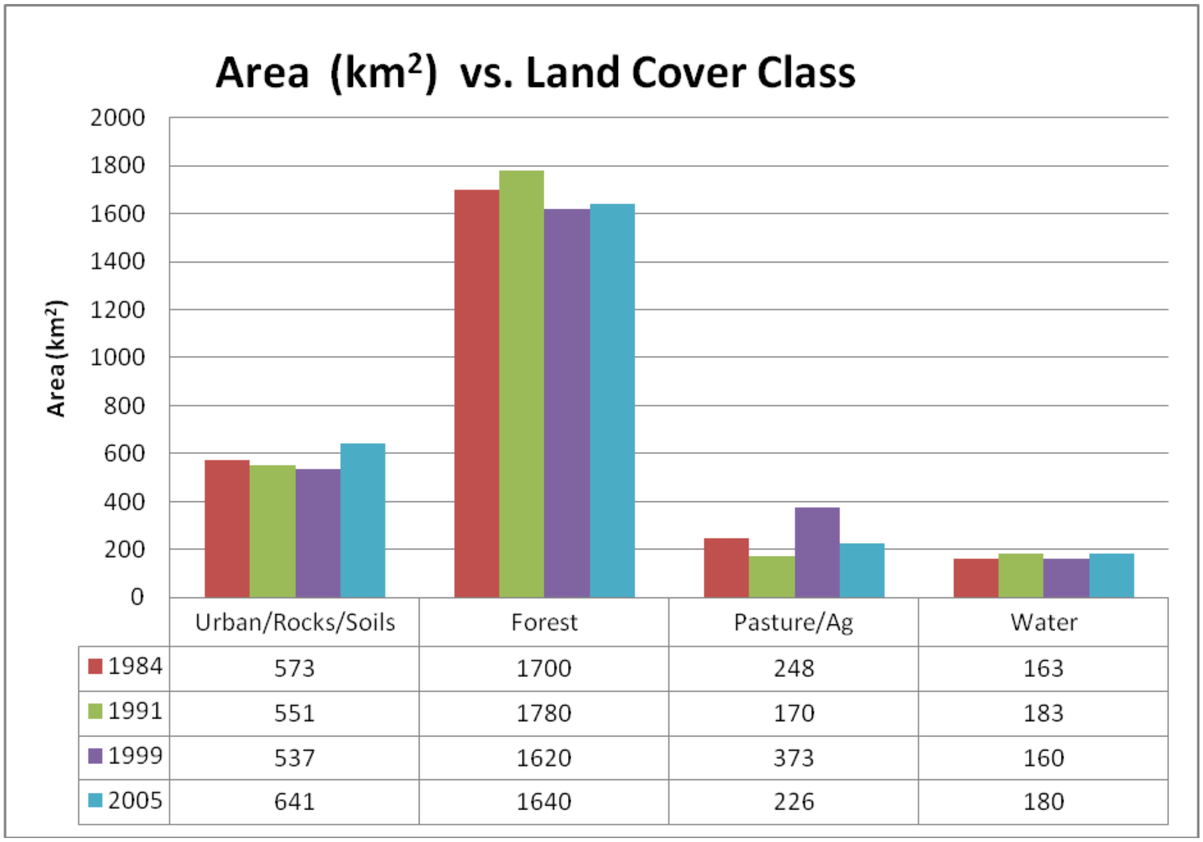


Figure 22: Lake Lanier Watershed LULC 2005



A breakdown of the areas of the land cover classes of the Lake Lanier watershed, for each of the years of this study can be represented as a histogram (Figure 23). There are some trends in the land cover that can be inferred from the area vs. land cover class histograms. The urban land cover shows an increase and the forest shows a decrease. The water surface area remains roughly the same for the period of this study. The change in the land cover class area from 1984 to 2005 and its impact on soil loss due to erosion will be analyzed in Chapter 5.

Figure 23: Area vs. Land Cover Class Histograms 1984, 1991, 1999, 2005



	Urban/Rocks/Soils	Forest	Pasture/Ag	Water
🟥 1984	573	1700	248	163
🟩 1991	551	1780	170	183
🟪 1999	537	1620	373	160
🟦 2005	641	1640	226	180

Comparison of 1991 and 1999 Land Cover Classification with USGS National Land Cover Data for 1992 and 2001

The National Land Cover Data (NLCD) was created by the USGS and is available for 1992 and 2001 (USGS Land Cover Institute, 2007). Both of these NLCD data sets have 21 land cover classes, percent tree canopy and percent imperviousness, all at 30-m spatial resolution and derived from Landsat imagery (Figure 24 and Figure 25). The NLCD data from 1992 and 2001 were subset to the Lake Lanier Watershed boundary and. These NLCD data from 1992 and 2001 were compared with the LULC derived for the watershed from Landsat imagery in 1991 and 1999, respectively. The NLCD LULC was reclassified into the four major land cover classes used in this study, for purposes of this comparison (Figure 26). The percent watershed area of each these four land cover classes was graphed verses each land cover type, resulting in percent area vs. land cover class histograms (Figure 27).

The percent area for the 'Water' class is roughly the same in all the land cover maps ranging from 5.5 to 6.8 percent of the Lake Lanier watershed area. The forest class in the 1991 Landsat derived LULC and the 1992 NLCD LULC is about 66 and 79 percent, respectively. The Forest class in the 1999 Landsat derived LULC and 2001 NLCD LULC is about 60 and 62 percent respectively. The greatest difference between the Landsat derived LULC and the NLCD LULC is in the 1991 urban/rocks/soils class. There is spectral mixing between the pasture/agriculture and the urban/rocks/soils classes that is very difficult to resolve, as will be discussed in the next section. However, since the LULC classes over roughly 80% or greater of the watershed area are the same on the NLCD and Landsat derived LULC, it will be shown later that the non-point

Figure 24: NLCD LULC 1992

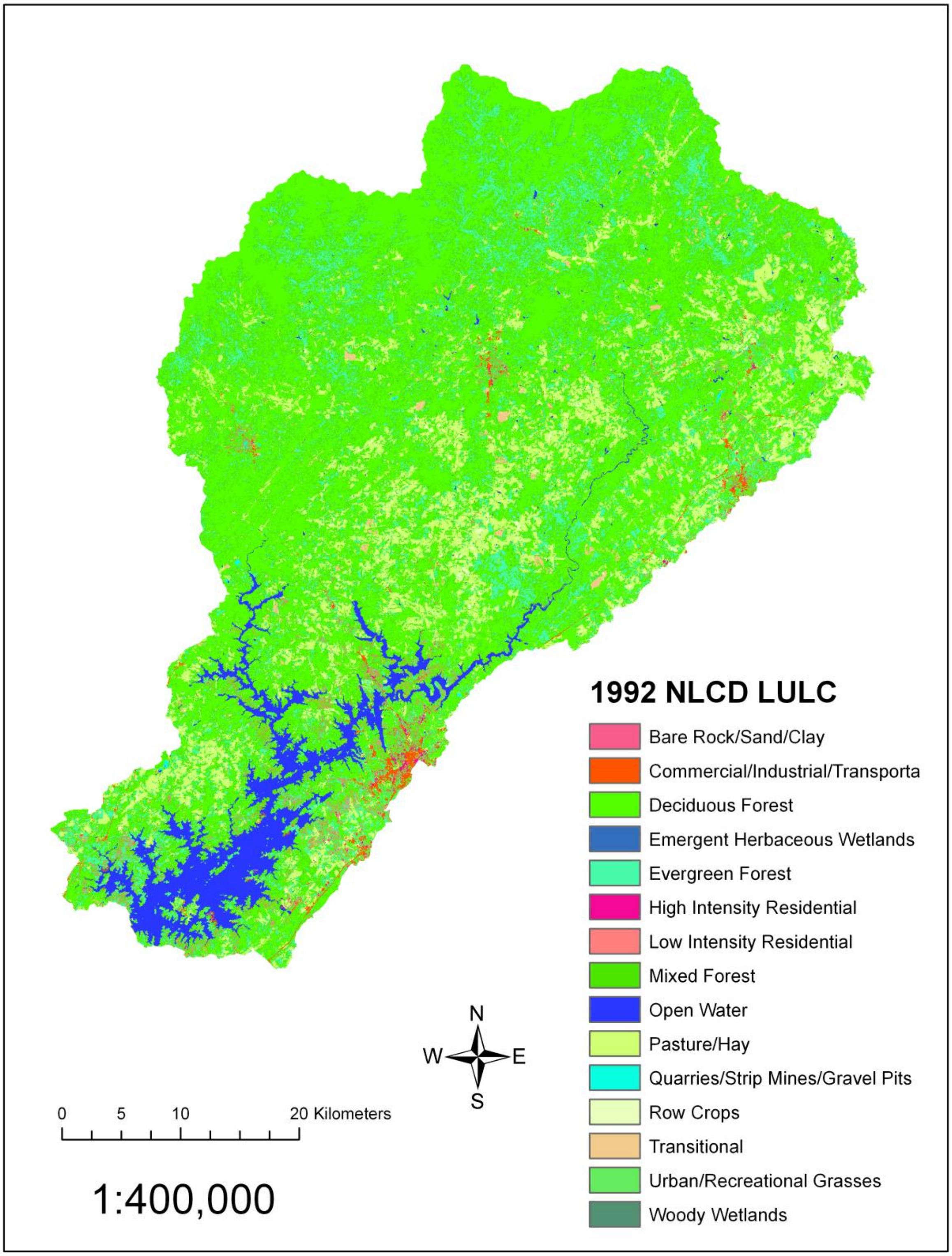
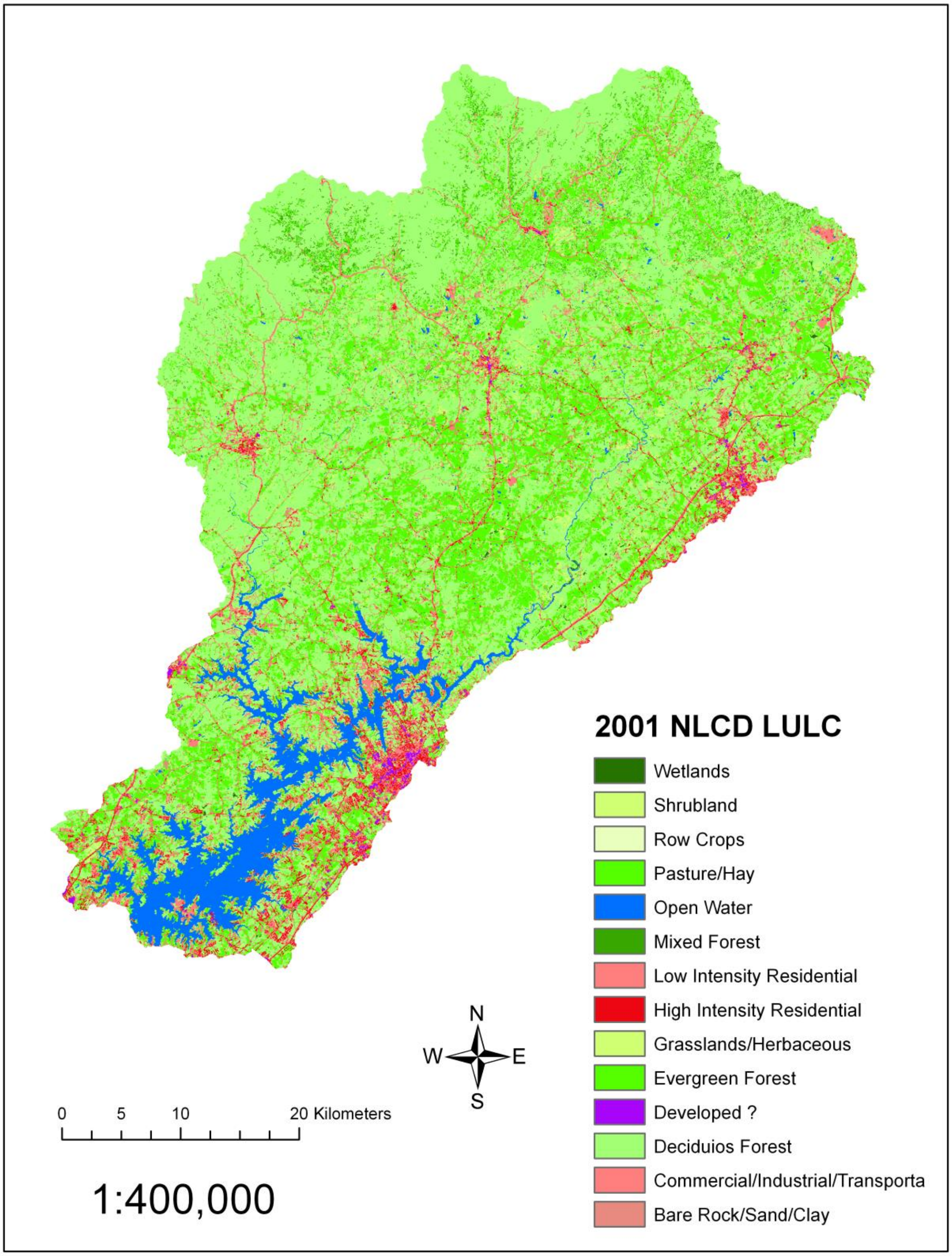


Figure 25: NLCD LULC 2001



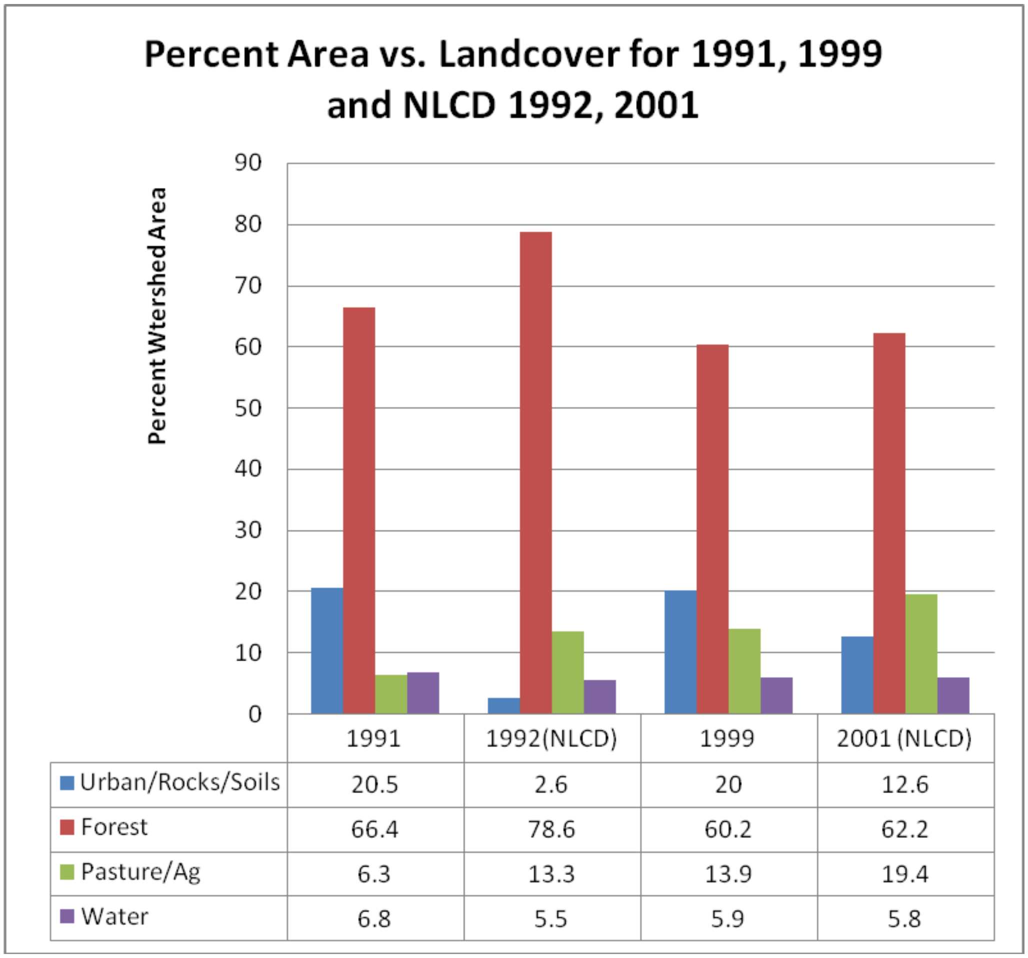
source USLE soil loss rates will be roughly similar for both the Landsat derived LULC and the NLCD LULC. This similarity in soil loss rates using the Landsat derived LULC and the USGS NLCD LULC will be analyzed in the following paragraphs.

Figure 26: Reclassification of NLCD LULC Class to the Four Major Land Cover Classes

	2001 NLCD LULC Class	Major Land Cover Class
0	Open Water	WATER
1	Low Intensity Residential	URBAN/ROCKS/SOILS
2	High Intensity Residential	
3	Commercial/Industrial/Transportation	
4	Developed ?	
5	Bare Rock/Sand/Clay	
6	Deciduous Forest	FOREST
7	Evergreen Forest	
8	Mixed Forest	
9	Shrubland	PASTURE/AGRICULTURE
10	Grasslands/Herbaceous	
11	Pasture/Hay	
12	Row Crops	
13	Wetlands	
14	Woody Wetlands	

The percent change for each land cover class from 1991 to 1999 in the Landsat derived LULC, and from 1992 to 2001 NLCD LULC is summarized in a table (Table 3). The percent change trends in both the Landsat derived and the NLCD LULC maps show similarities for most classes. The Water class remains roughly the same while the Forest class decreases 6 and 16 percent in the Landsat derived and the NLCD LULC, respectively. It is noteworthy that both the sets of data show about the same increase of pasture area of 7.6 percent by the Landsat derived LULC and of 6 percent by the NLCD data. This is significant, as the Pasture/Agriculture class has the largest land cover USLE C-factor of 0.25, which is much larger than the next largest C-factor of 0.01 for the Urban/Rocks/Soil class. This implies that there will be a significant increase in the USLE modeled soil loss rate from the early to the late 1990's, using both the Landsat derived and the NLCD LULC. This will be borne later out by the results of the erosion modeling.

Figure 27: Percent Area vs. Landcover for 1991, 1999 and for NLCD 1992, 2001



	1991	1992(NLCD)	1999	2001 (NLCD)
🟦 Urban/Rocks/Soils	20.5	2.6	20	12.6
🟥 Forest	66.4	78.6	60.2	62.2
🟩 Pasture/Ag	6.3	13.3	13.9	19.4
🟪 Water	6.8	5.5	5.9	5.8

It is also noteworthy that there is a large discrepancy between the 1991 Landsat derived LULC and the 1992 NLCD for the Urban/Rocks/Soils class, at 20 percent and 2.6 percent respectively. This is most likely due to the fact that bare agricultural fields in the September 1991 Landsat image will be classified as Urban/Rocks/Soils. Whereas, in the 1992 NLCD, the agricultural fields will be classified as agriculture, as the LULC is derived from both leaf on and leaf off imagery.

Table 3: Percent Change in Land Cover for 1991 and 1999 Landsat Derived LULC, and for NLCD 1992 and 2001

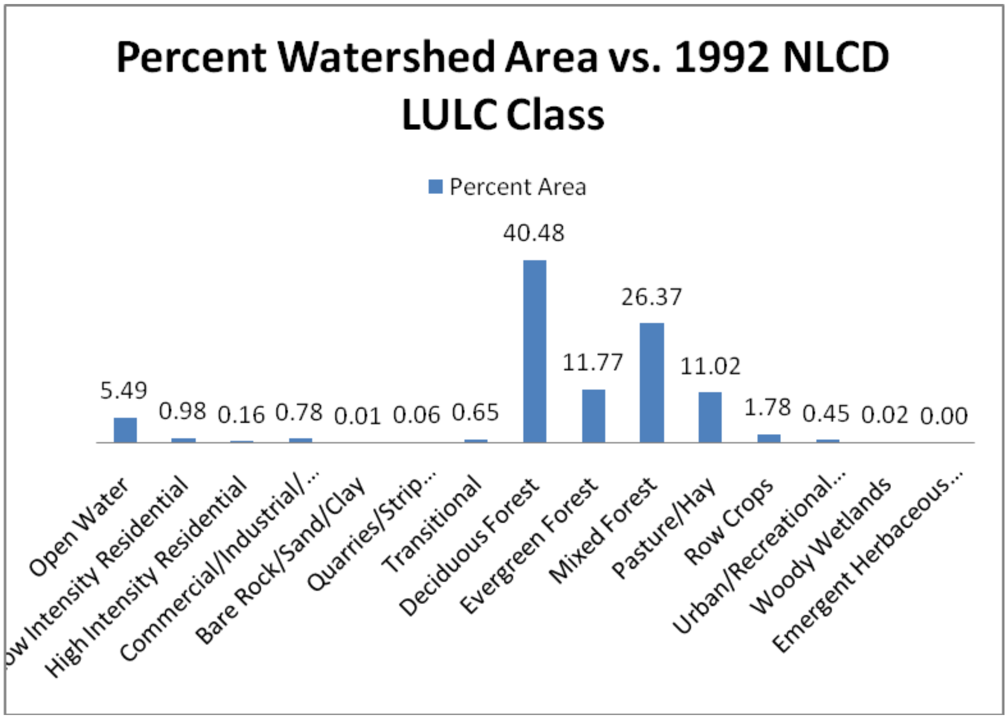
LULC Class	**Landsat Derived 1991**	**Landsat Derived 1999**	**Percent Change**	**NLCD 1992**	**NLCD 2001**	**Percent Change**
U/R/S	20.5	20.0	**-0.5**	2.6	12.6	**+10.0**
Forest	66.4	60.2	**-6.2**	78.6	62.2	**-16.4**
Pasture/Ag.	6.3	13.9	**+7.6**	13.3	19.4	**+6.1**
Water	6.8	5.9	**-0.9**	5.5	5.8	**+0.3**

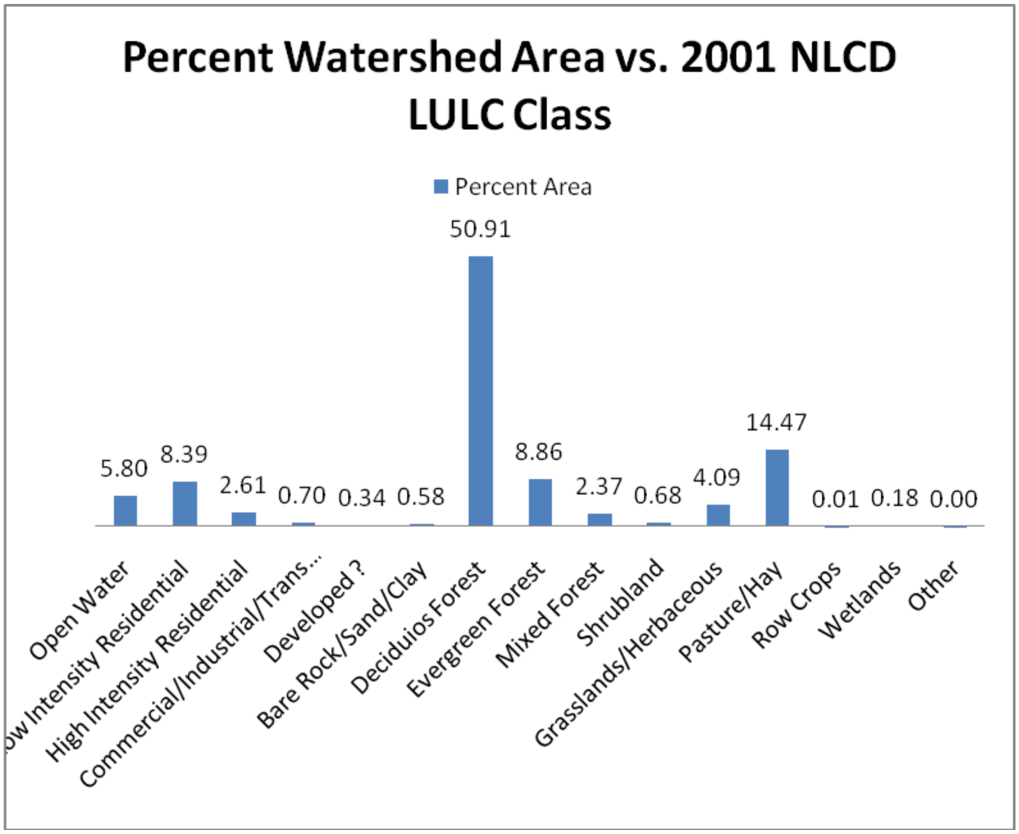
The USLE land cover and management C-factor is assigned to each land cover class based on the previous USLE erosion study by the USGS (Faye et al. 1980, p 49). In this study, the Pasture class has a C-factor value of 0.07 and Agriculture has a C-factor value of 0.52. It is not possible to spectrally distinguish between vegetated agricultural fields and pasture using methods of supervised classification on multispectral imagery. Therefore, both of these land cover types were treated as the same land cover class of Pasture/Agriculture. From the land-cover subsets of the 1992 and 2001 NLCD for the Lake Lanier watershed, histograms of the area vs. land cover class shows pasture area to be several-fold (> 5 times) greater than cultivated row crop area (Figure 28). Since the ratio between agricultural land and pasture is not known for the Lake Lanier watershed for all the years of this study, the C-factor is set to 0.25. This is similar to the reasoning for the C-factor for Pasture/Agriculture by Semerjian and Williams (2001) in their USLE erosion modeling of the Soque River Watershed, which is a subset of the Lake Lanier watershed. Substantial ground-truthing by fieldwork and air-photos would be needed to accurately establish the land-cover of the Lake Lanier watershed such that the C-factors can be accurately assigned to each land cover class. For this study, the C-factors for the four major land cover classes are assigned as shown in the Table 4. Of these land cover classes, it is noteworthy that USLE soil erosion is the most dependant on the class of pasture/agriculture, as its C-factor of 0.25 is more than an order of magnitude greater than the next largest C-factor.

Table 4: C-Factors for the Four Major Land Cover Classes in the Lake Lanier Watershed

Land Cover Class	C-factor
Urban/Rocks/Soils	0.01
Pasture/Agriculture	0.25
Forest	0.001
Water	0.0

Figure 28: Percent Watershed Area vs. 1992 and 2001 NLCD LULC Class





2005 Land-Cover Accuracy Assessment

Performance of a supervised classification of the Landsat images with eCognition yielded credible land cover maps. This was initially ascertained by overlaying the original image on the map and detailed visual inspection using the Erdas Imagine ‘swipe’ and ‘flicker’ utilities. An accuracy assessment of the 2005 land cover map was carried out and an error matrix was constructed. The 2005 National Agricultural Imagery Program (NAIP) 1-m resolution color images was used as a reference to ‘ground truth’ the 30-m spatial resolution land cover map. Two hundred and fifty six points were chosen at random and were geographically stratified across the 2005 land cover map. Each of these points was then checked for the type of land cover on the higher spatial resolution 1-m color 2005 NAIP imagery. The results of this accuracy analysis indicate an overall accuracy of 80.3 percent (Table 5). Although there is further room for the refinement of the land cover maps using other measures in conjunction with spectral signatures such as texture, proximity, shape and fieldwork, this accuracy is acceptable for use of the classified land cover for erosion modeling in this large area watershed.

During this comparison of the spectrally derived land cover map and the high resolution color airphotos, spectral mixing between some classes was apparent. The bare soil at agricultural farms was spectrally indistinguishable from urban structures, and in many instances was erroneously classified as such. This was true only in the cases where the agricultural soil was bare and with no vegetation on it and this was a small portion of the farm land. Therefore, the soil erosion rate will be underestimated by this model as many farms with bare soil are misrepresented as urban. The land cover USLE C-factor for urban cover is much lower in USLE erosion modeling as opposed to the C-factor for bare soil. For this reason, in the accuracy assessment, the Urban/Rocks/Soils classification has the lowest producers and users accuracies and Kappa statistic.

The overall accuracy is calculated by dividing the total number of correctly classified pixels by the total number of reference pixels (Table 5). The producer's accuracy is the number of correctly classified pixels in a category divided by the total number of pixels used in the training set used for that category. The user's accuracy is the total number of correctly classified pixels in each category by the total number of pixels classified in that category. The Kappa statistic is used as a measure of agreement of the classified map with the actual terrain (Table 6). This statistic serves as an indicator of the extent to which the percentage of correct values of an error matrix are due to 'true' agreement verses 'chance' agreement (Lillesand and Kiefer 1999).

Table 5: 2005 Land Cover Classification Error Matrix Generated by ERDAS Imagine

Training Set Data (Known Cover Types)					
Classification Data	**Urban/Rocks/Soils**	**Forest**	**Pasture/Agriculture**	**Water**	**Row Total**
Urban/Rocks/Soils	29	7	12	0	48
Forest	10	147	10	0	167
Pasture/Agriculture	1	1	15	0	17
Water	0	1	1	22	24
Column Total	41	156	37	22	256

Class Name	**Producers Accuracy**	**Users Accuracy**
Urban/Rocks/Soils	29/41 = 70.7 percent	29/48 = 78.7 percent
Forest	147/156 = 94.2 percent	147/167 = 88.0 percent
Pasture/Agriculture	15/37 = 40.5 percent	15/17 = 88.2 percent
Water	22/22 = 100 percent	22/24 = 91.7 percent
Overall Accuracy = (29+147+15+22) / 256 = 80.3 percent		

Table 6: Kappa Statistics for Land Cover Classification Accuracy Assessment

Conditional Kappa for each Land Cover Class	
Urban/Rocks/Soils	0.529
Forest	0.693
Pasture/Agriculture	0.863
Water	0.909
Overall Kappa Statistics = 0.697	

Digital Elevation Model (DEM) Processing for the Length-Slope Factor in USLE Erosion Modeling

The primary driver for the rainfall runoff is the terrain relief and slope. The greater the slope of the surface, the greater the kinetic energy imparted to the surface water flow. The longer the length of the flow, the more sediment can be transported. Therefore, both the length of flow and the slope of a plot land are directly related to the amount of soil eroded. In the USLE, the effects of both length of flow on a plot and the slope of a plot are combined into one factor known as the length-slope or the LS factor. The USLE (Wischmeier and Smith, 1965) length-slope (LS) factor is given by the following equation:

$$LS = \left(\frac{\lambda}{72.6}\right)^{m} (65.41 \sin^2\theta + 4.56 \sin\theta + 0.065) \qquad \text{Equation 2}$$

Where λ = length of the plot in ft

θ = angle of slope

$m = 0.5$ when $\sin\theta > 0.1$

$m = 0.6$ when $\sin\theta < 0.1$

This particular version of the USLE was used in this project as it is the same as the version used by Faye et. al (1980) in the first erosion and sedimentation study of the Lake Lanier watershed in the late 1970's. Estimates of sediment discharge based on this non-point source USLE modeling will be compared with both the results of Faye et al. (1980) and Leigh et al. (1998). This spatially distributed modeling is performed with the watershed subdivided into a grid of 30 m x 30 m cells each associated with a homogeneous land cover, soil type and slope. The slope and the aspect of these adjacent grid cells determine the hydrological routing of the runoff. This eventually defines the spatial patterns of the soil erosion and deposition. Since the USLE calculation is done for each 30 m x 30 m grid cell, the length of flow λ is taken to be 30 m or 98.4 ft.

The digital elevation models (DEM's) for the counties included in the Lake Lanier watershed were downloaded from the National Map Seamless Server Website (USGS 2007) and then mosaiced together using Leica Imagine software. This DEM mosaic served as the input into the erosion model in ArcGIS 9.2. The DEM is clipped to the watershed boundary and then the slope is calculated for each grid cell in degrees (Figure 29). The Sine of the slope angle in degrees is evaluated to give a raster that is known as the 'percent slope'. As is apparent from equation 2, the soil erosion rate has a quadratic dependence on the percent slope (Sin θ) term. This means that the soil erosion rate is the most sensitively dependent on the percent slope of the terrain. The length slope LS-factor raster was calculated using equation 2 (Figure 30).

The USLE Rainfall Runoff R-factor and Crop Management Practice P-factor

The rainfall runoff is dependent on the energy of the rainfall, its intensity and its duration. The R-factor is an indicator of the average annual rainfall runoff from the terrain. This is used to estimate the average annual soil loss rate for the study area. The R factor is equal to the energy-intensity (EI) index which can be calculated for an individual rainfall event or over any given duration of interest (USDA 1978). The EI index value for a particular rainstorm event is the product of the total storm energy E (in hundreds of ft-tons per acre) times I_{30} , which denotes the maximum 30- minute intensity of the storm (inches/hour). Local values of the rainfall erosion index can be derived from isoerodent maps (USDA 1978). The annualized R-factor for the Lake Lanier watershed is 340. This value is predicated upon an annual rainfall equivalent to a long term average rainfall for a particular region. However, in the case of lower than average rainfall, the actual erosion may actually increase due to decreased foliage in drought conditions. These effects are not accounted for in this modeling study.

The crop management practice P-factor refers to the tillage practices used in agricultural plots. The P-factor for the Lake Lanier watershed is not known for the specific times the satellite imagery for the land-cover was acquired. Therefore the impact of agricultural tillage and crop management practices is not accounted for in this study and the P-factor value is set to 1.

Figure 29: Lake Lanier Watershed Slope in Degrees

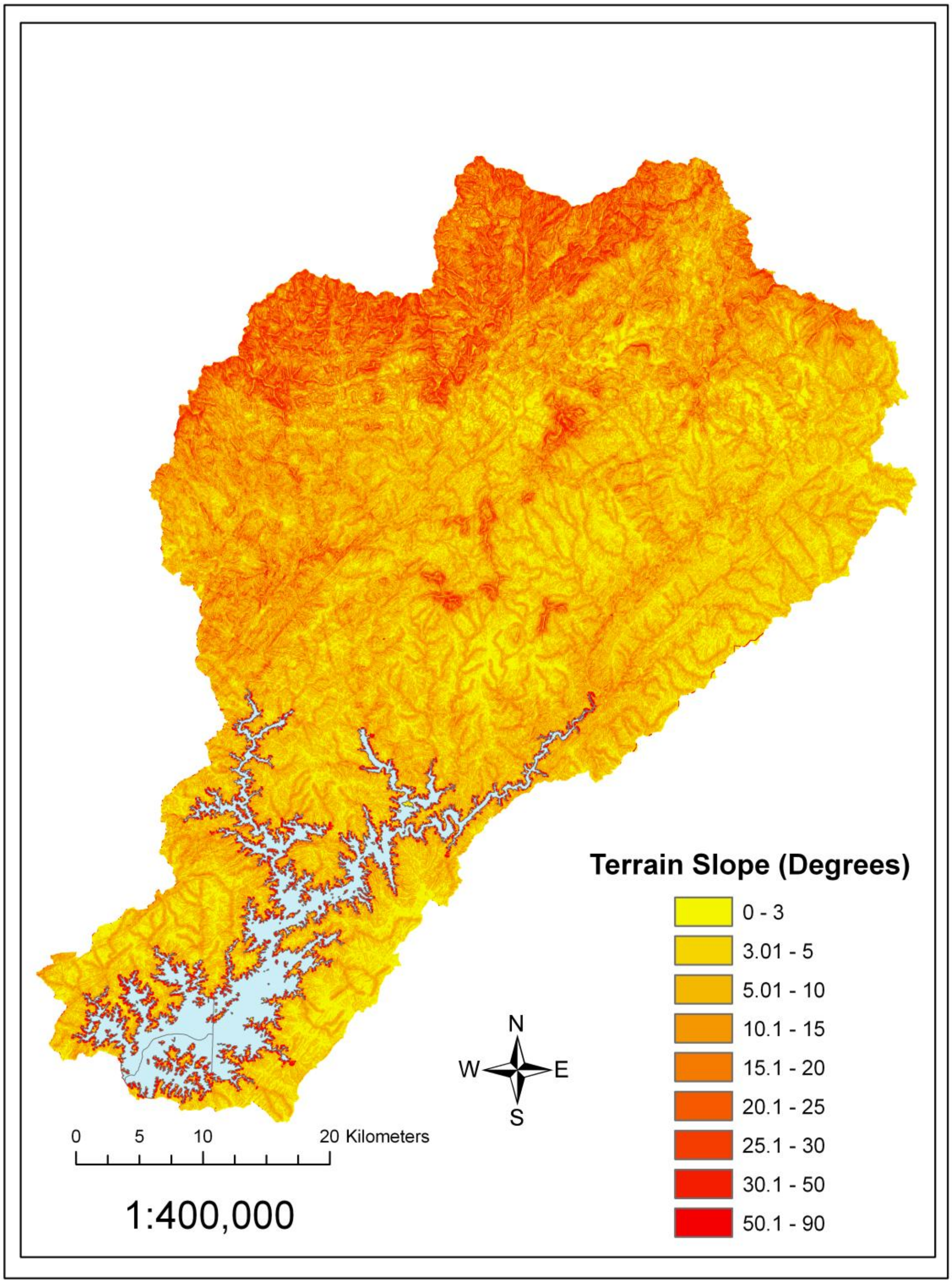
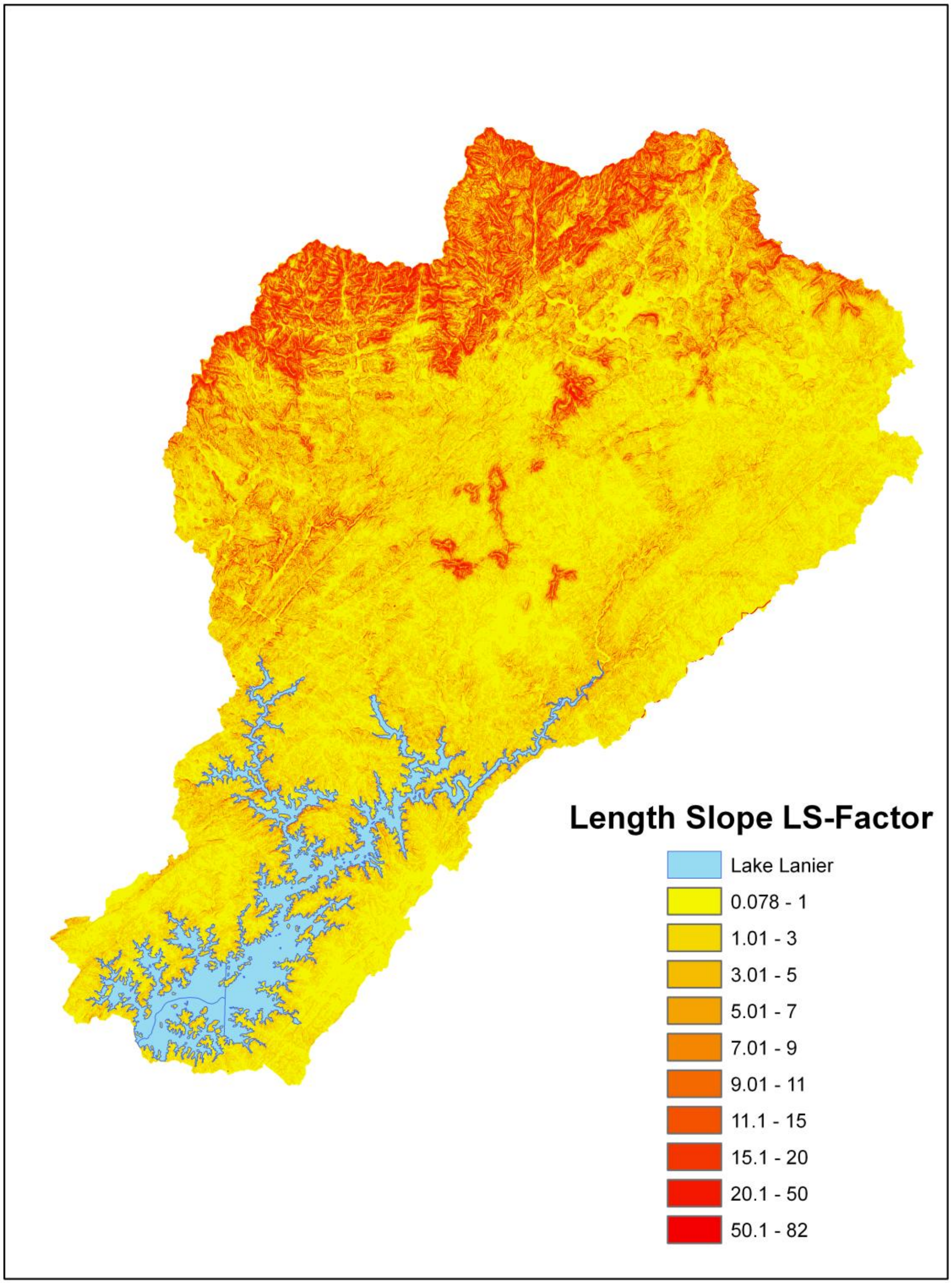


Figure 30: Lake Lanier Watershed Length Slope LS Factor



Soil Erosion Modeling Results for 1984, 1991, 1992, 1999, 2001 and 2005

The erosion and sediment modeling was performed using the ArcGIS spatial analysis functions and the Model Maker. Arc Objects are a library of software components that embody the functionality of the ArcGIS environment. The Model Maker is a visual programming environment in which Arc Objects functionality can be organized and integrated together in a flowchart-like manner. Once the sequence of operations is established and fully debugged, it can be saved as a model in ArcTools and can be used by others with the same or different data layers in an ArcGIS environment. The models can be also be exported in different computer languages such as VPython and Visual Basic, and can then be modified by other users if needed. The ArcGis Model developed for the USLE soil erosion modeling is shown in the Figure 31.

The USLE ArcGIS model begins with the mosaiced DEM raster of the counties in the Lake Lanier watershed, which is input to the Slope function in the Spatial Analyst – Surface Toolbox. This results in a raster representing the slope of each 30 m x 30 m grid-cell in degrees. The units of the slope raster are converted to radians and then the sine of the slope angle is evaluated to create the ‘sin θ’ or the percent slope raster. This percent slope raster is then used in the calculation of the USLE length-slope LS-factor, as given by equation 2. The product of the length-slope LS factor, land cover C-factor, soil erodibility k-factor and the rainfall R-factor gives the USLE soil erosion for a particular grid-cell at a particular Earth surface location.

Figure 31: ArcGIS 9.2 Model for USLE Soil Erosion
(Entire USLE Model is Represented in Four Overlapping Sub-Figures a,b,c,d)

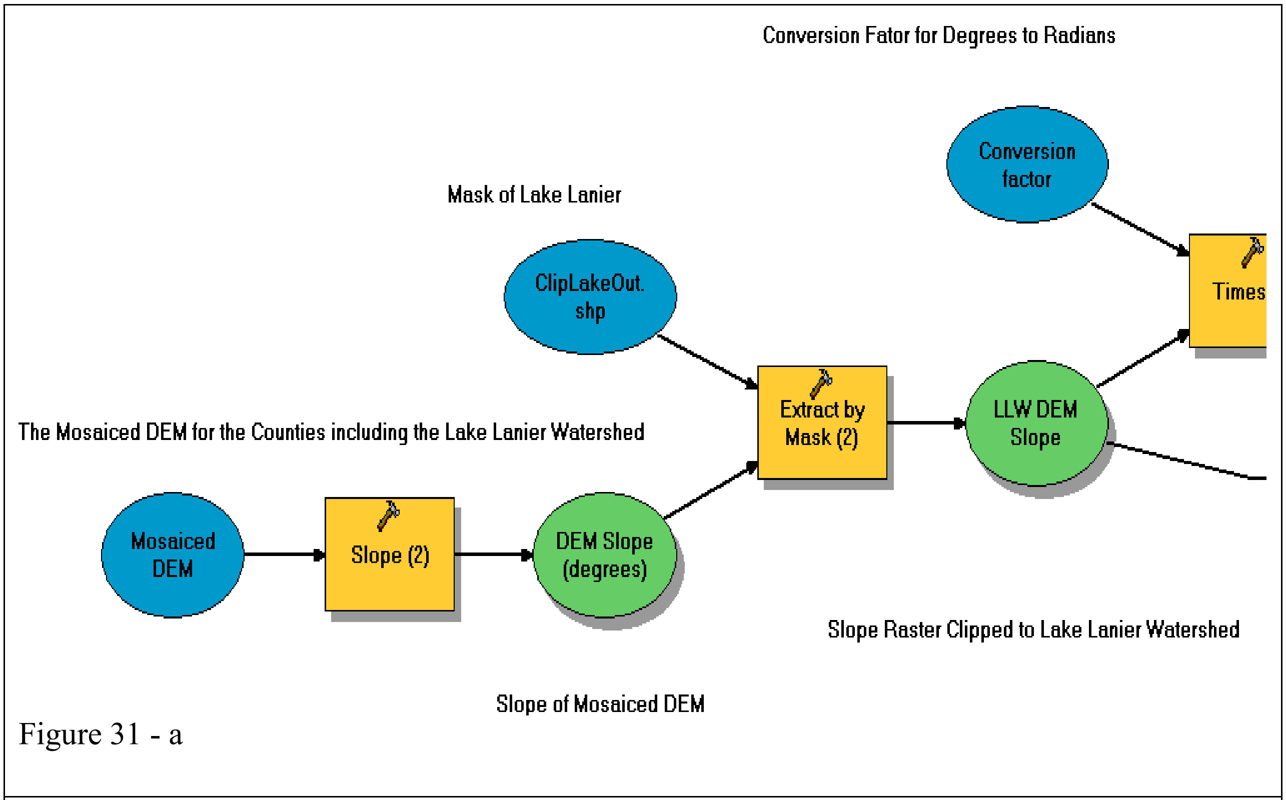


Figure 31 - a

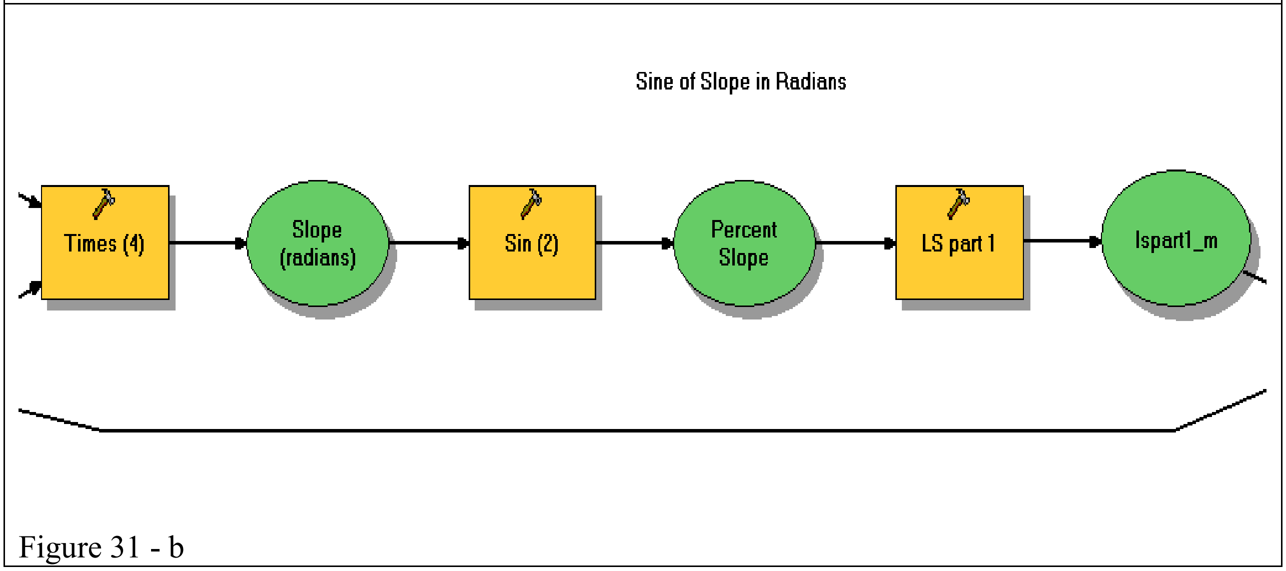


Figure 31 - b

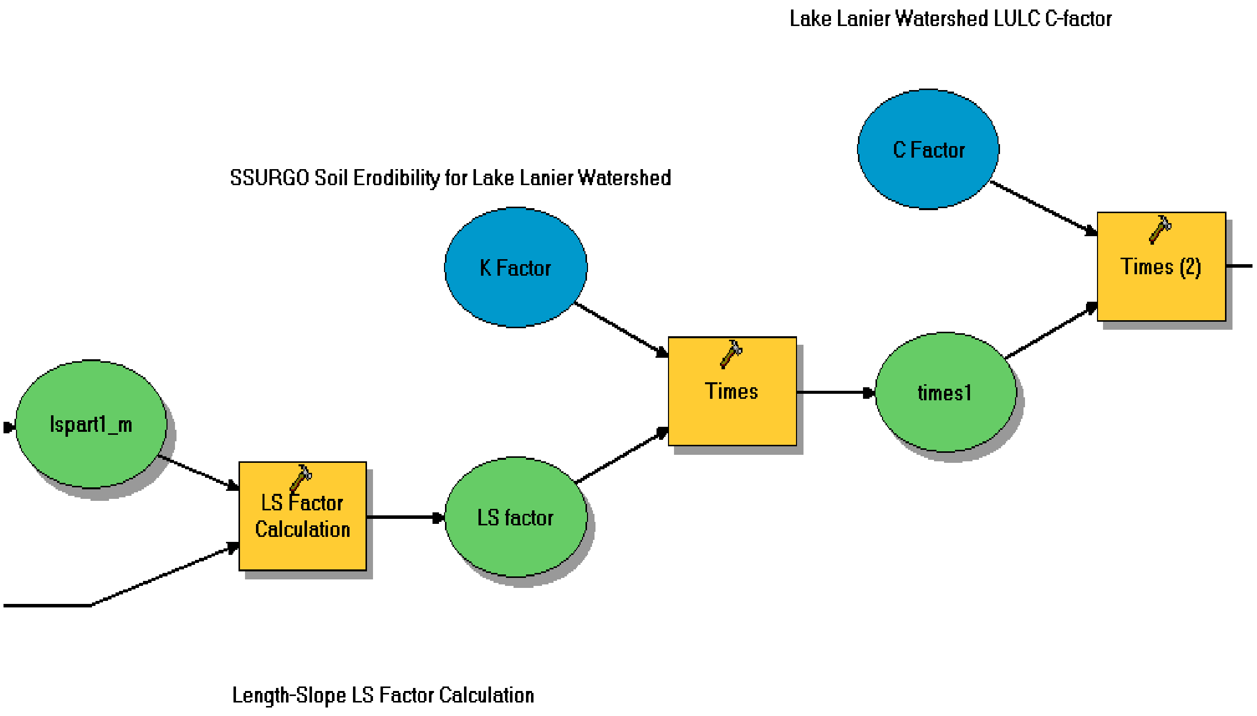


Figure 31 - c

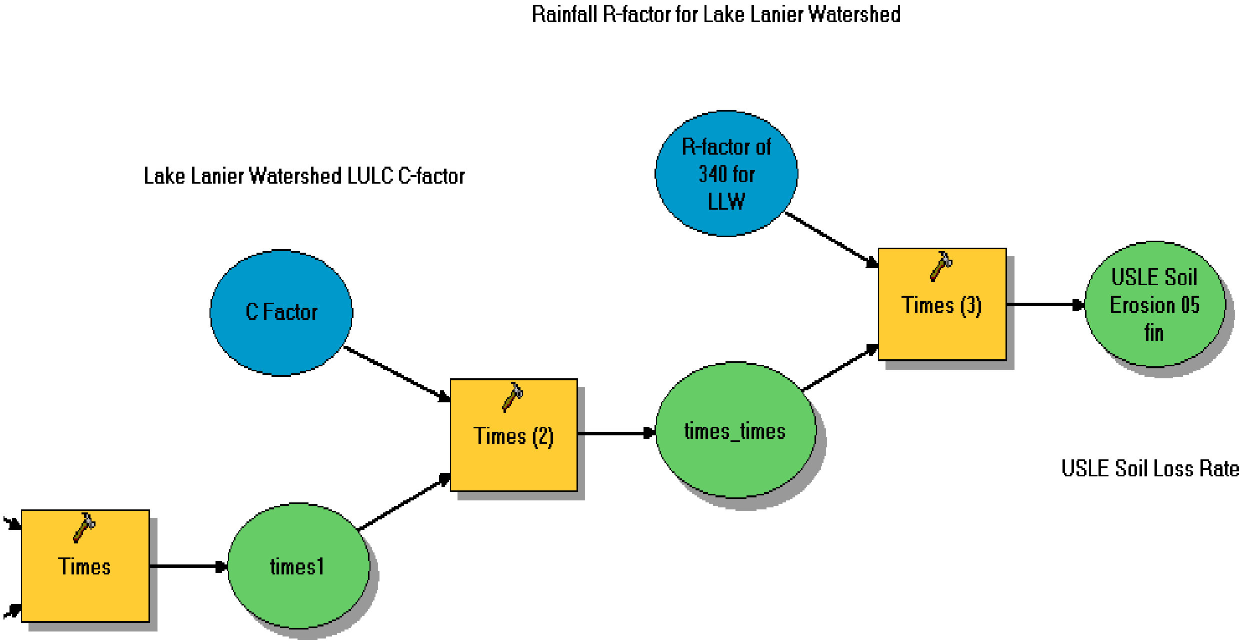


Figure 31 - d

The USLE based erosion, or soil loss rate, in tons/acre/year was calculated for each 30 m x 30 m grid cell in the Lake Lanier watershed. In addition to watershed scale representation of the spatial calculations, a higher scale close up of the non point source erosion and sedimentation results and analysis is also presented for clarity (Figure 32).This is the first time a spatially distributed USLE based non-point source erosion modeling has been performed for this watershed (Figure 33 through 38). The calculations in the 1984 distributed non-point source erosion modeling are compared to the lumped USLE erosion modeling results made by Faye et al. (1980) on the primary Lake Lanier sub-watersheds of the Upper Chattahoochee, Chesatee and the Soque Rivers in the analysis of the results in Chapter 5. The non-point source erosion modeling results are summarized in Table 7. The soil erosion rate in the Lake Lanier watershed ranges from a minimum of 1.52 tons/acre/year in 1991 to a maximum of 3.71 tons/acre/year in 1999. The calculated total erosion soil loss in the watershed ranges from approximately 1 million tons/year in 1991 and 2 million tons /year in 1999. The maximum values of the soil loss rates are about 3000 tons/acre/year due to the high slopes on portions of this hilly watershed and are interpretable as describing regions with possibly extreme soil loss rates.

It is noteworthy that the average annual USLE soil loss rate calculated with the NLCD LULC for 1992 is 2.73 tons/acre/year compared to 1.52 tons/acre/year calculated with the 1991 Landsat imagery derived LULC. Similarly, the soil loss rate calculated with the 2001 NLCD LULC is 3.21 tons/acre/year compared to 3.71 tons/acre/year for the Landsat imagery derived LULC. The 1984 USLE Soil loss rate calculated with the older STATSGO soil data is 3.04 tons/acre/year compared with the soil loss rate of 2.30 tons/acre/year obtained by using the more recent and detailed SSURGO soil data.

Table 7: Average Annual Spatially Distributed USLE Modeling Based Soil Erosion (tons/acre/year) in the Lake Lanier Watershed for 1984-2005

	1984 SSURGO Soils Landsat LULC	**1984** STATSGO Soils Landsat LULC	**1991** SSURGO Soils Landsat LULC	**1992** SSURGO Soils NLCD LULC
USLE Soil Loss Rate	2.30 tons/acre/year	3.04 tons/acre/year	1.52 tons/acre/year	2.73 tons/acre/year
Total	1.45 x 10^6 tons	1.88 x 10^6 tons	0.954 x 10^6 tons	1.72 x 10^6 tons
Standard Deviation	14.1 tons/acre/year	16.8 tons/acre/year	10.2 tons/acre/year	16.1 tons/acre/year
Max	2538 tons/acre/year	2196 tons/acre/year	1818 tons/acre/year	2175 tons/acre/year

	1999 SSURGO Soils Landsat LULC	**2001** SSURGO Soils NLCD LULC	**2005** SSURGO Soils Landsat LULC
USLE Soil Loss Rate	3.71 tons/acre/year	3.21 tons/acre/year	2.19 tons/acre/year
Total	2.33 x 10^6 tons	2.03 x 10^6 tons	1.37 x 10^6 tons
Standard Deviation	18.3 tons/acre/year	14.6 tons/acre/year	11.6 tons/acre/year
Max	2617 tons/acre/year	2524 tons/acre/year	1633 tons/year/year

Figure 32: Close Up Region for Erosion and Sedimentation Results and Analysis

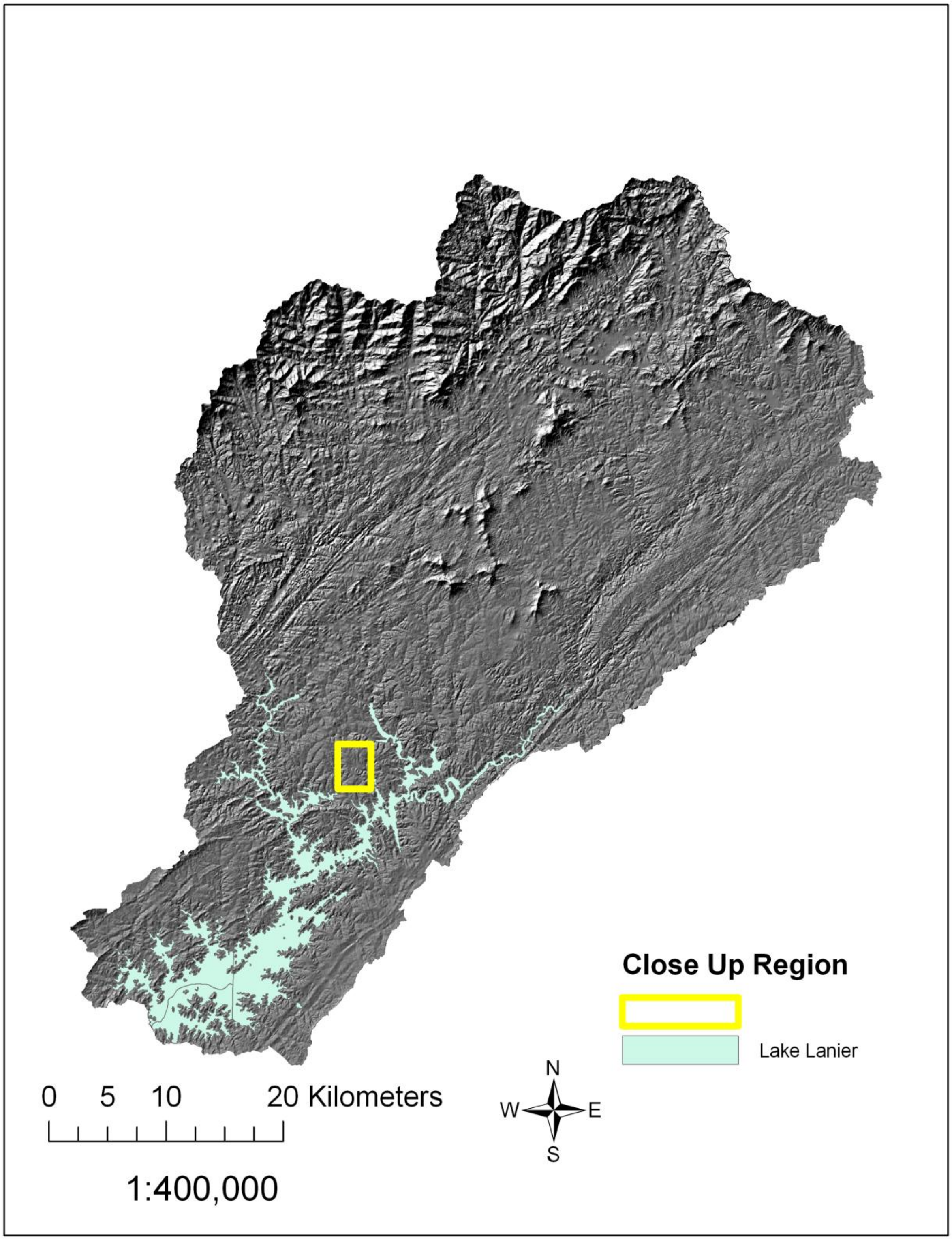


Figure 33a: USLE Based Soil Erosion (tons/acre/year) for 1984

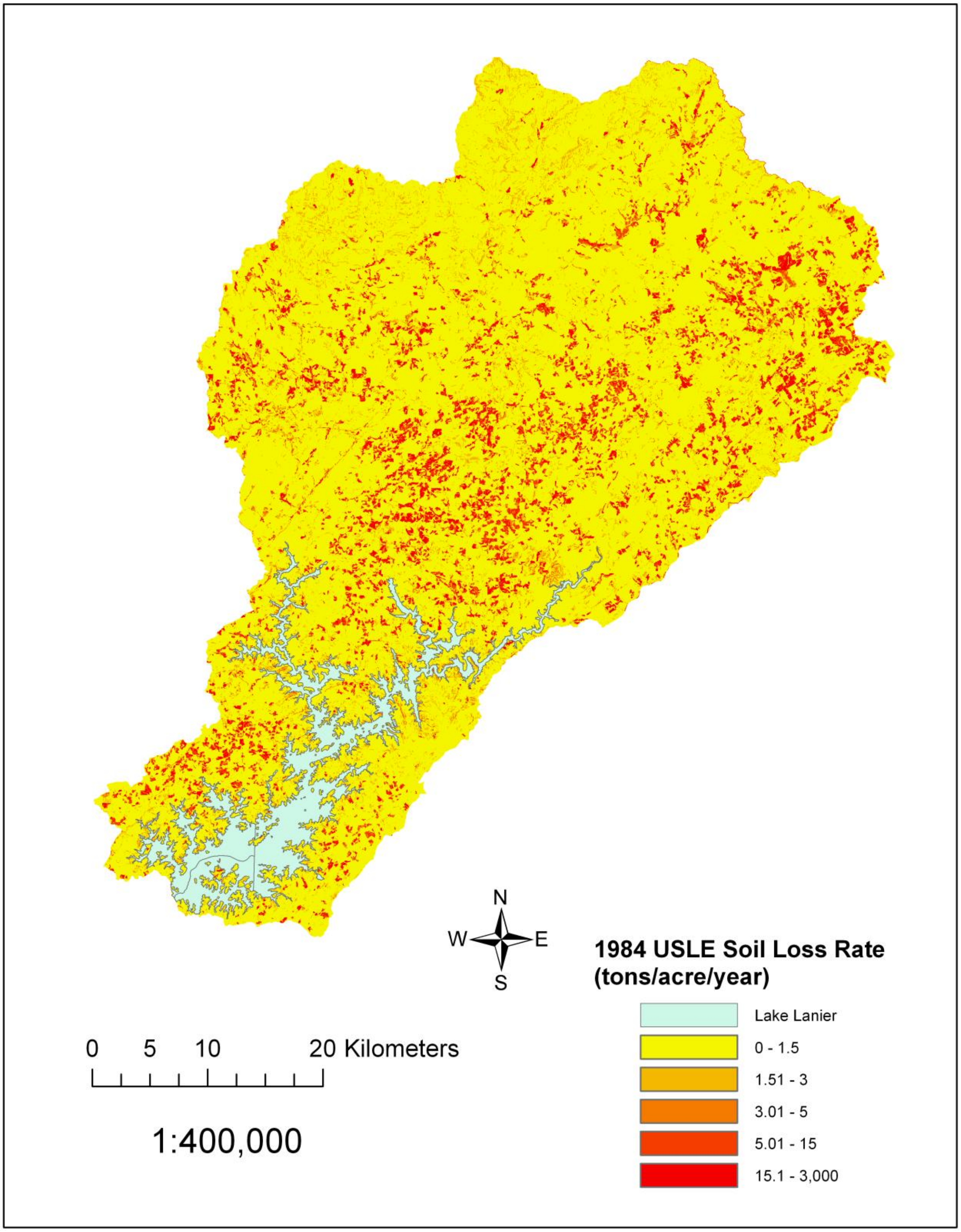


Figure 33b: USLE Based Soil Erosion (tons/acre/year) for 1984 Close Up

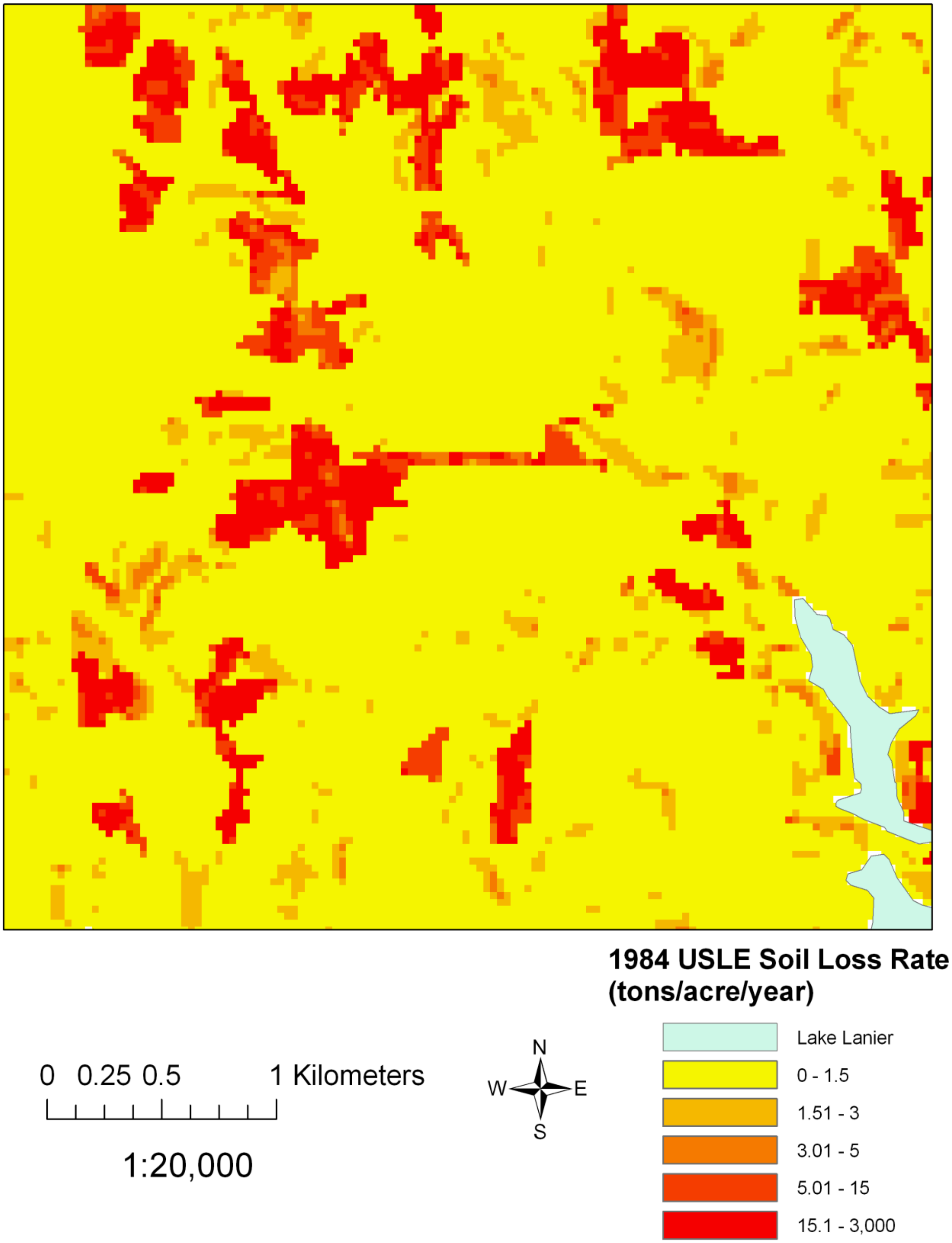


Figure 34a: USLE Based Soil Erosion (tons/acre/year) for 1991

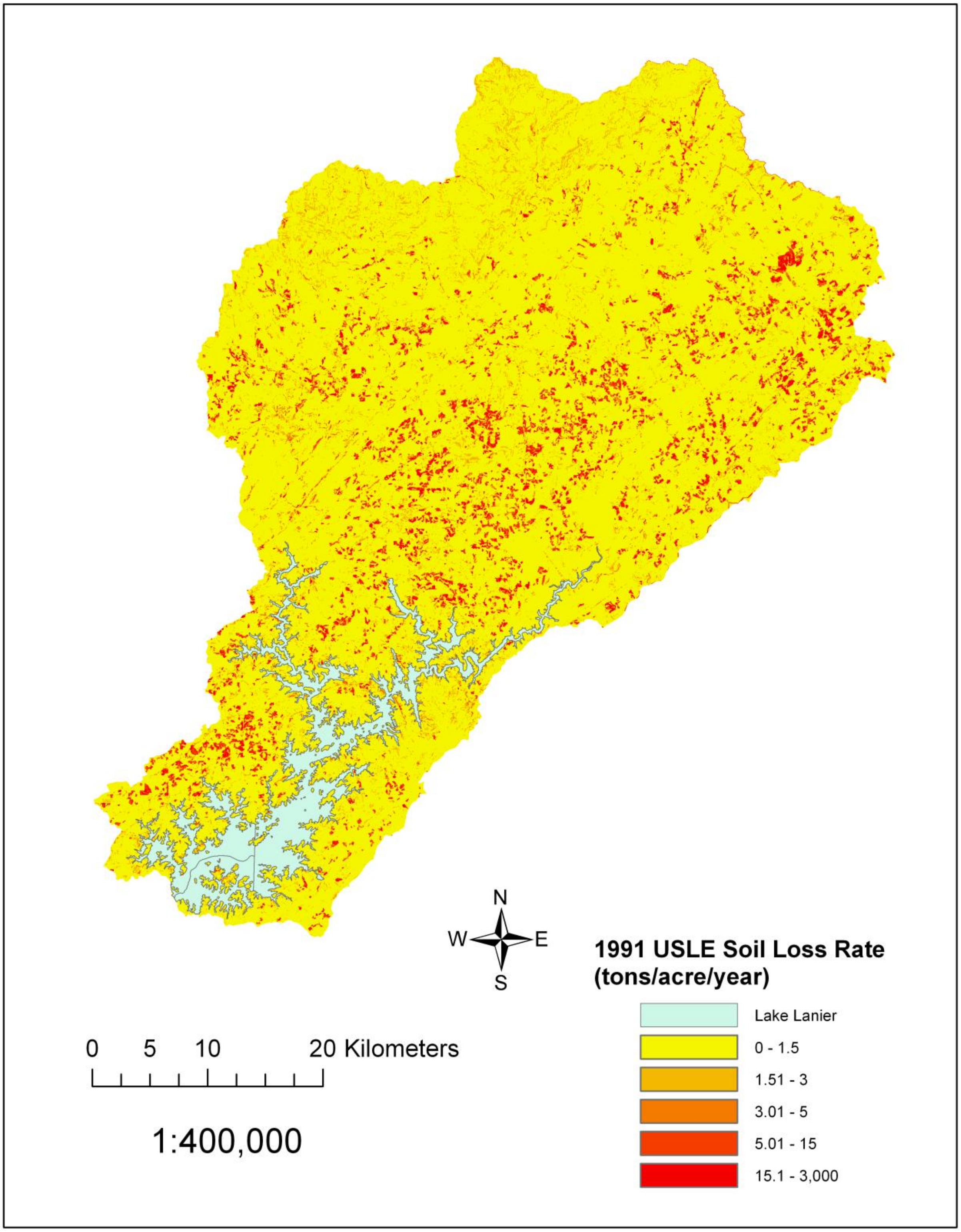


Figure 34b: USLE Based Soil Erosion (tons/acre/year) for 1991 Close Up

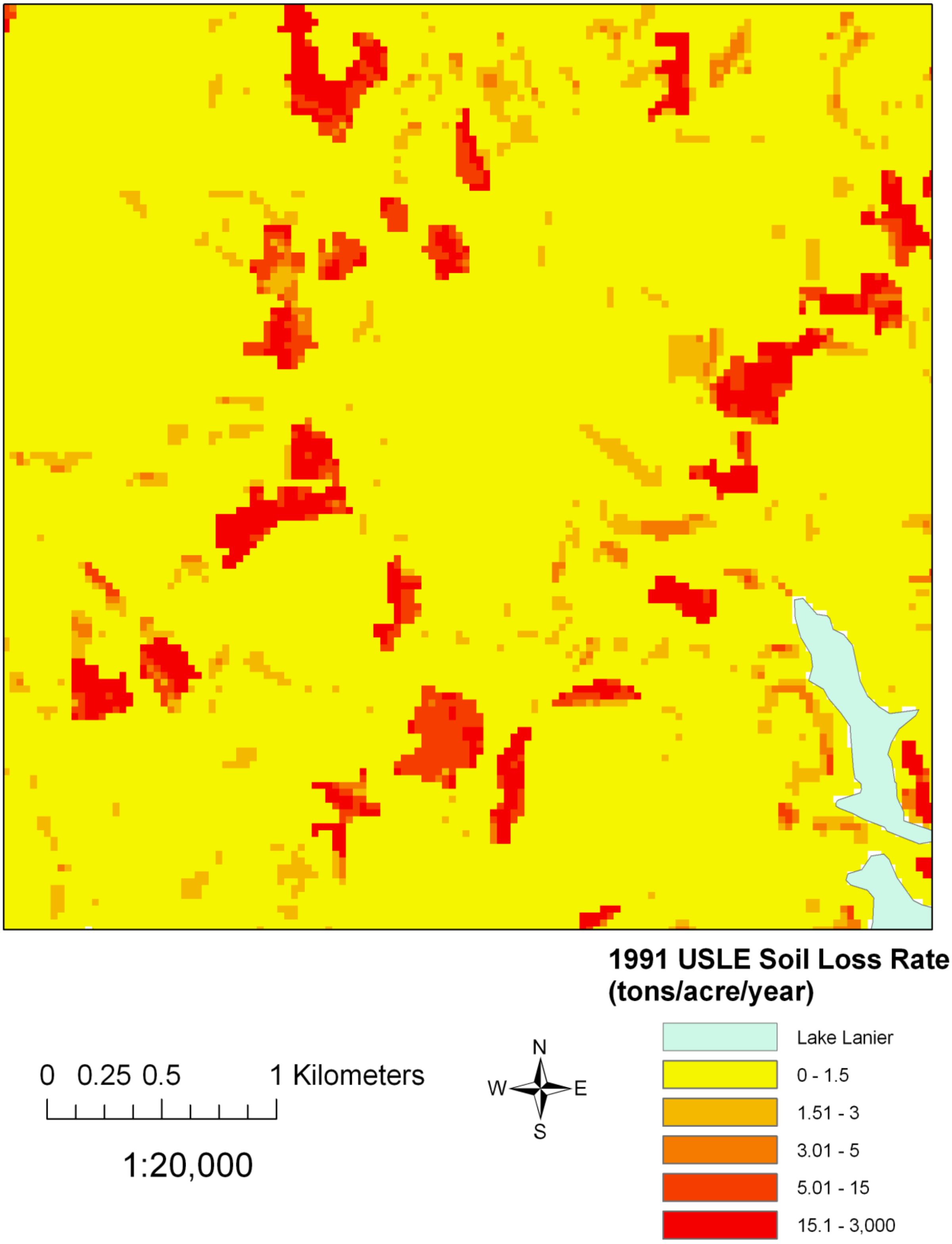


Figure 35a: USLE Based Soil Erosion (tons/acre/year) for 1992 (NLCD Based)

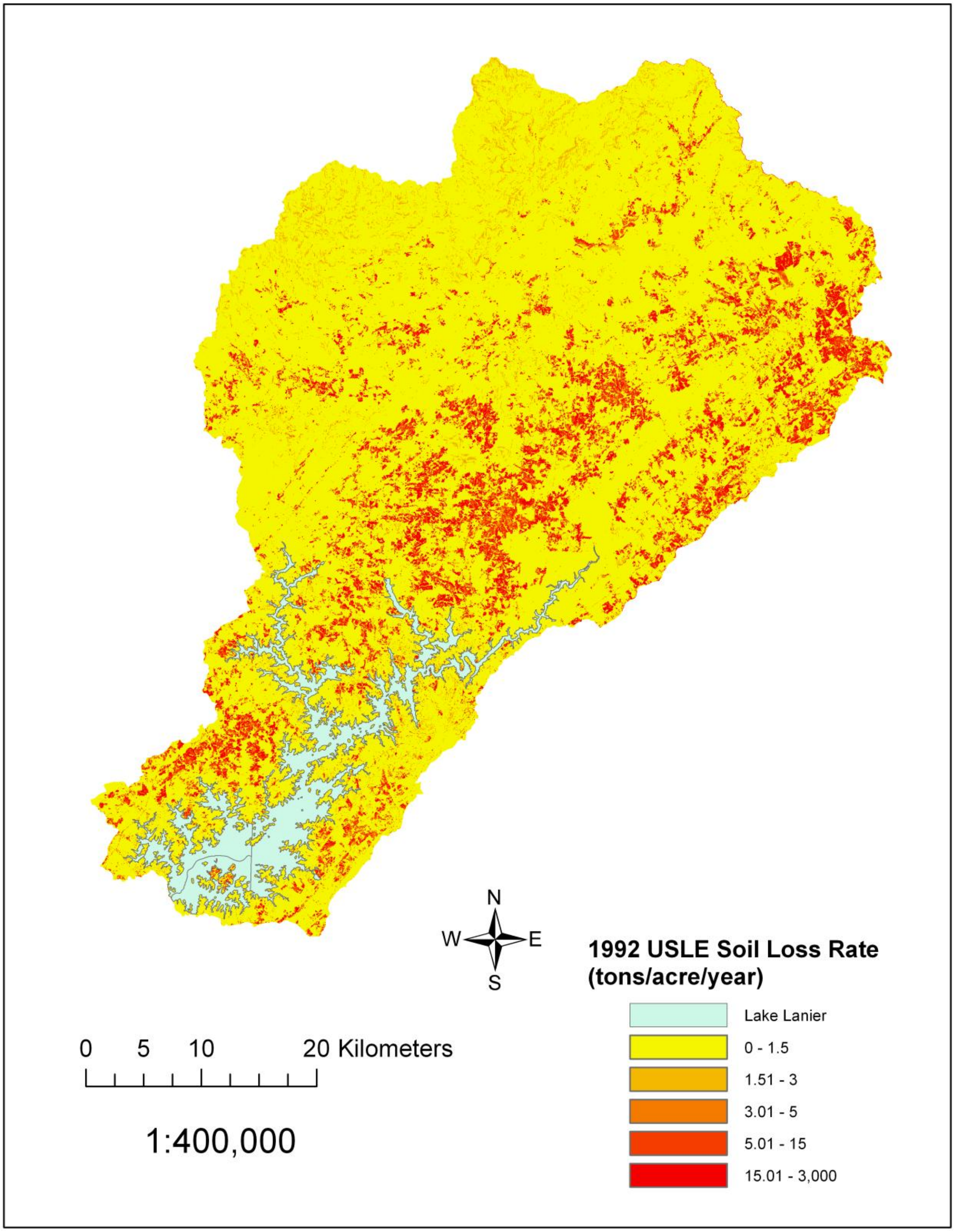


Figure 35b: USLE Based Soil Erosion (tons/acre/year) for 1992 (NLCD Based) Close Up

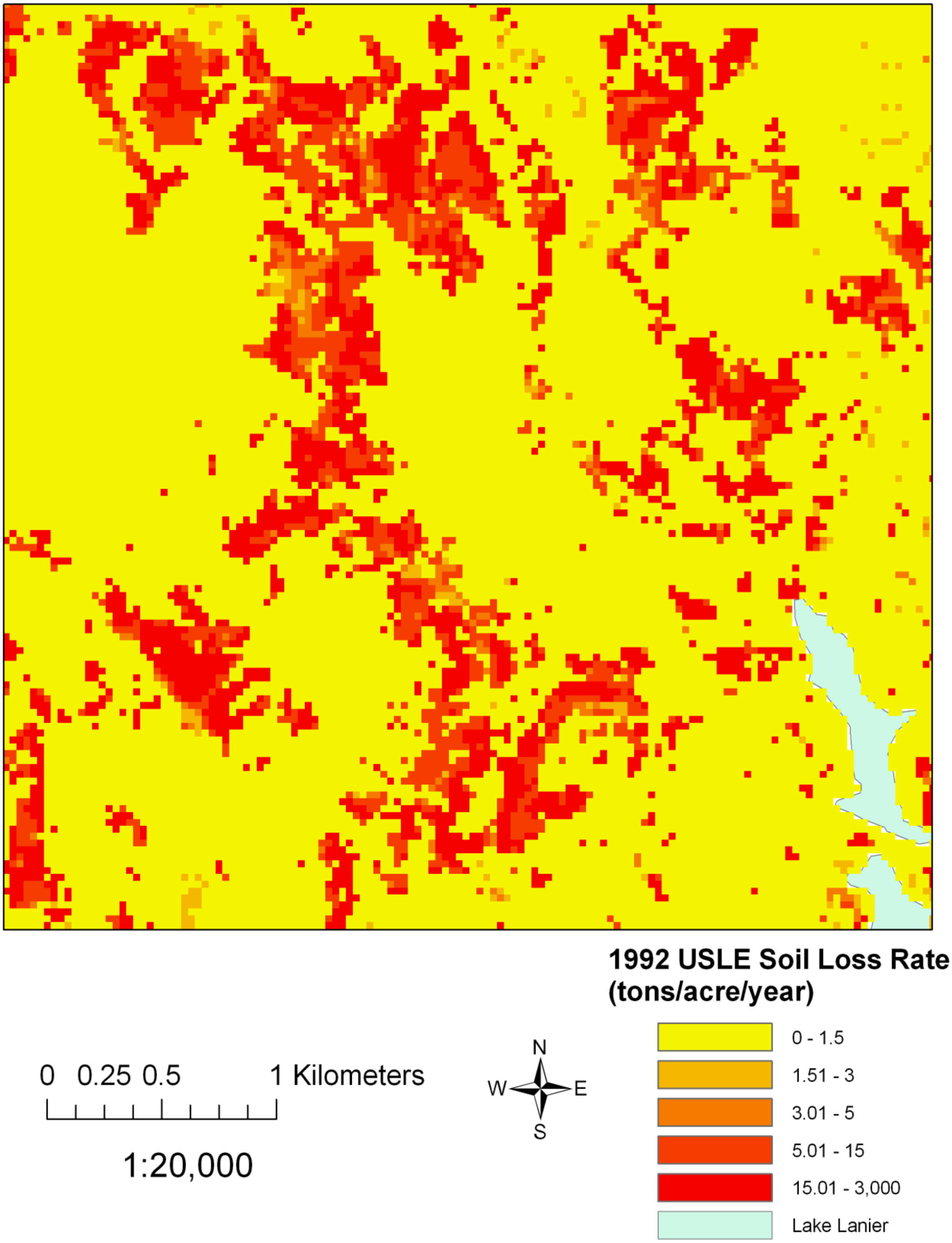


Figure 36a: USLE Based Soil Erosion (tons/acre/year) for 1999

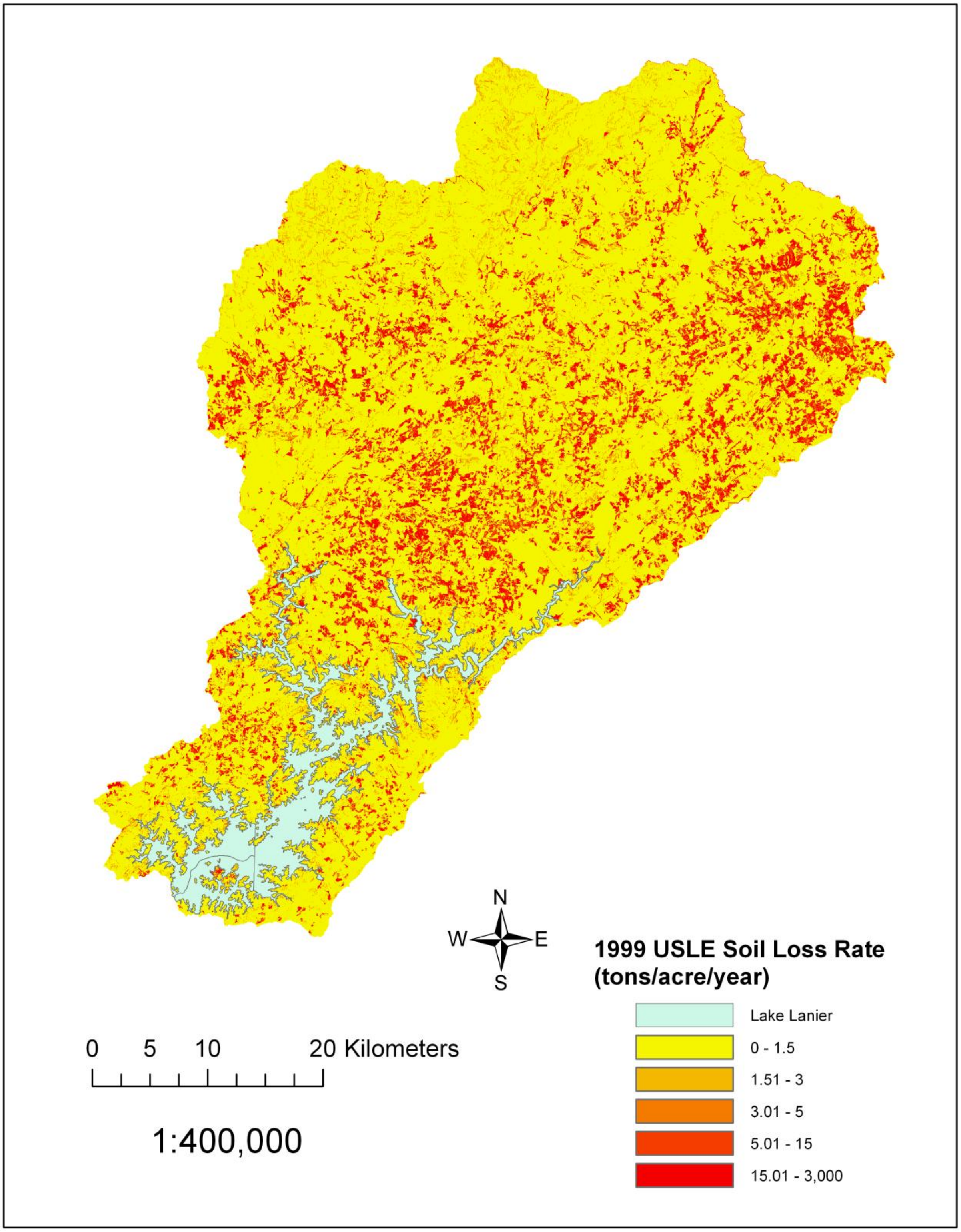


Figure 36b: USLE Based Soil Erosion (tons/acre/year) for 1999 Close Up

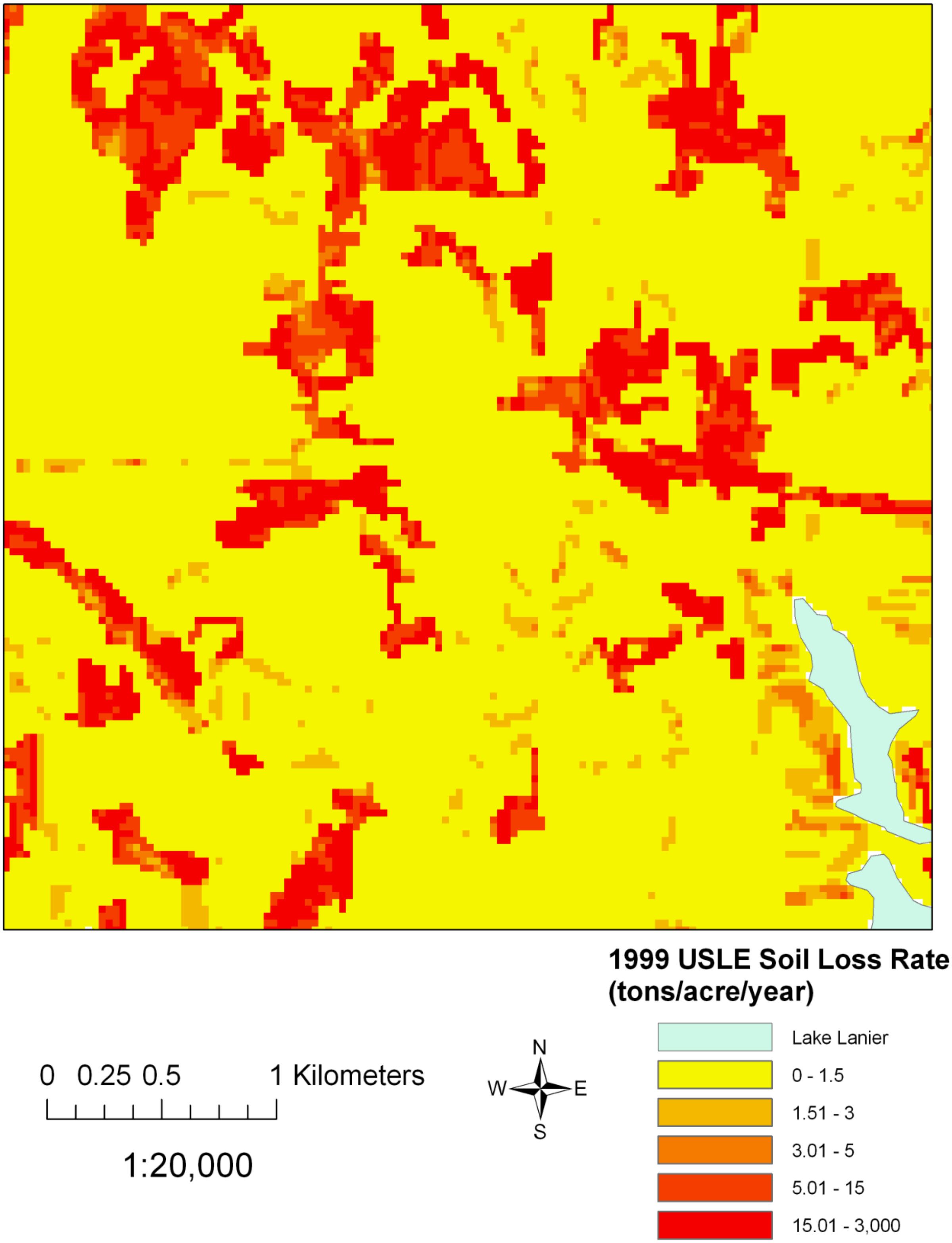


Figure 37a: USLE Based Soil Erosion (tons/acre/year) for 2001 (NLCD Based)

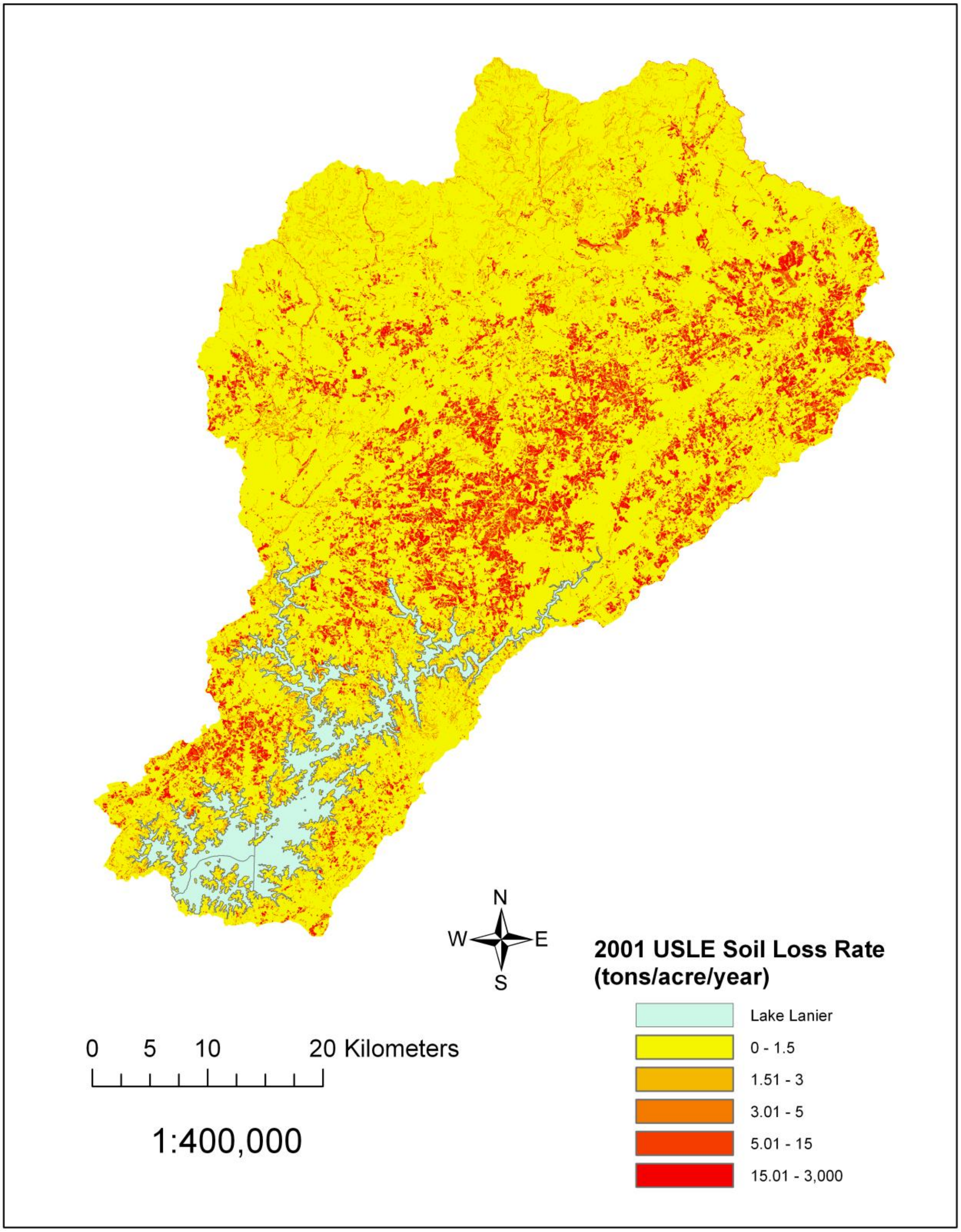


Figure 37b: USLE Based Soil Erosion (tons/acre/year) for 2001 (NLCD Based) Close Up

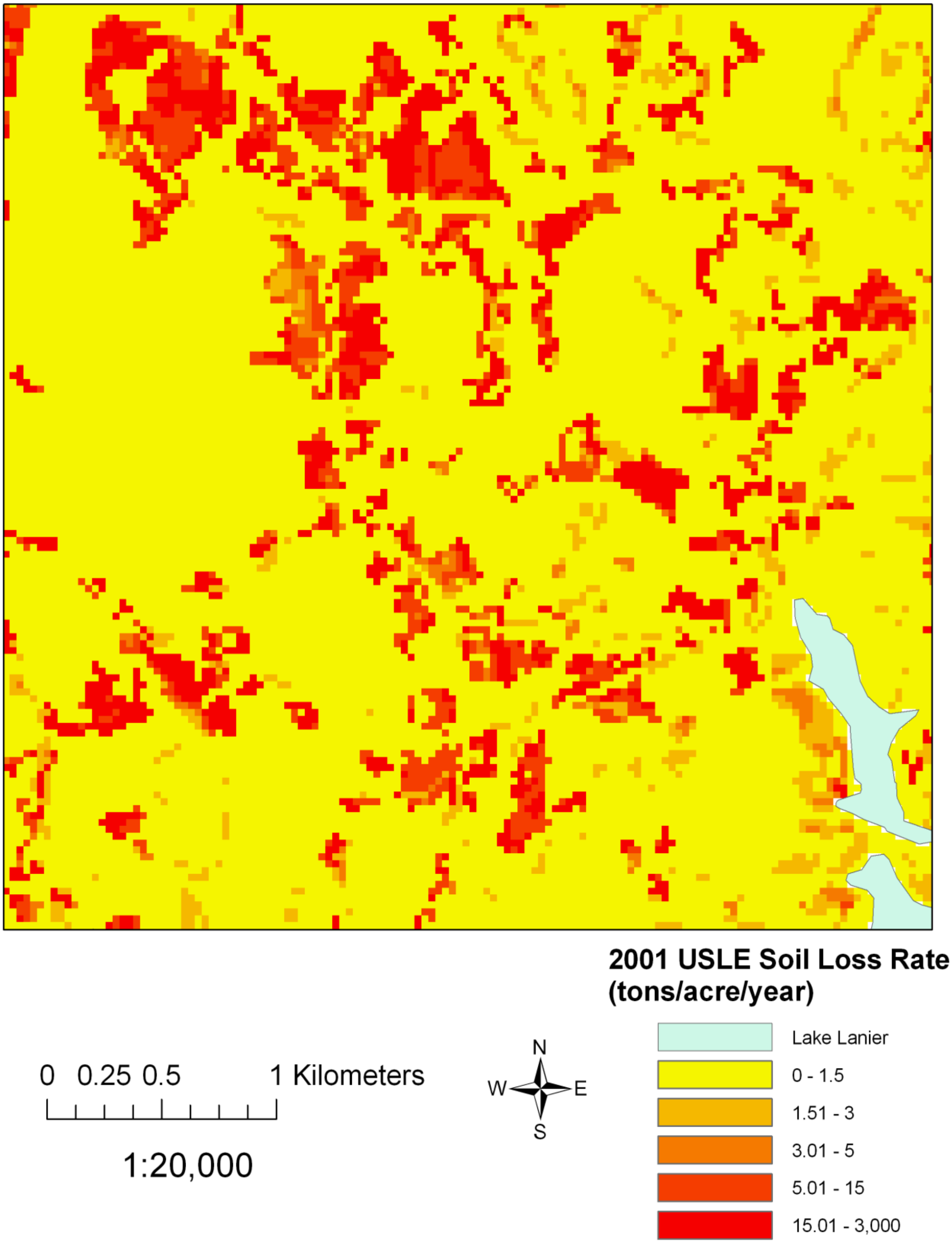


Figure 38a: USLE Based Soil Erosion (tons/acre/year) for 2005

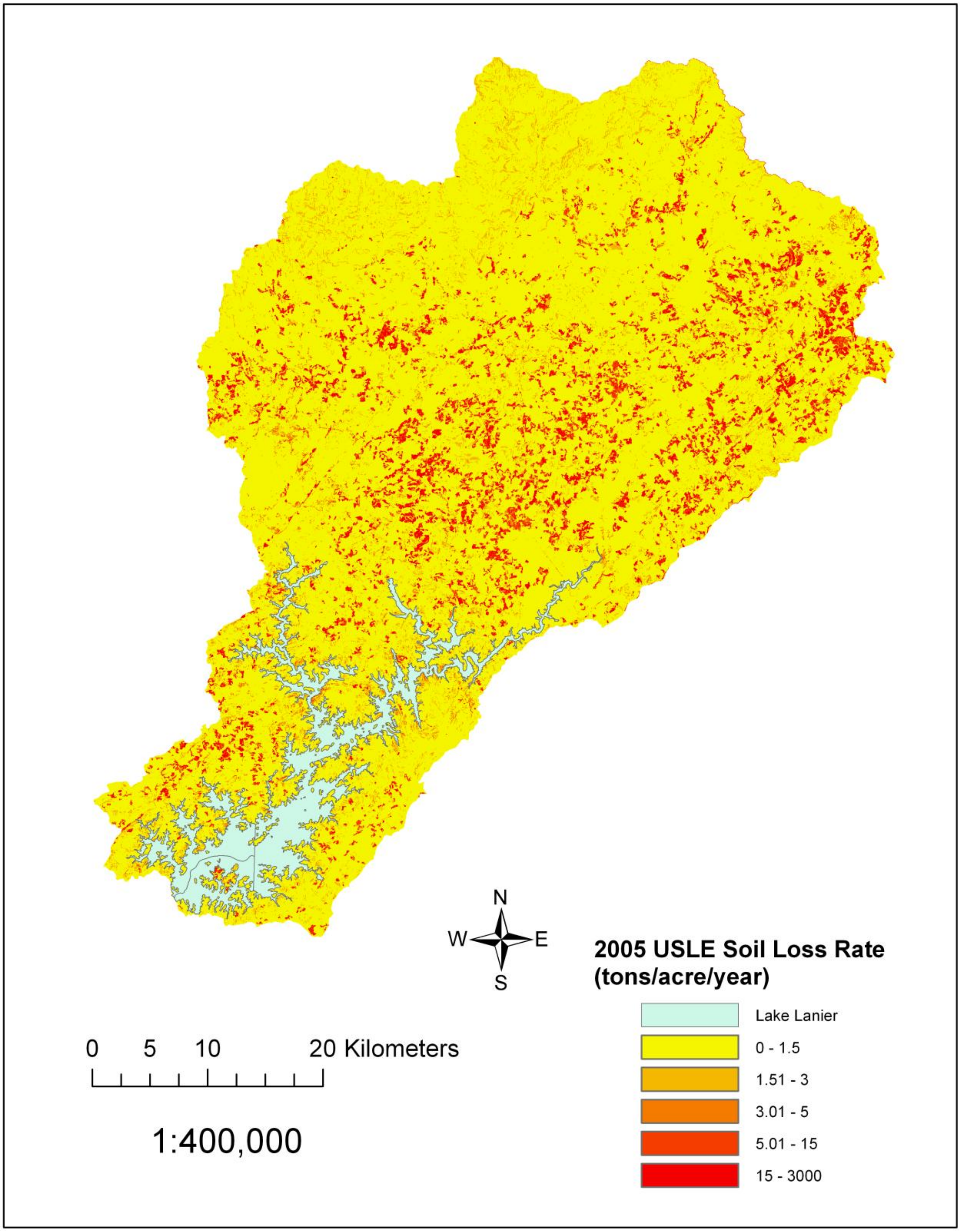
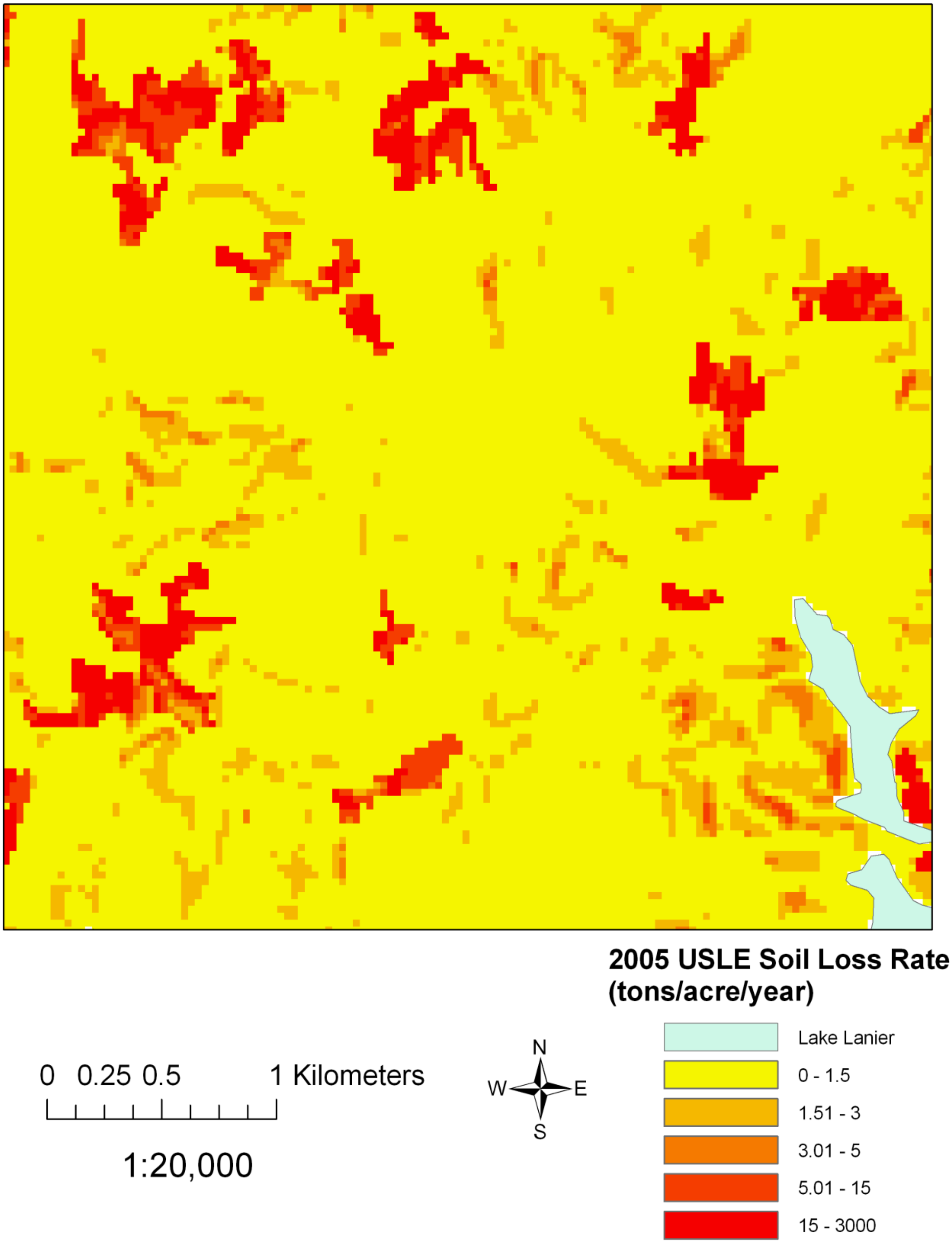


Figure 38b: USLE Based Soil Erosion (tons/acre/year) for 2005 Close Up

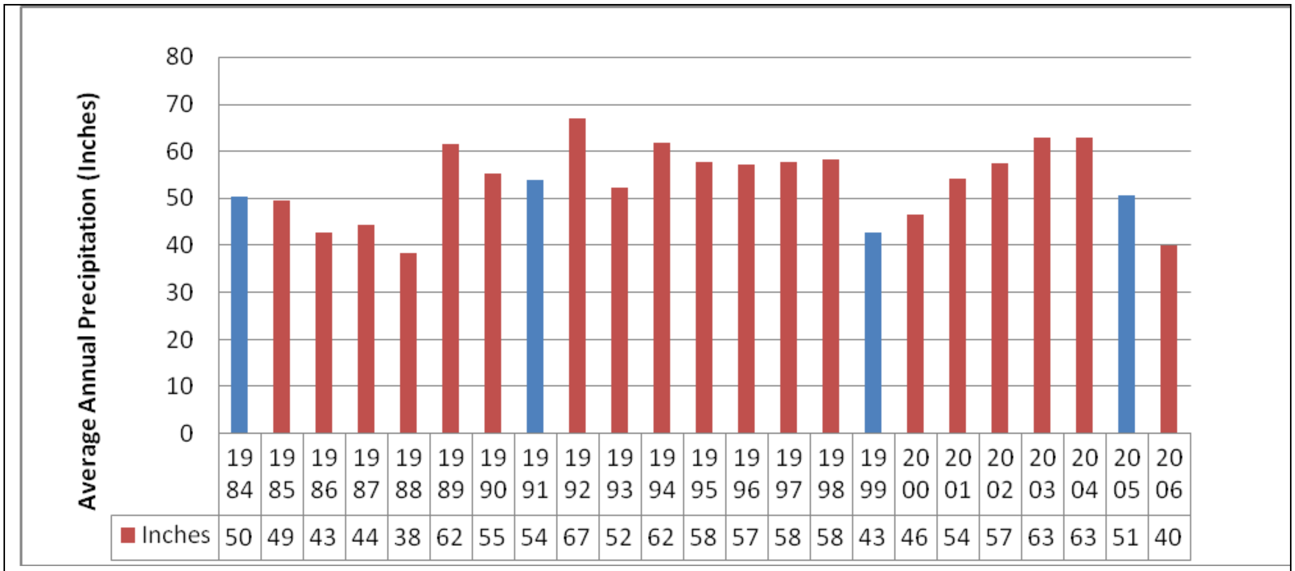


If the soil erosion rate is greater than the rate at which the soil is being produced by the weathering of the underlying geologic underlayment, the erosion rate is said to exceed the tolerance limit. The erosion tolerance rates for the soils in the continental U.S. are between 2 to 5 tons per acre per year (USDA 1978). The soil erosion rates in the Lake Lanier watershed are within these soil tolerance limits. The average annual soil erosion rates shown in Table 6 are indicative of both the change in land cover and climactic conditions. The overall USLE modeled sheet erosion has decreased from 1984 when the watershed was largely agricultural to 2005 as it increasingly urbanizes. This is because the amount of impervious surface increases with the increase in urbanization leading to a decrease in sheet erosion. However, this decrease in sheet erosion is accompanied by increased erosion due to stream scour exacerbated by increased runoff energy, due to surface flow off of impervious surfaces. This increase in erosion and sedimentation due to increased stream scour is not accounted for in this modeling.

Another phenomenon not factored in this erosion modeling is the impact of change in land cover on erosion. The change in land cover that is observed in this watershed is primarily that of Pasture/Agriculture and Forest being converted to Urban. This land cover transition can typically involve denuding the land of vegetative cover for a time period. This results in a period of increased erosion associated with bare soils which delivers a pulse of sediment to the lake. Although, modeling in this study does not account for the additional sediment load to Lake Lanier, estimates for this type of erosion can be substantial and will be discussed later in Chapter 6. It is observed that the total erosion in the Lake Lanier watershed as modeled by the USLE is roughly 1.5×10^6 tons/year over the years of 1984 through 2005. We shall see in Chapter 5 that this amount can be easily doubled due to changes in land cover in the watershed.

The USLE soil loss rate for 1999 at 3.71 tons/acres/year for 2001 at 3.21 tons/acre/year is substantially higher relative to 1991, 1992 and 2005, which are around ~2 tons/acre/year. The primary reason is that there is a large increase in the Pasture/Agriculture land cover class detected in 1999 and 2001, relative to 1991, and will be discussed in the analysis in the next section. Greater erosion also leads to greater sediment load potential on the streams of the watershed in 1999, as will be discussed in the sediment modeling later in Chapter 3. Another factor to be considered is that 1999 was a year of severe drought with about 25 percent less than the average rainfall (Figure 39). This means while the actual soil loss rate in 1999 can be up to 25 percent less than the calculated 3.71 tons/acre/year. However, due to decreased foliage in drought conditions, the erosion can increase as well and this phenomenon is difficult to quantify.

Figure 39: Average Annual Precipitation for Gainesville, GA 1984 – 2006

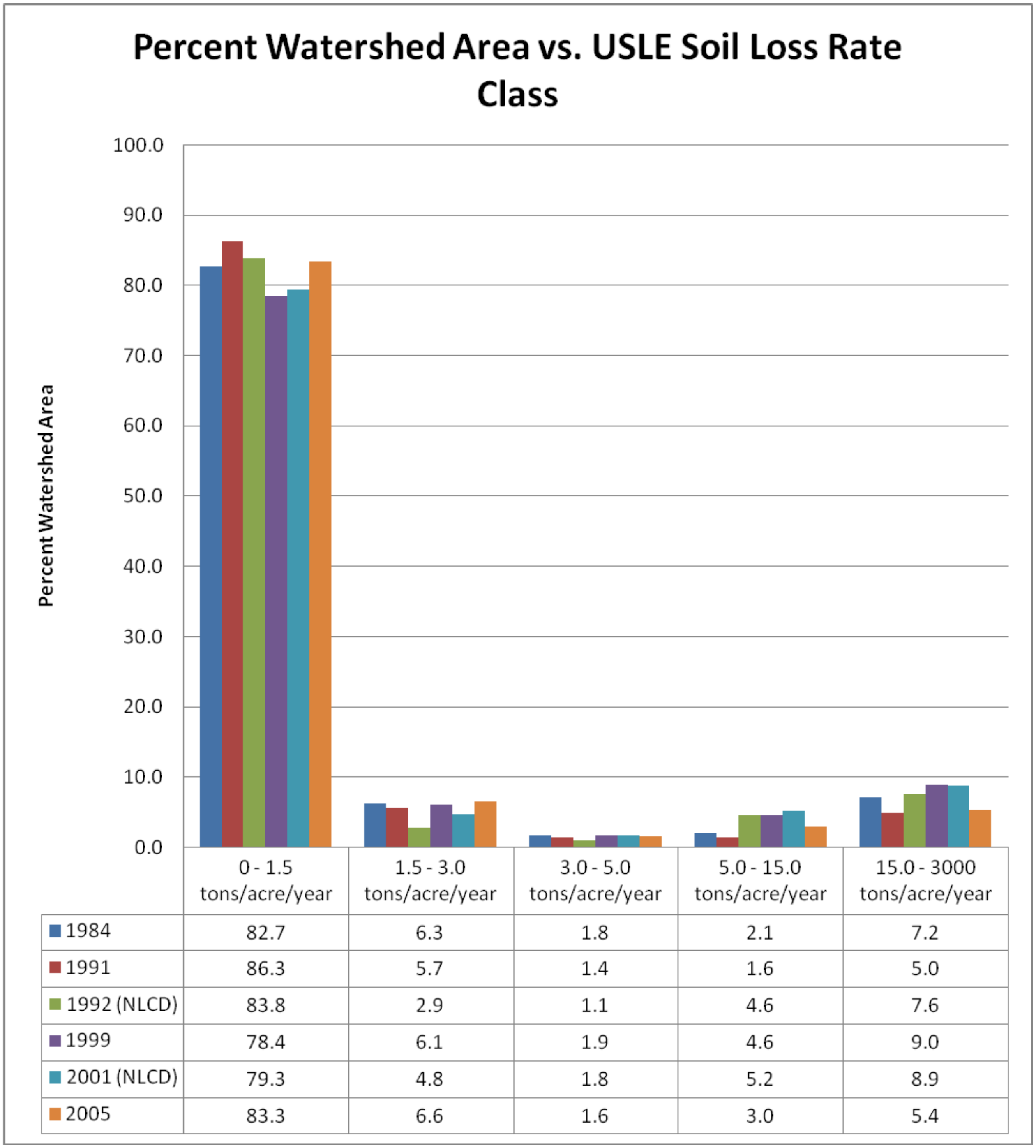


A Histogram Analysis of the USLE based Spatially Distributed Erosion

Spatially distributed results of the USLE soil erosion calculation created a raster layer of soil loss rate in tons/acre/year for each 30 m x 30 m grid cell in the Lake Lanier watershed. In order assess these erosion results, the continuous range of calculated soil erosion was divided into five classes based on the following criteria. Erosion up to 1.5 tons/acre/year is deemed to be within the allowable soil tolerance (USDA 1978). Erosion between 1.5 to 5 tons/acre/year is marginally within the soil erosion tolerances and 5 to 15 tons/acre/year represents excessive erosion 'hot spot'. Erosion rates greater than 15 tons/acre/year are 'extreme hot spots', requiring a closer inspection of watershed regions needing erosion remediation. The color codes for these classes listed in the legend in have progressively greater red hues represent increasing erosion potential. The classes defined above serve as the basis of the cartographic representation of the soil loss rate and its histogram analysis from 1984 to 2005.

The area vs. soil loss rate histogram analysis depicts a bar graph of the percent area associated with each different erosion class over the years in which the modeling was done (Figure 40). A few trends are clear about the spatial extent and change of the erosion classes over the years. The largest soil loss rate classes are the highest in 1984, 1999 and 2001 as all of these years have a relatively large Pasture/Agriculture class. In addition, 1999 has the highest erosion rate as it haves the largest Pasture/Agriculture class which contributes the most to erosion; 1999 also has a 16 percent decrease in Forest cover in the 1990's which further increases the land cover C-factor several-fold for these areas of change. About 8 percent of the total watershed area of 215 km^2 (~86 square miles) is in a region of high erosion potential (> 5 tons/acre/year) through the time period of this study. This does conceal the fact that higher urbanization will lead to greater sedimentation due to higher stream scour, which is not accounted for in this modeling.

Figure 40: Lake Lanier watershed Percent Area vs. Soil Loss Rate Class 1984, 1991, 1999 and 2005



	0 - 1.5 tons/acre/year	1.5 - 3.0 tons/acre/year	3.0 - 5.0 tons/acre/year	5.0 - 15.0 tons/acre/year	15.0 - 3000 tons/acre/year
🟦 1984	82.7	6.3	1.8	2.1	7.2
🟥 1991	86.3	5.7	1.4	1.6	5.0
🟩 1992 (NLCD)	83.8	2.9	1.1	4.6	7.6
🟪 1999	78.4	6.1	1.9	4.6	9.0
🟦 2001 (NLCD)	79.3	4.8	1.8	5.2	8.9
🟧 2005	83.3	6.6	1.6	3.0	5.4

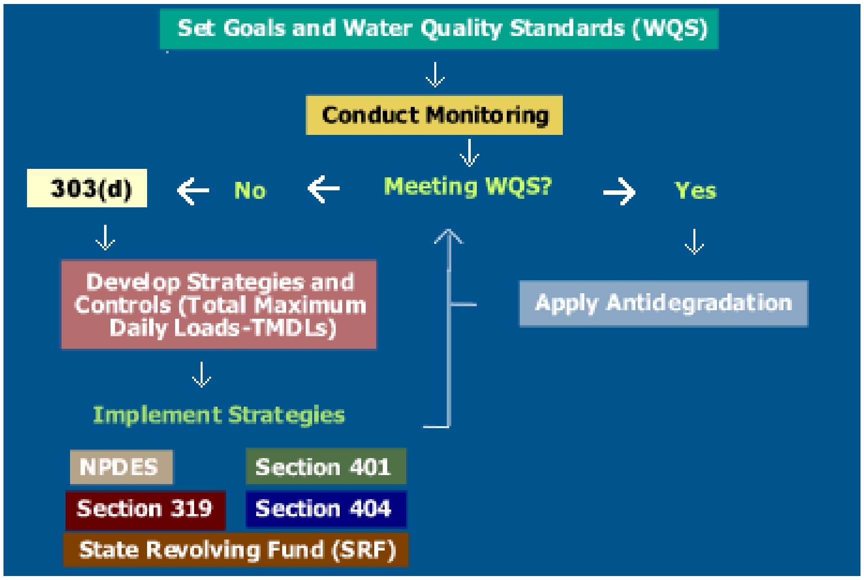
CHAPTER 3

SEDIMENTATION MODELING

The process of the deposition of transported eroded soil is known as sedimentation; transported and deposited soil is known as the sediment. This deposition may take place due to sheet and rill flow, or sediment may be deposited in a stream channel where the water flow transitions to the hydraulic regime of open channel flow. This project is constrained to the modeling of erosion and deposition of soil due to sheet and rill flow only. The result is a grid of sediment yield, which is the sediment deposited at each grid cell due to upslope erosion. Every pixel on the sediment yield grid is treated as a ‘pour point’ or outlet of an upslope sub-watershed. The greater the sediment loading at a pixel or grid cell, the greater the amount of sediment is potentially deposited at that location. The sediment loading at stream-banks can be a useful tool for the identification of stretches of streams with a higher sediment upslope loading which is ultimately transported into Lake Lanier. The location of the regions where the sediment discharge into the drainage network is the greatest is essential information for soil conservation and remediation efforts. A histogram analysis of the sediment yield pixels contiguous with the streams is a very visual and useful indicator of the extent of sediment flow in streams via a ‘sediment yield spectrum’. This provides a quantitative measure of the area for each sediment yield class in the watershed and can be used as an indicator of the impairment of the watershed due to erosion and sedimentation. An index of impairment due to sediment discharge in the streams will be developed in later in the section in which the non-point source sediment yield is analyzed.

The Clean Water Act (CWA 1972) has a regulatory framework to ensure that the National Water Quality Standards (WQS) are upheld as a result of mandated monitoring of the Nation's water bodies. If the WQS are not met, the Section 303(d) of the Clean Water Act is invoked setting into motion the development and application of mitigation strategies and controls. This includes the quantification of acceptable pollutant loads as the Total Maximum Daily Loads (TMDL's). The enforcement of TMDL's by sampling only is a daunting task due to the sheer number of water bodies at a national scale. Non-point source erosion and sediment modeling with GIS tools, based on remotely sensed watershed data holds a great promise in being able to identify areas of greatest impairment such that monitoring and remediation efforts are focused in the most cost effective manner. This would make the implementation of water quality legislation effective and viable. The 'big picture' of the Clean Water Act is shown in Figure 41.

Figure 41: Operational Framework of the Clean Water Act (EPA 2003)



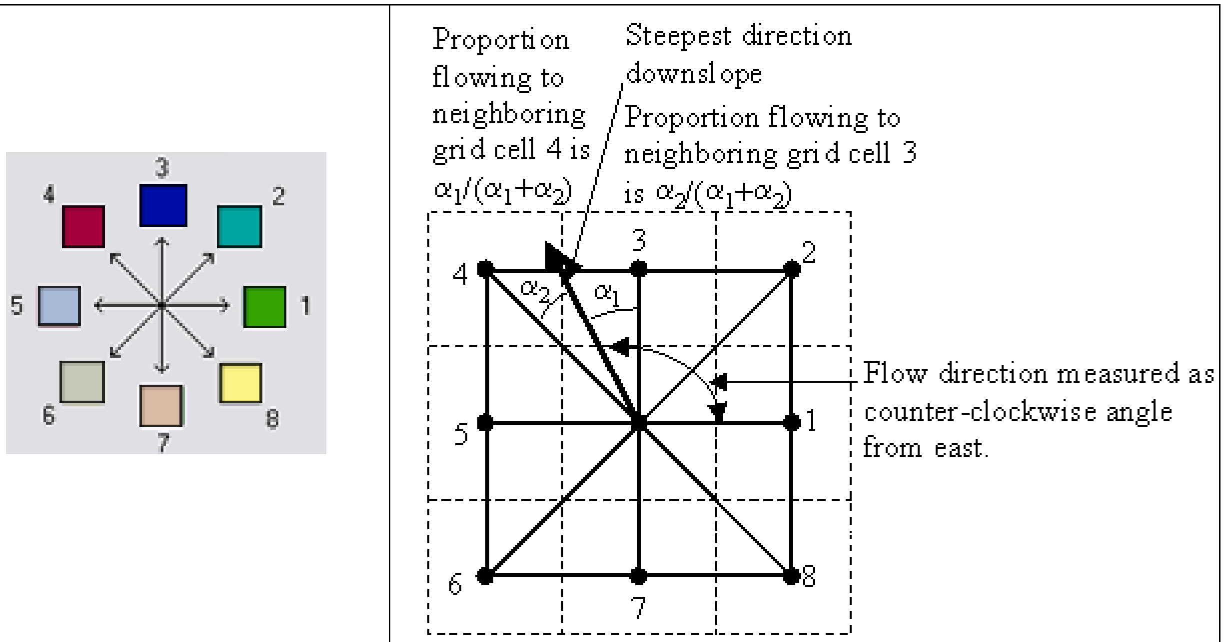
Terrain Processing for Surface Hydrology Modeling

The DEM of the Lake Lanier Watershed is at a 30-m spatial resolution and is subset to the Lake Lanier watershed boundary from the National Elevation Dataset (NED) (USGS 2006). The sediment modeling entailed a series of steps that were necessary including a substantial amount of pre-processing of the terrain DEM to prepare the layers for spatial calculations. These steps are outlined in the following paragraphs.

The soil erosion process is driven by the surface hydrology which in turn, is a function of the topography of the terrain. This topography is represented by the digital elevation model (DEM) which forms the basis of the terrain analysis and the delineation of the drainage network in the basin. TauDEM (Tarboton 1997) and ArcHydro (Maidment 2002) are programs for analyzing DEM's for surface water flow processes. Both of these shareware programs are downloadable (CRWR 2003, Tarboton 2005) from the Web and can operate on the DEM's as extensions from within the ArcGIS 9.2 software. In addition ArcGIS ArcTools has surface analysis and hydrology functions that complement the capabilities of both ArcHydro and TauDEM extensions. All of these extensions and functions lend a very powerful capability for DEM surface analysis and surface hydrology modeling, all within the standard platform of ArcGIS software.

Both of ArcHydro and TauDEM were installed on ArcGIS 9.2 and their DEM processing capabilities were explored. The basic terrain processing capabilities of both programs are similar. They both begin by filling all the pits in the DEM to ensure hydraulic connectivity of within the watershed model. The presence of any pits or sinks in the DEM would serve as drainage points in the surface water flow and give erroneous results. Subsequently both models calculate the DEM ‘slope’ and ‘aspect’ of each grid cell which then gives the flow direction raster. ArcHydro determines the flow in eight possible directions, either diagonal or parallel to a grid cell. TauDEM, however, has an innovative way of formulating the flow direction in multiple directions of flow, with the direction encoded as an angle between 0^o and 360^o (Figure 42). Depending on the direction of the flow into the contiguous and down-slope grid cells, the angle of flow allows the apportioning of flow into the down-slope cells.

Figure 42a and 42b: The D8 and the D-Infinity Flow Direction Grid (Tarboton 2005)



(a)
Eight Possible Flow Directions

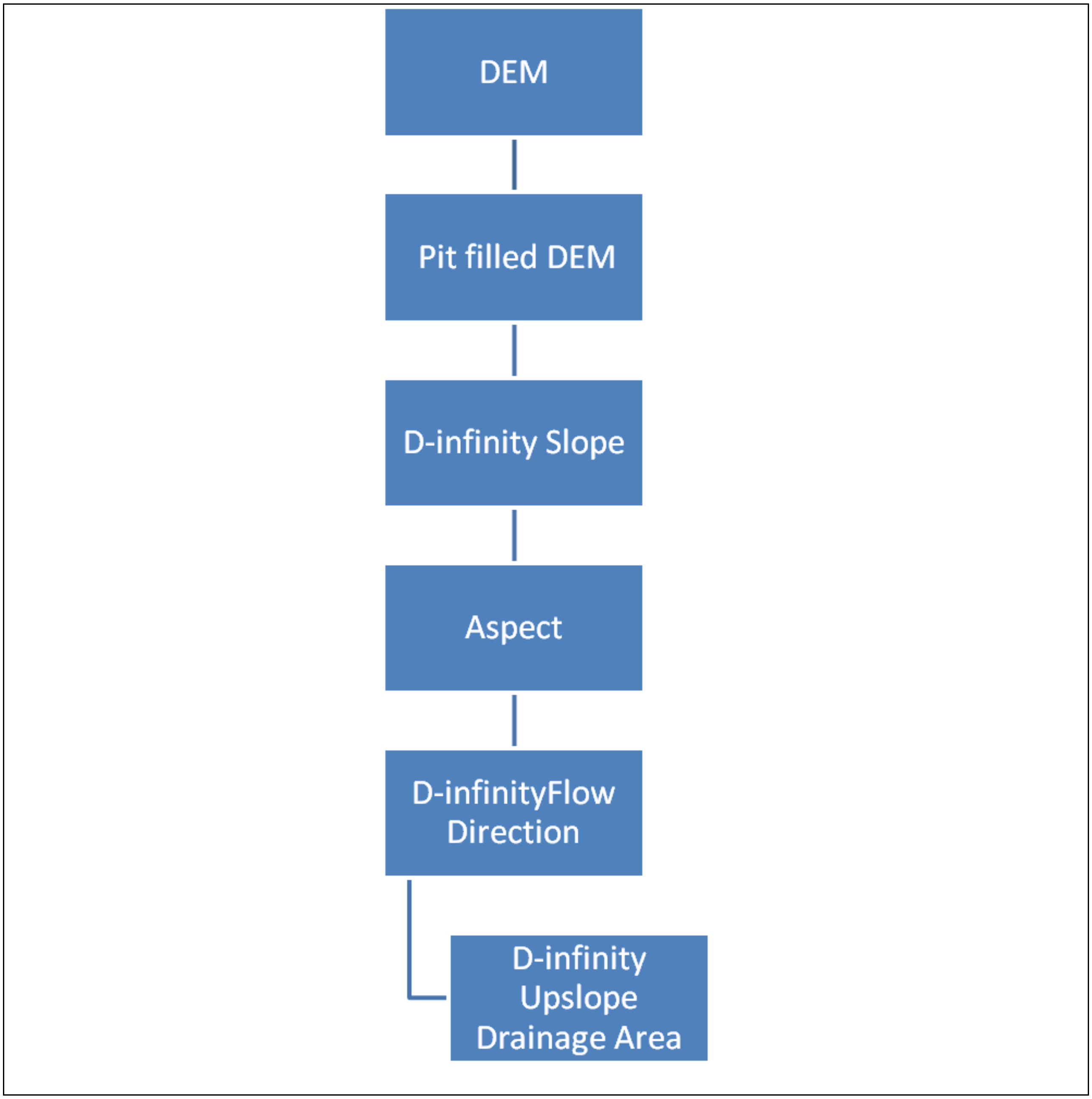
(b)
Multiple Possible Flow Directions

TauDEM was chosen for the terrain processing due to its capability to represent multiple directions as that is closer to the actual phenomenon of rainfall runoff. Furthermore, TauDEM has an entire suite of specialized terrain processing functions including the D-infinity flow direction based ‘upslope drainage area’ for each cell. This entire process can be represented as a flowchart in (Figure 43). The ArcGIS 9.2 software was used for the modeling process. Once the input data layers were ready Map Algebra was performed within the GIS Model Maker environment. The grid size for this study is 30 m x 30 m, which corresponds to the spatial resolution of both the DEM and the Landsat imagery used to derive the land cover used in this analysis.

As discussed in Chapter 2, the USLE soil loss rate rasters based on both the STATSGO soil database and the higher spatial resolution SSURGO soil database were developed for the study area for use in this study to compare the results of erosion predictions of these two databases for 1984. The USLE based erosion gives the soil loss rate which is the annual soil erosion in tons per acre per year for each 900 m^2 (or 0.2224 acre) grid cell. Multiplying the USLE soil loss rate by the area of each cell in acres gives the amount of eroded soil in tons that is available in each grid cell for the sedimentation process. The Sediment Delivery Ratio (SDR) gives the fraction of the eroded soil that is delivered to the next down-slope cell in the flow-path. The multiplication of the soil erosion grid by the SDR grid gives the sediment supply for each cell.

The FlowAccumulation tool in ArcGIS 9.2 operates on the FlowDirection grid and sums up the cells along a particular flowpath of the surface water flow, giving each cell a value of 1 by default. The FlowAccumulation tool can also perform this cell summation along the flow-path

Figure 43: Flowchart of Terrain Processing Using TauDEM

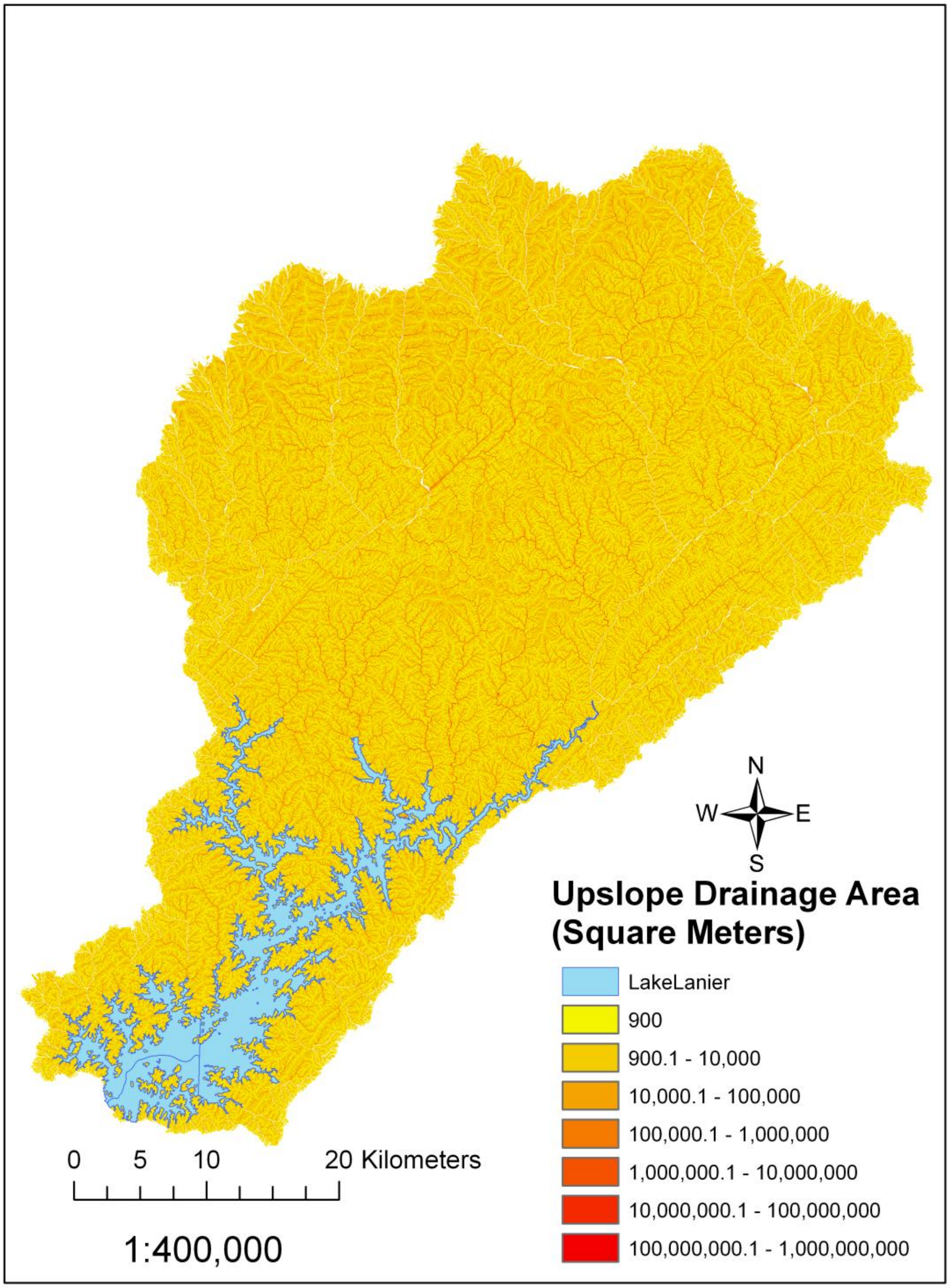


with a weighted grid. This means that the default value of 1 for each cell is multiplied by a weight in the summation along the flow-path. If the weight grid is the sediment supply grid, the FlowAccumulation routine then gives the sum of the sediment supply along each cell in the flow path, giving the total upslope eroded soil available as sediment loading, at each grid cell.

The weight grid for the FlowAccumulation routine has to be in integer format, whereas the amount of eroded soil for each cell is represented as a floating point number. To work around this while preserving accuracy, the sediment supply grid from the USLE modeling was multiplied by 1000 and then used as a weight grid for the FlowAccumulation routine. This grid of weighted cell values is then summed up along the upslope flow paths for each cell and then divided by 1000 to remove the multiplicative factor. The product of eroded soil supply grid with the SDR grid gives the sediment deposition potential at each grid point. When the sediment reaches the stream channel it exits the sheet flow regime modeled by the USLE and enters an open channel hydraulic flow regime.

TauDEM was used to generate the D-infinity slope based ‘specific upslope drainage area’ for each grid cell, which gives the upslope area contributing to each cell per unit contour width, which in this case is taken to be the cell width of 30 m. Multiplication of this grid by 30 m gives the ‘upslope drainage area’ for each grid cell of 900 m^2 area (Figure 44). The ‘upslope drainage area’ for watersheds in the region of the study area has been empirically correlated to the sediment delivery ratio (SDR) (Roehl 1962, Boyce 1975). This empirical relation between the drainage area and the SDR was the basis for the calculation of the SDR grid and the sediment yield modeling. The details of this drainage area based SDR are elaborated upon in the next section.

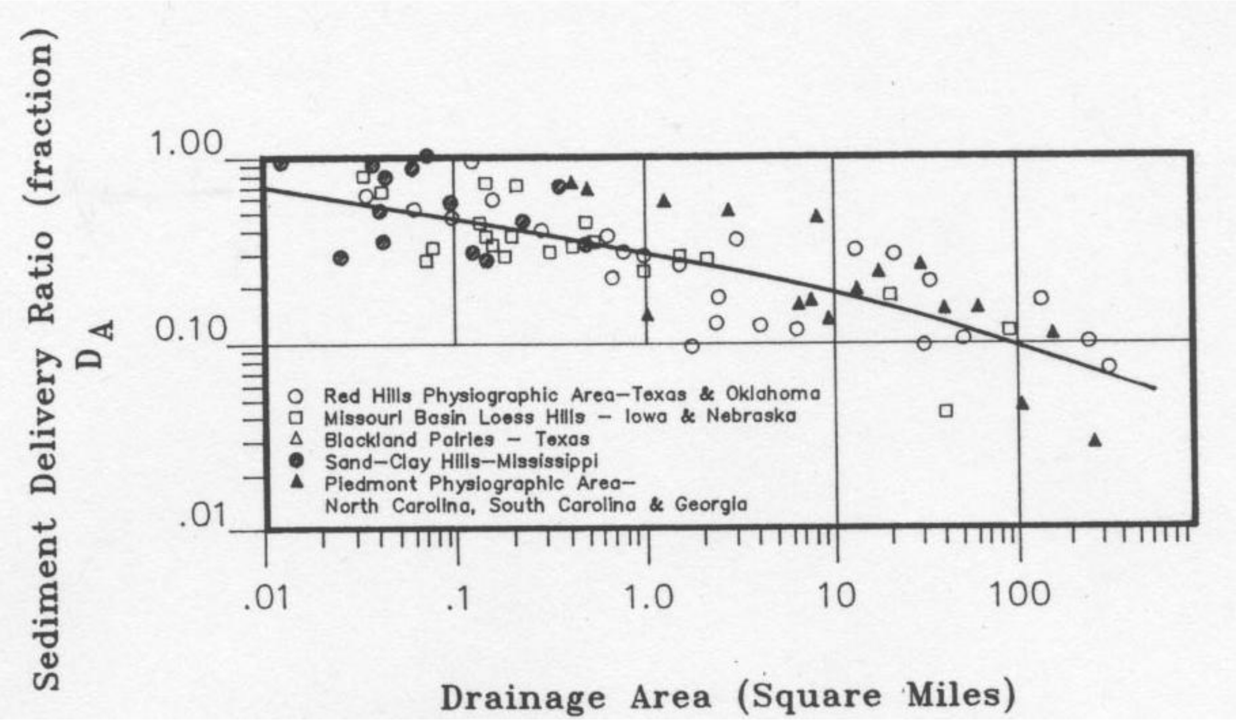
Figure 44: Upslope Drainage Area (m^2) Grid



The Empirical Area Based Sediment Delivery Ratio (SDR)

An empirical relationship between the sediment delivery ratio (SDR) and the drainage area in square miles, was reported by Boyce et al. (1975) and expounded upon by Haan et al. (1994) (Figure 45). This graph is a result of field measurements of sediment for watersheds in many different physiographic regions of the southern and Midwestern United States. In particular, this relationship includes watersheds in the Piedmont physiographic area of the southern U.S. which includes the Lake Lanier watershed.

Figure 45: Sediment Delivery Ratio vs. Drainage Area (Haan et al. 1994)



The values of the SDR as a function of the drainage area in square miles, were inferred from the graph in Figure 45 and the drainage area was then converted to square meters (Table 8).

Table 8: Drainage Area vs. SDR

Drainage Area (m^2)	Sediment Deliver Ratio (SDR)
900.0	0.70
25889.0	0.66
51778.0	0.60
76670.0	0.55
103556.0	0.50
258890	0.46
2600000	0.30
26000000	0.18
260000000	0.10

The numbers in Table 8 were curve fitted piecewise with a linear function and a power law to obtain algebraic relationship between SDR vs. Drainage Area (Figure 46 and Figure 47). The data relating the SDR to the upslope drainage area 'A' is curve fit with two equations to best fit the different behavior of the SDR for drainage areas less than and greater than 10^5 m^2 (0.1 km^2), as shown below in equation 3:

$$SDR = (-1.97 \times 10^{-6}) A + 0.703 \quad \text{for area } A < 100000 \text{ m}^2$$

$$SDR = 4.55 A^{-0.188} \quad \text{for area } A > 100000 \text{ m}^2 \qquad \text{Equation 3}$$

Where A = drainage area in m^2.

If the value from each of the formulae exceeded 0.7, the SDR was set to 0.7 to remain consistent with the original graph SDR vs. Drainage Area in Figure 36, from which these relationships were derived.

Figure 46: Linear Portion of the Piecewise SDR vs. Drainage Area for Drainage Area < 10^5 m^2 (0.1 km^2)

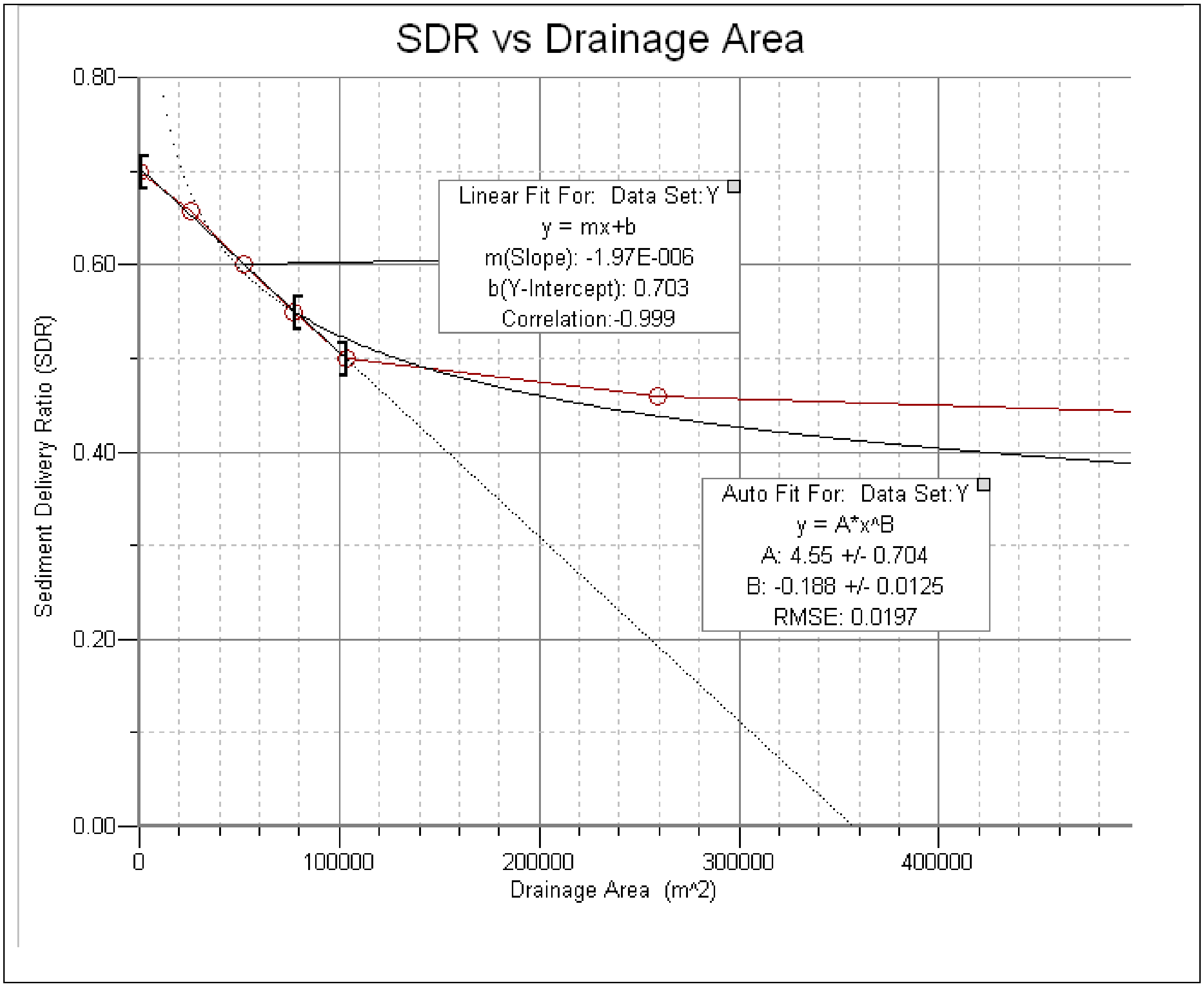
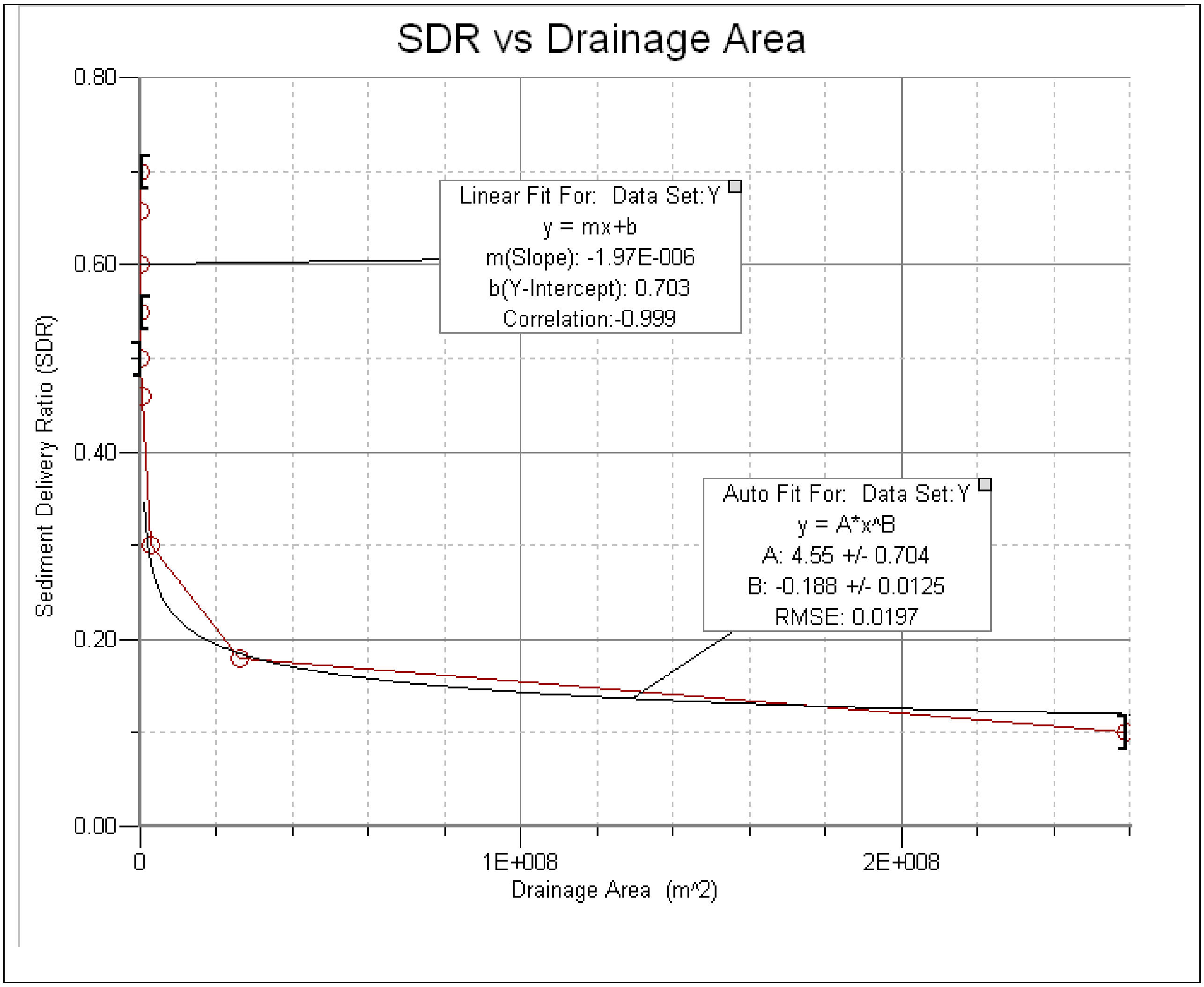


Figure 47: Exponentially Varying Portion of SDR vs. Drainage Area
For Drainage Area > 10^5 m^2 (0.1 km^2)



Area Based SDR Sedimentation Modeling

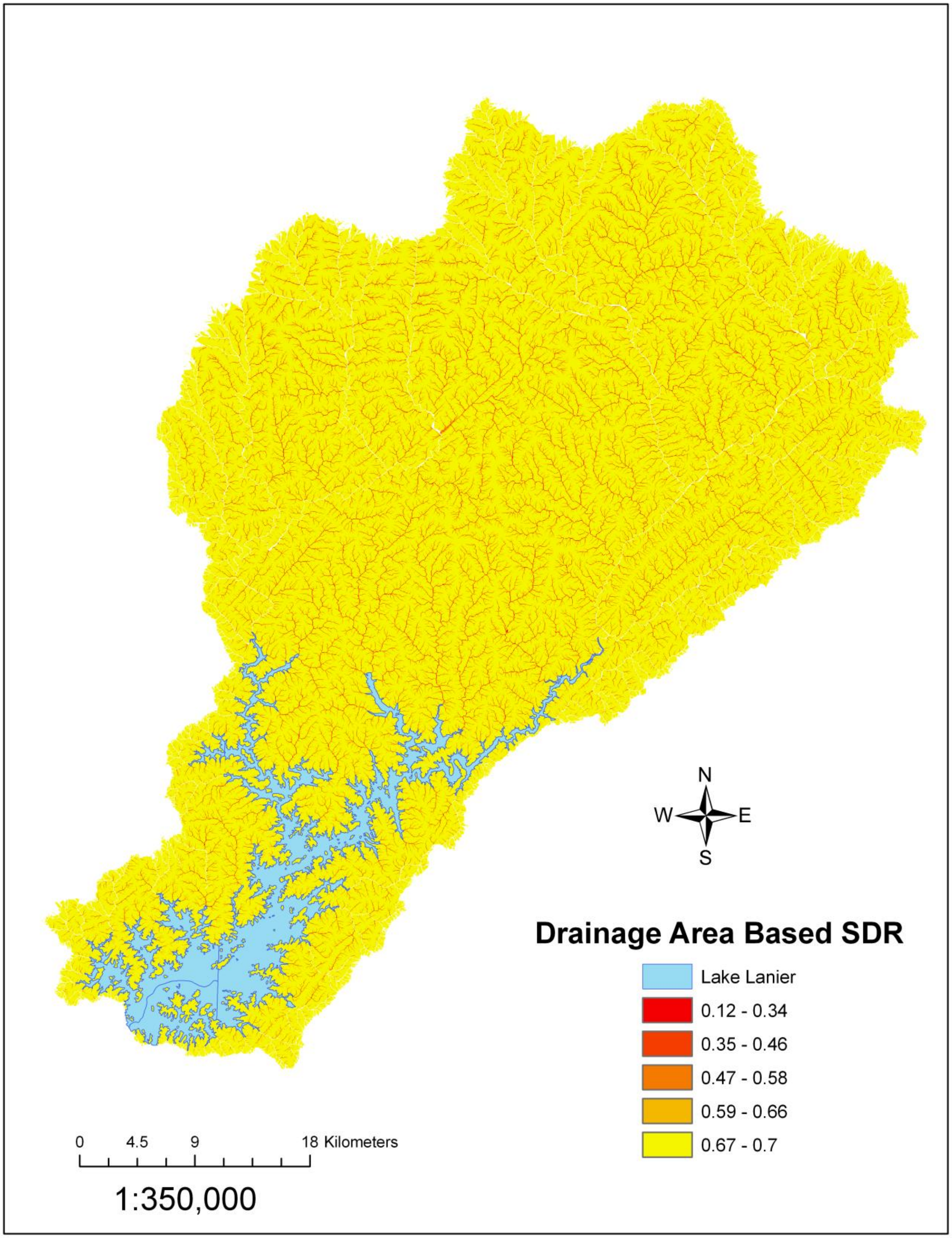
An upslope drainage area grid for each 30 m x 30 m cell in the entire watershed was calculated using the TauDEM software as an extension in ArcGIS 9.1, as discussed in the previous section. The raster calculator in the ArcGIS Spatial Analyst was then used to calculate the SDR for each cell in the watershed, using equation 3 and the upslope area feeding the surface water flow into that cell. The spatially distributed drainage area based SDR grid is shown in Figure 48.

The FlowAccumulation function then operated upon the FlowDirection grid, with the USLE sediment supply grid (in tons/year) as the weight grid. This calculated the total eroded soil in the upslope area for each cell, with each cell treated as the watershed outlet for the upslope area draining to that cell. The total eroded soil in the upslope drainage area for a particular cell is the erosion load of that cell. The raster with the erosion load for each cell was then multiplied by the upslope area based SDR grid to give the sediment yield $S_{(i,j)}$ for each (i,j) cell in the watershed, in tons/year, as given by the following equation:

$$S_{(i,j)} = SDR \times \sum \text{Soil Eroded from Upslope Drainage Area Cells to the (i,j) Cell} \qquad \text{Equation 4}$$

Thus $S_{(i,j)}$ represents the total sediment yield potential at any given cell. It is indicative of the total sediment loading for a grid-cell point that is an outlet for an upslope drainage area. This is not an absolute value for the sediment yield, but is a relative measure of the spatial distribution of the sediment yield potential. Re-classed and color-coded sediment yields of all grid cells results in a data set that can be used for a visual appraisal of the areas most and the least prone to sediment deposition in the watershed. Of particular interest is the sediment yield at the stream

Figure 48: Spatially Distributed Drainage Area Based Sediment Delivery Ratio



banks, which can help identify the stream stretches which are the most and the least vulnerable to sediment input due to sheet erosion in the surrounding terrain. This knowledge can help direct the optimal placement of best management practices to minimize sediment input into the streams and eventually into the lake.

A schematic of the drainage area based sediment yield potential model is shown in Figures 49 a and b. The sediment yield potential at every grid cell is the sum of the upslope drainage area sediment supply of that cell multiplied by the area based SDR of that cell, in units of tons/year. The Lake Lanier watershed annual non-point source sediment yield potential maps for 1984, 1991, 1999 and 2005 are shown in Figure 50 through Figure 53, respectively. These sediment yield potential maps provide a geo-coded visual display of the spatial distribution of the regions of greatest sediment deposition and provide natural resource managers information on where to best focus soil conservation efforts.

The overall results of modeling the sediment potential in the Lake Lanier watershed are summarized in Table 9. The average sediment yield potentials during 1984 and 1999 are roughly twice as much as in 1991 and 2005. In particular, the sediment yield potential in 1999 is the highest. The total sediment moved annually due to sheet and rill flow in the entire watershed is on the order of about 10^9 tons per year, during the period of this study. Most of this sediment is deposited on land and a very small fraction of this amount ends up in the streams and then transported to the lake. These results are analyzed in greater detail in the next section.

Table 9: Lake Lanier watershed Annual Sediment Yield Potential

	Max* (tons/year)	Sum (tons/year)	Average* (tons/year)	SD (tons/year)
1984	764590	725,910,000	268.1	7632.5
1991	517,000	472,000,000	174.3	4990
1999	1,166,200	1,043,500,000	385.4	11,719
2005	726,700	615,000,000	227.1	6,784

* Per 30 m x 30 m pixel

Figure 49 a and b: Drainage Area SDR based Sediment Yield Potential Model (Sediment Yield Model is Represented in 2 Sub-Figures a and b)

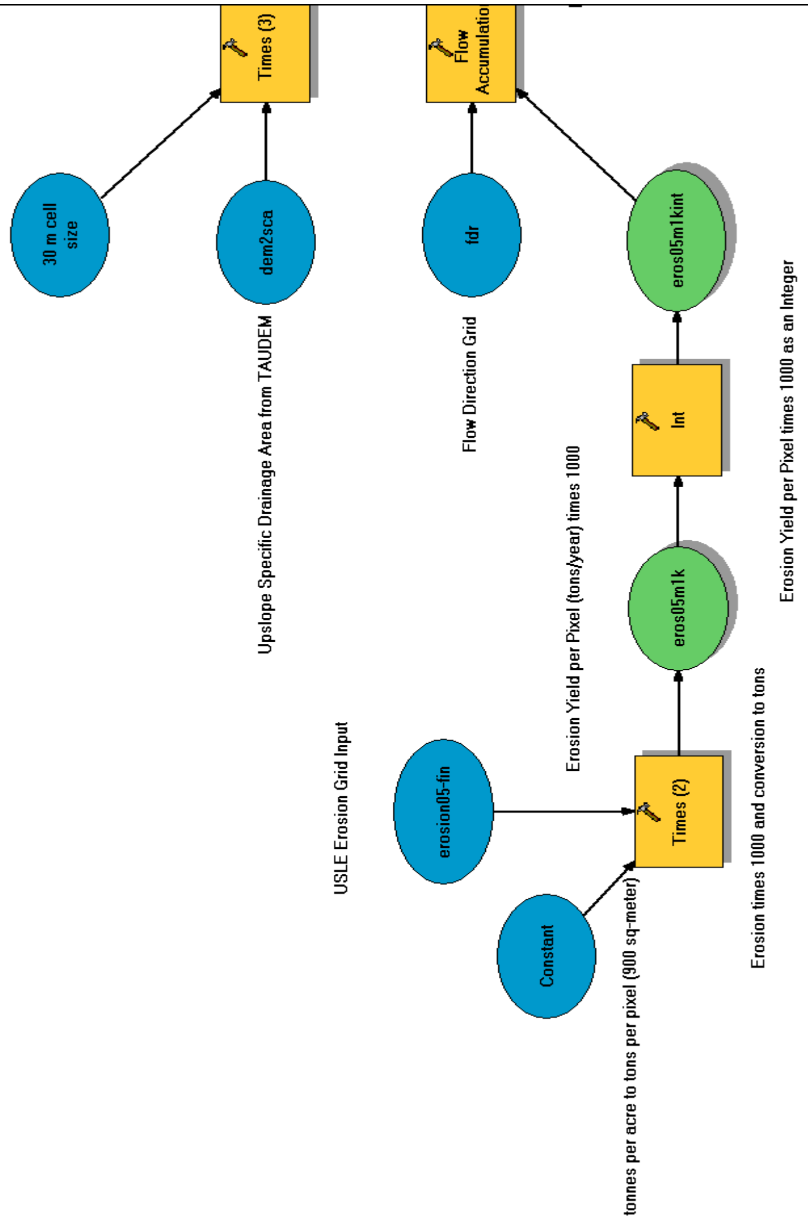


Figure 49 a

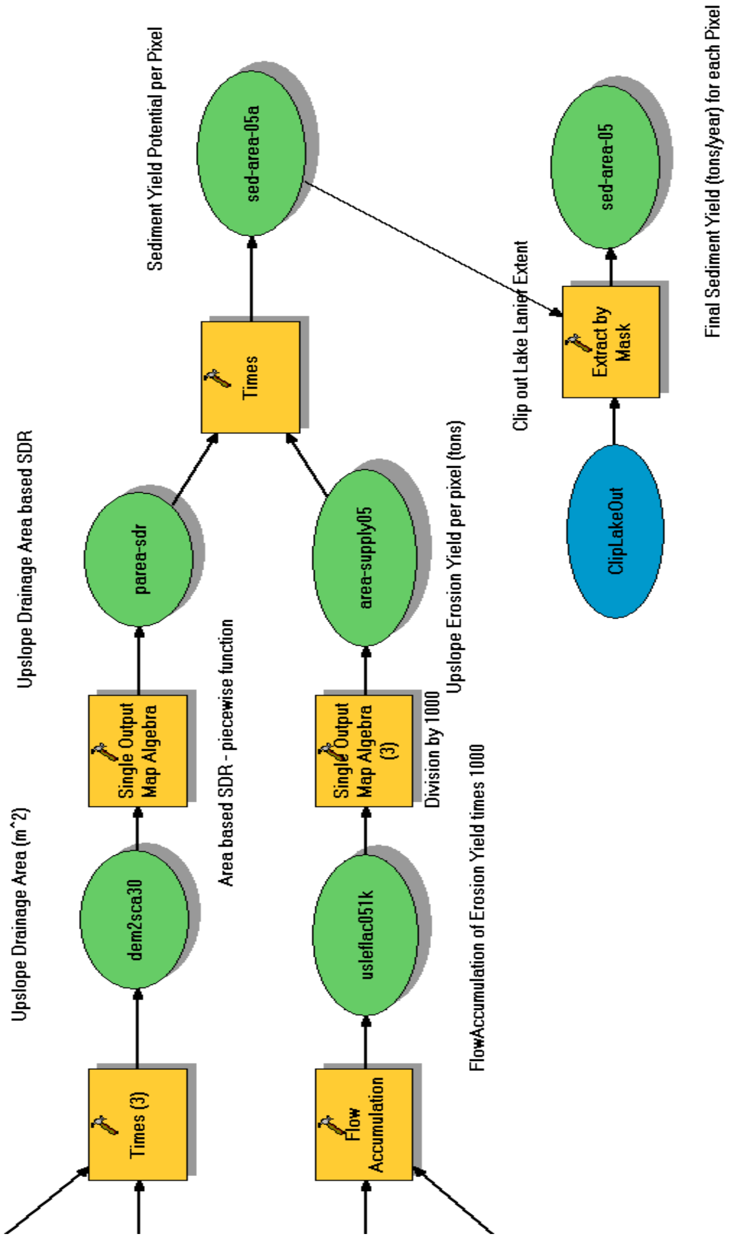

Upslope Drainage Area (m^2)
Times (3)
dem2sca30
Area based SDR - piecewise function
Single Output Map Algebra
parea-sdr
Upslope Drainage Area based SDR
Flow Accumulation
usleflac051k
FlowAccumulation of Erosion Yield times 1000
Single Output Map Algebra (3)
Division by 1000
area-supply05
Upslope Erosion Yield per pixel (tons)
Times
sed-area-05a
Sediment Yield Potential per Pixel
ClipLakeOut
Clip out Lake Lanier Extent
Extract by Mask
sed-area-05
Final Sediment Yield (tons/year) for each Pixel

Figure 49 b

Figure 50a: 1984 Non-Point Source Sediment Yield Potential

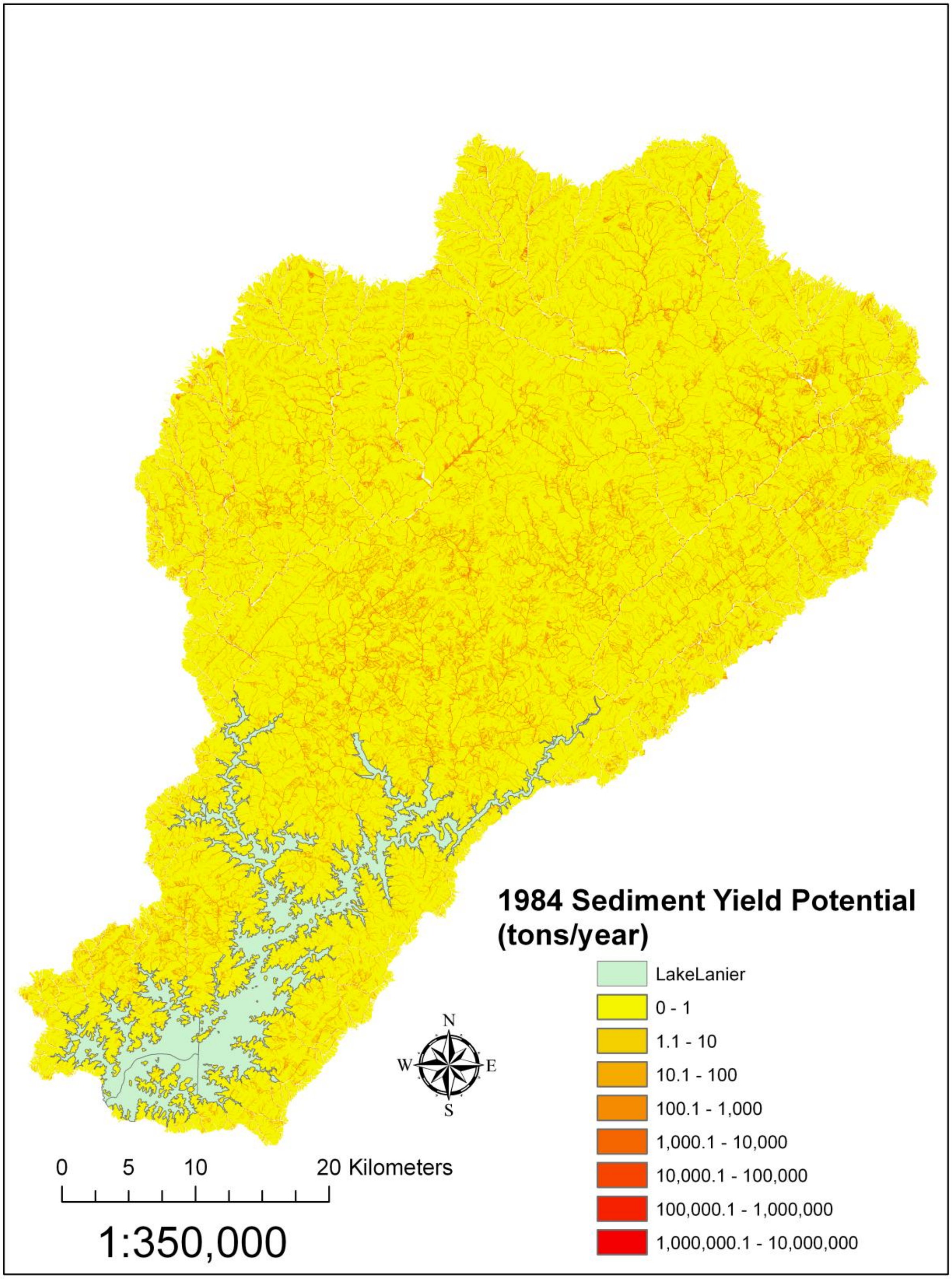


Figure 50b: 1984 Non-Point Source Sediment Yield Potential Close Up

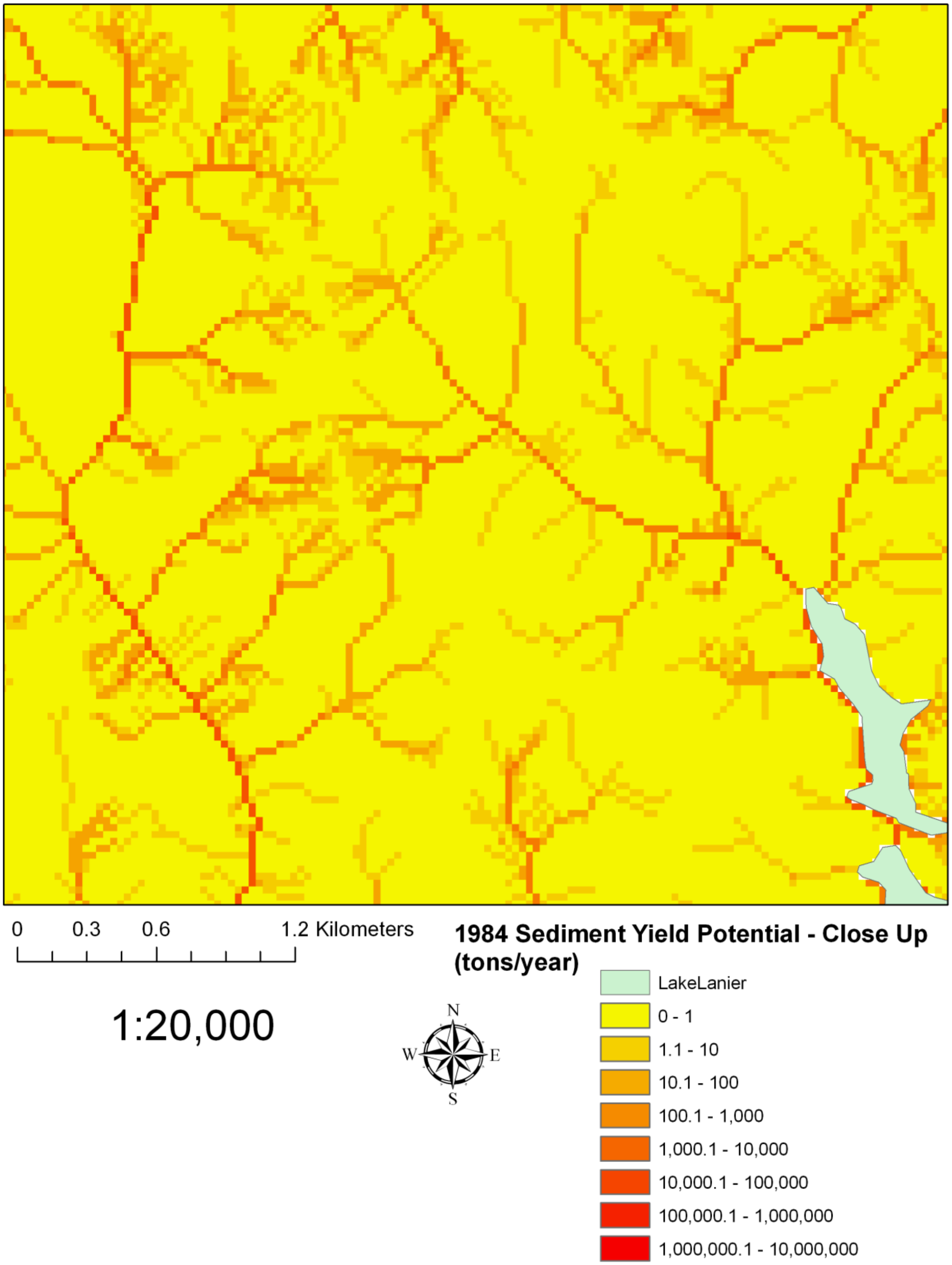


Figure 51a: 1991 Non-Point Source Sediment Yield Potential

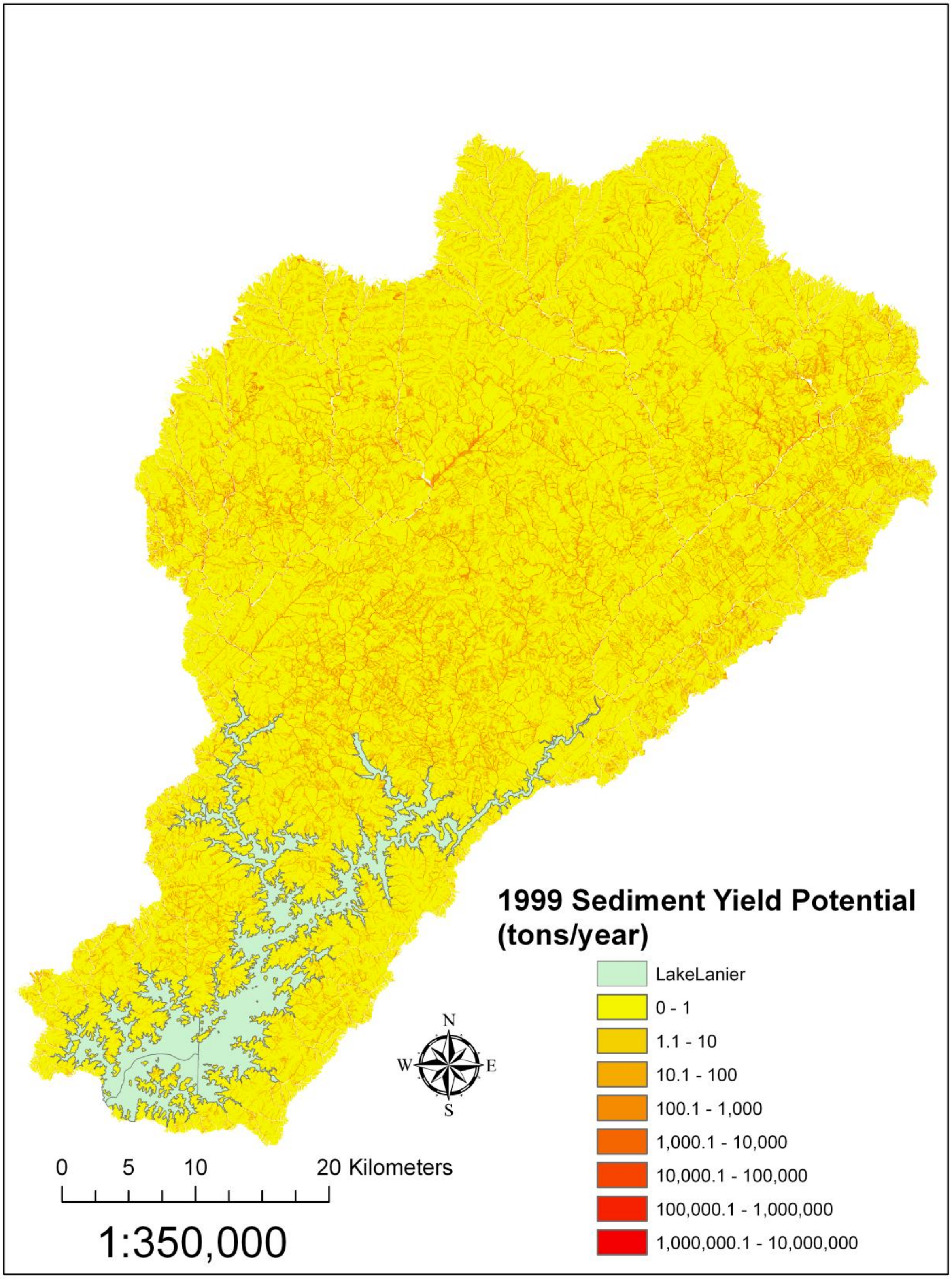


Figure 51b: 1991 Non-Point Source Sediment Yield Potential Close Up

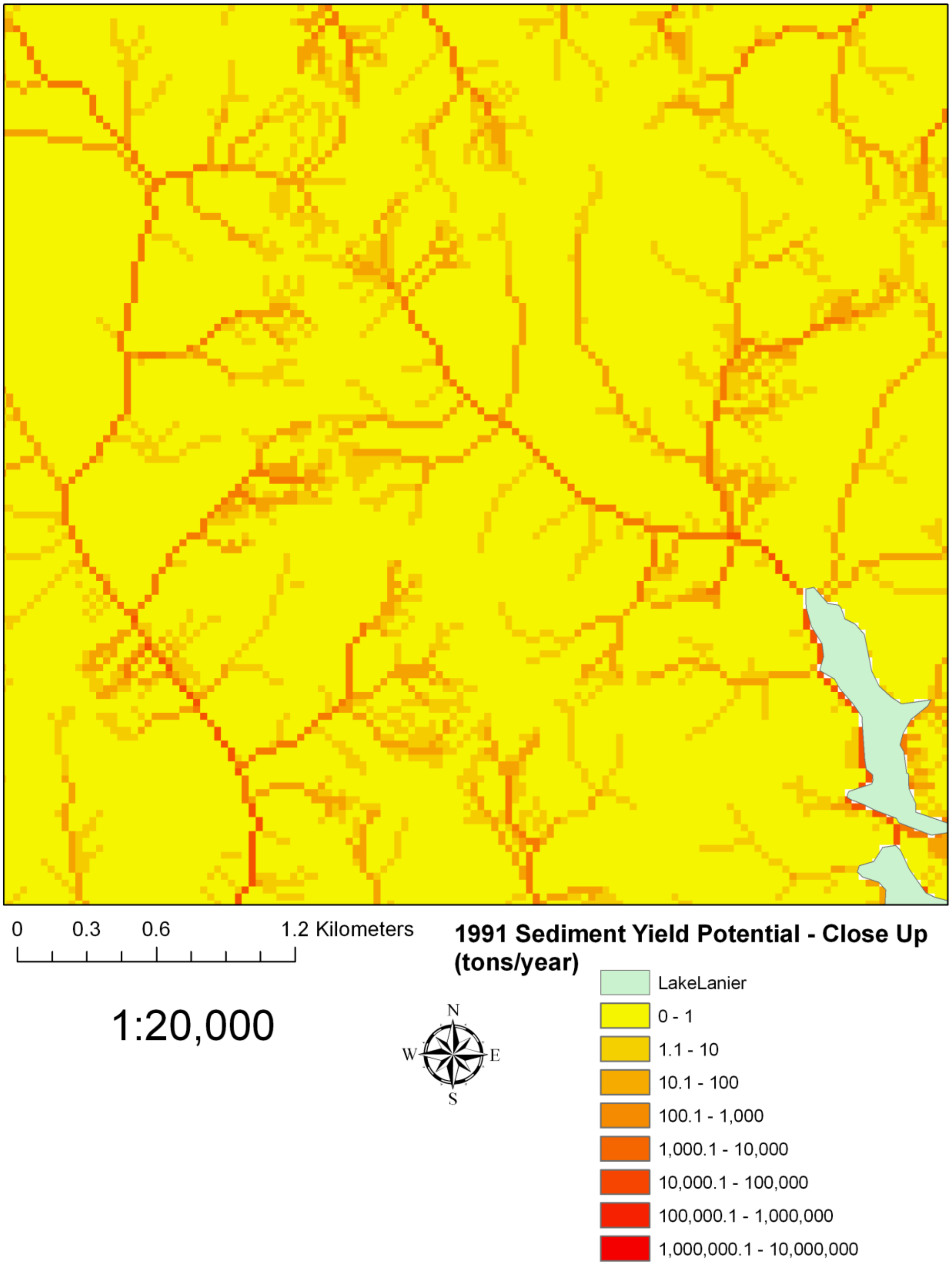


Figure 52a: 1999 Non-Point Source Sediment Yield Potential

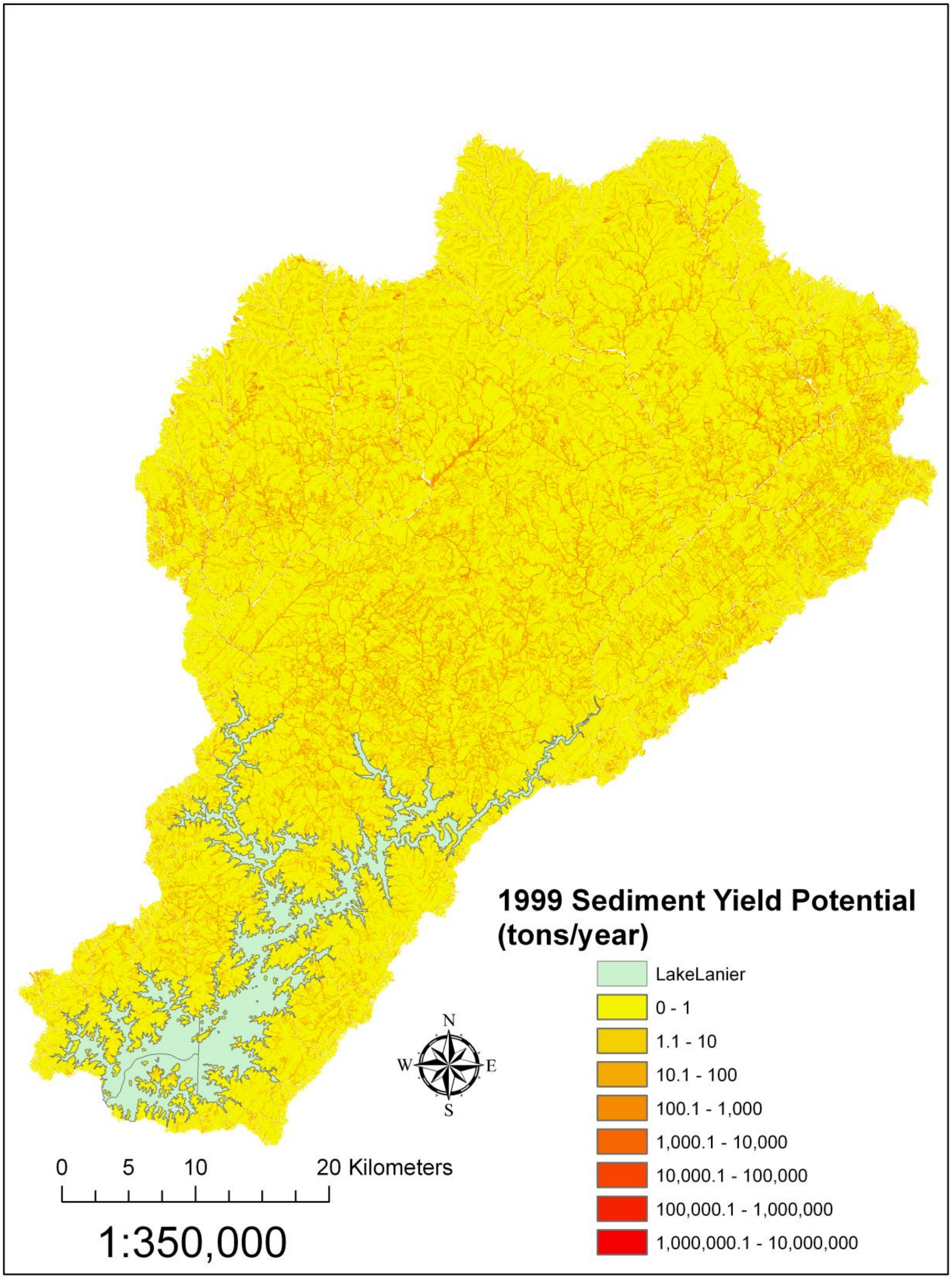


Figure 52b: 1999 Non-Point Source Sediment Yield Potential Close Up

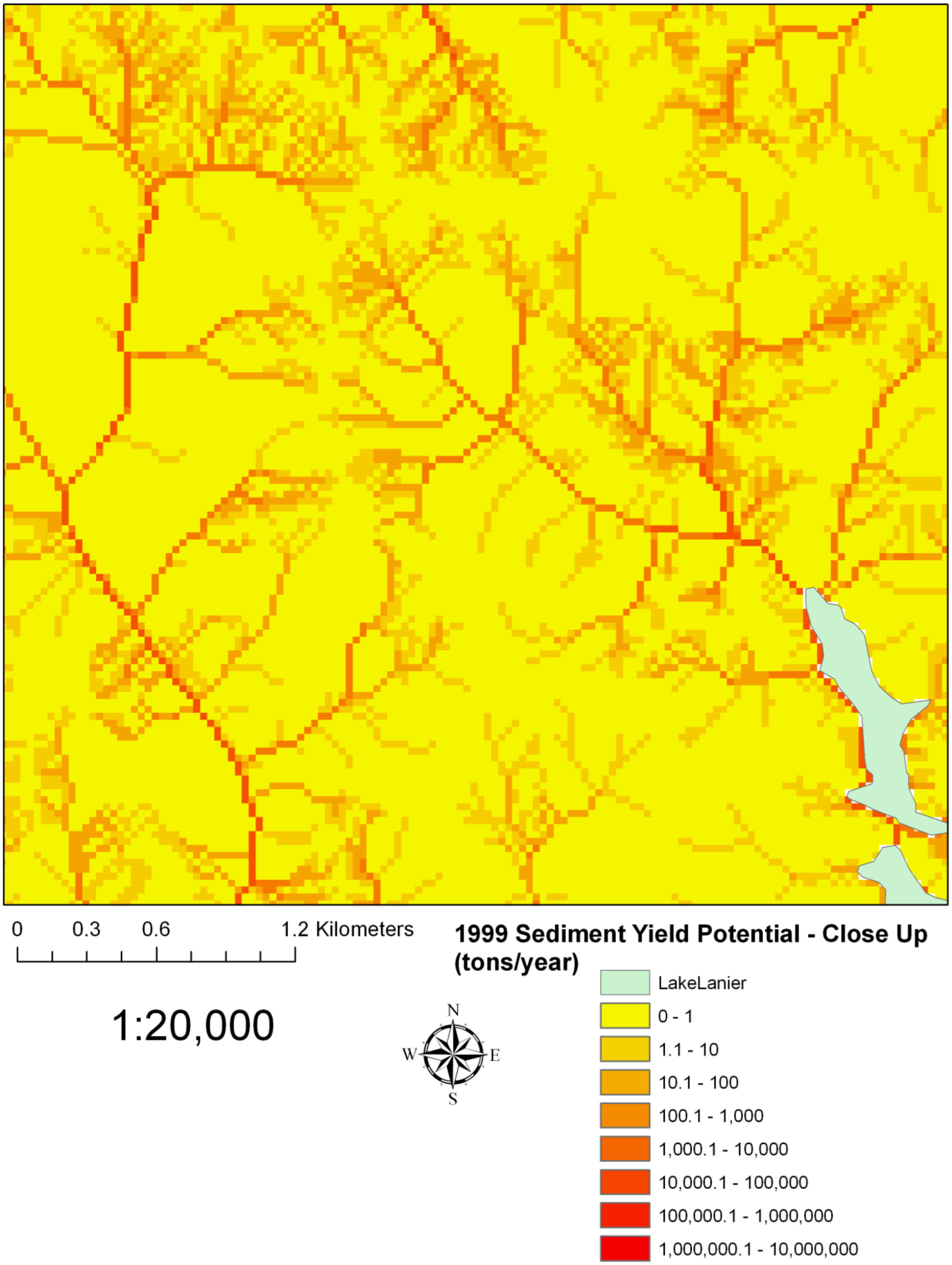


Figure 53a: 2005 Non-Point Source Sediment Yield Potential

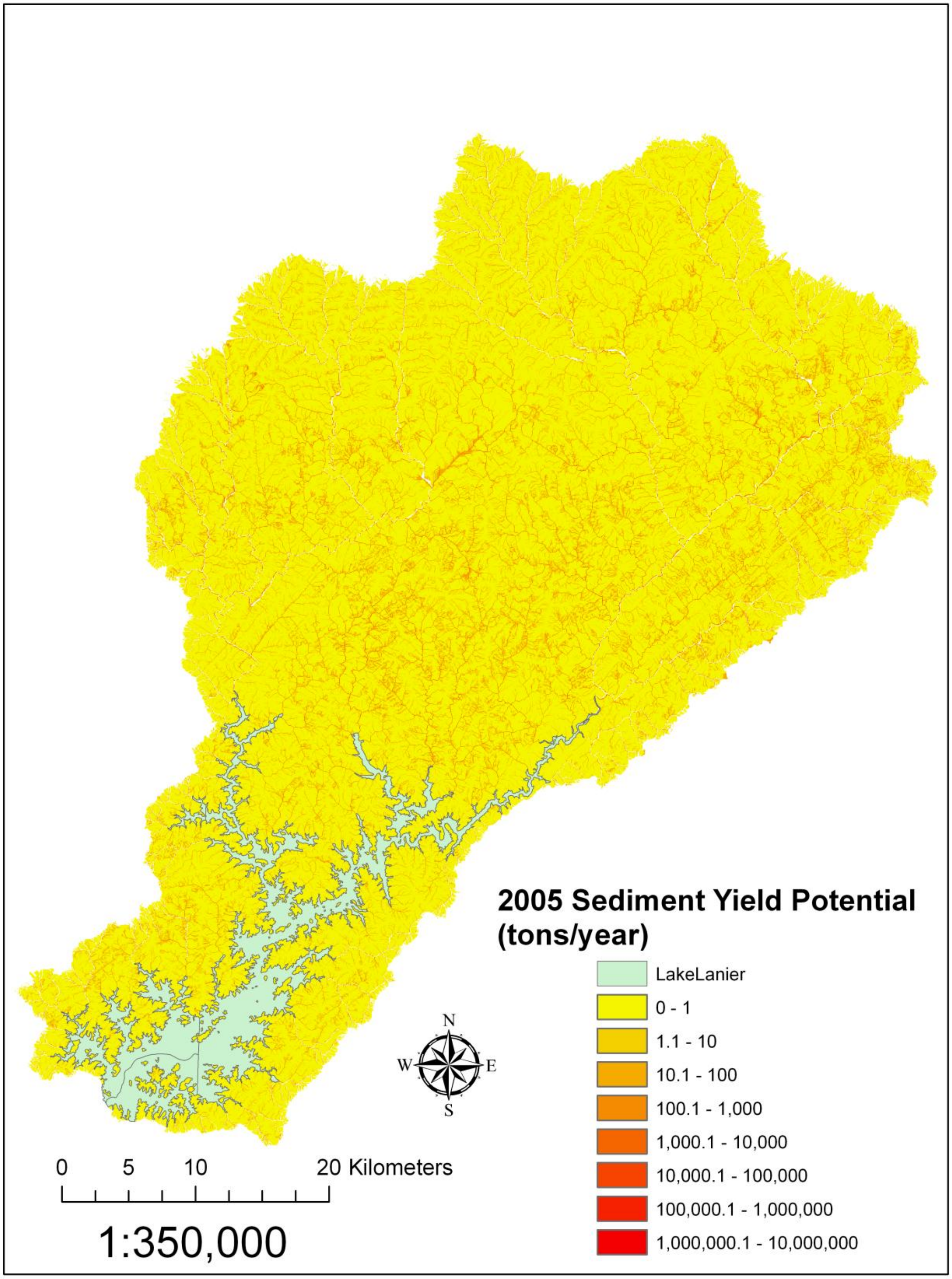
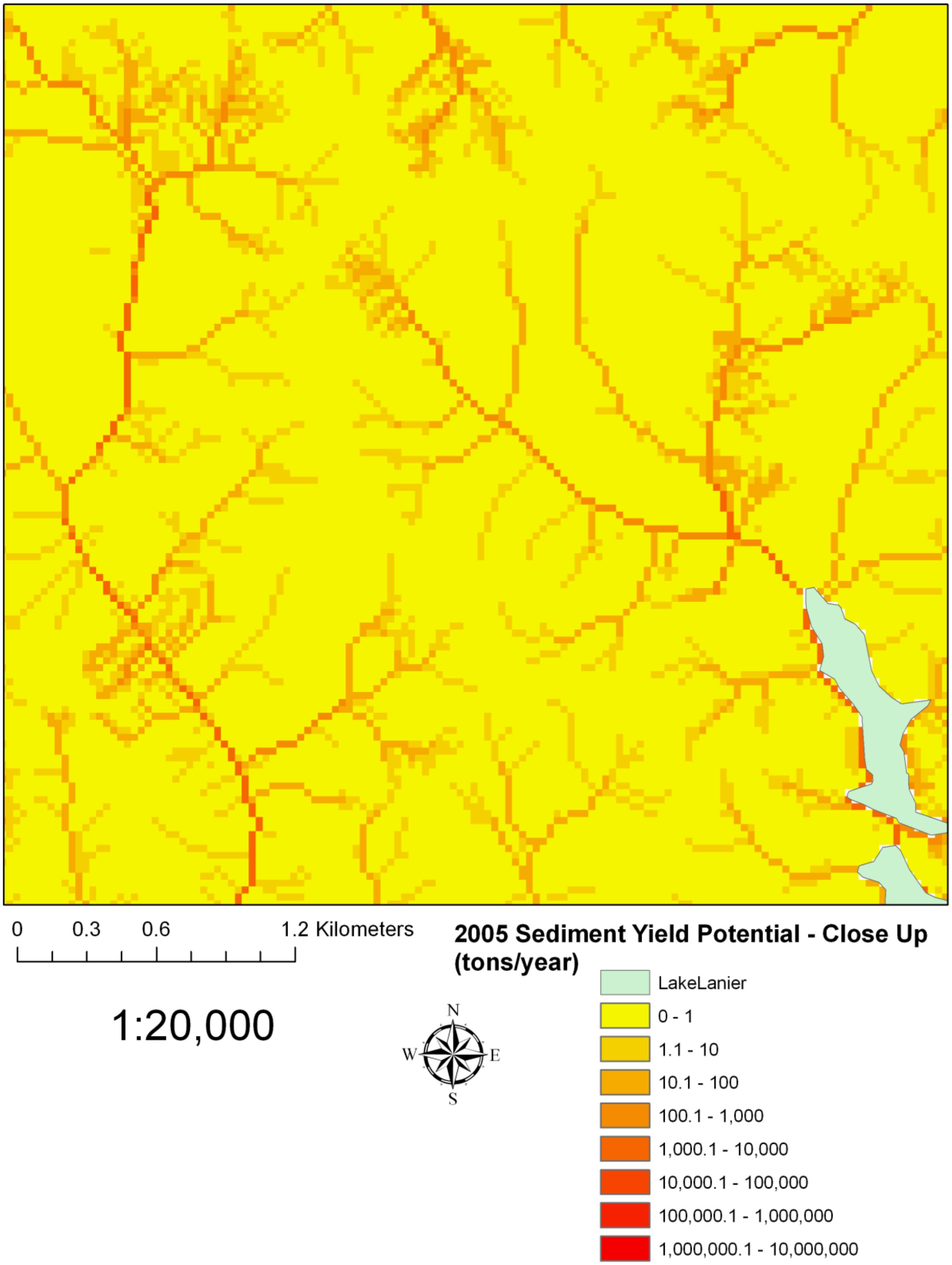


Figure 53b: 2005 Non-Point Source Sediment Yield Potential Close Up



Analysis of Sediment Yield Potential Modeling

A histogram analysis of sediment potential, both in the entire watershed and within a 30 meter buffer around the streams, is indicative of the overall susceptibility of Lake Lanier to sediment input. The histograms of sediment yield potentials during the years 1984, 1991, 1999 and 2005 vary from 1 ton/year to about 10^6 tons/year. This range can be best displayed as a semi-log graph of sediment yield potential class vs. area (Figure 54 through Figure 57). The reclassification of continuous sediment yield potential into discrete classes in increasing powers of 10 provides a natural scheme to classify the degree of susceptibility of a watershed region to sediment deposition. The logarithm of the sediment potential can then provide an '***index of sediment impairment***' which, in this case, ranges from very low sediment impairment of 1 to an extremely large sediment impairment of 6 (Table 10). The sediment yield potential queried along a stream bank buffer will identify the regions and extent of sediment susceptibility along the banks of streams in the watershed. This type of analysis will be shown in detail in Chapter 5.

The Area vs. Index of Impairment Classes histogram over the time period of 1984-2005 provides a summative graphical representation of the extent of watershed area prone to sediment deposition (Figure 58). The percent areas attributed to the different sediment potential classes remain roughly the same over the period of study. The most sediment prone regions of the watershed show increases in 1984 and 1999, commensurate with increases in the highest erosion soil loss rate areas for these same years.

Table 10: Index of Impairment and Sediment Yield Potential Class

Index of Impairment	Sediment Yield Potential Class (tons/year)
0	0 – 1
1	1 – 10
2	10 - 100
3	100 - 1000
4	1000 - 10000
5	10000 - 100000
6	100000 - 1000000

Figure 54: 1984 Area (km^2) vs. Lake Lanier watershed Sediment Yield Potential Class (tons/year)

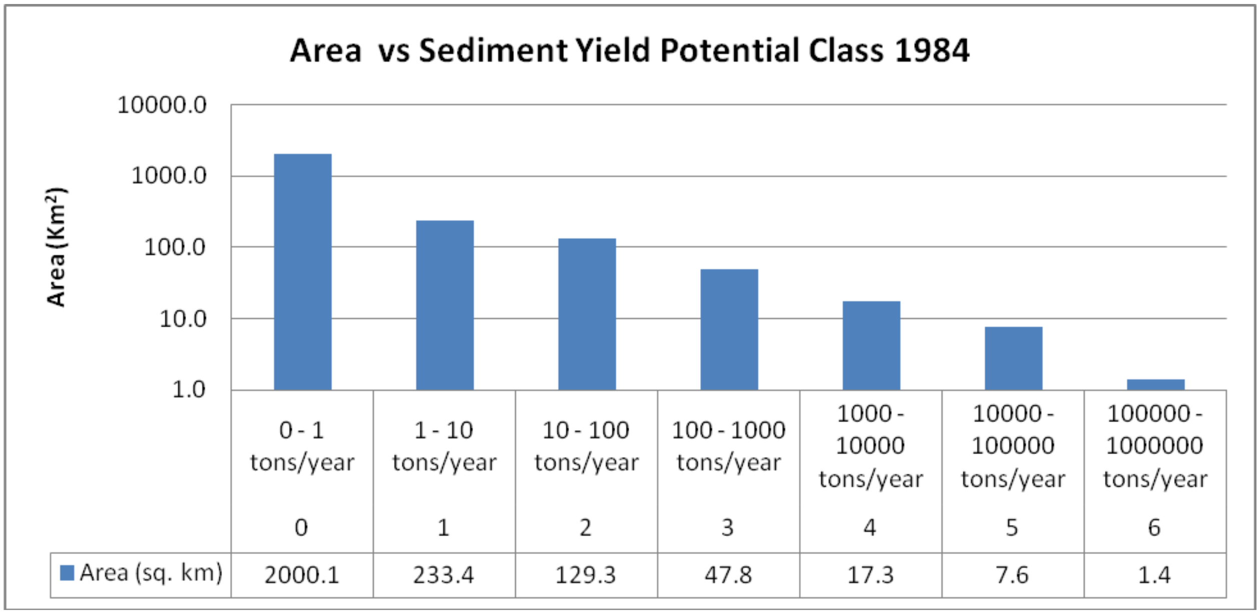


Figure 55: 1991 Area (km^2) vs. Lake Lanier watershed Sediment Yield Potential Class (tons/year)

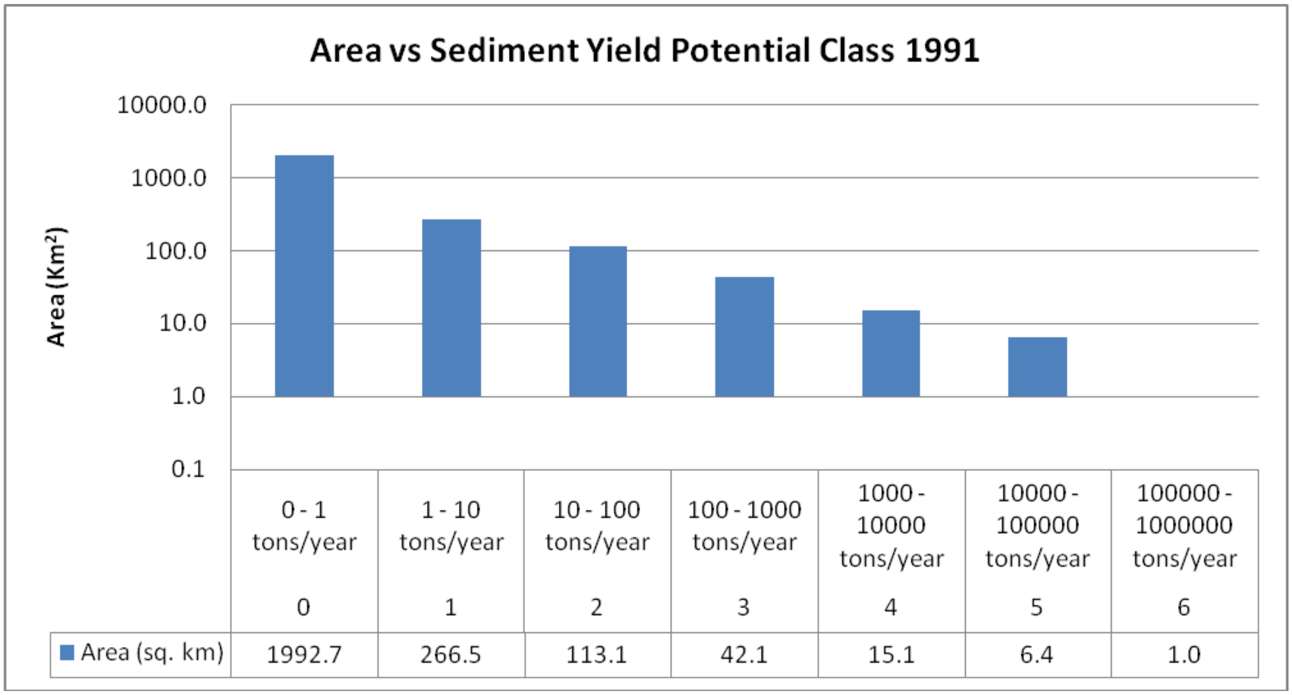


Figure 56: 1999 Area (km^2) vs. Lake Lanier watershed Sediment Yield Potential Class (tons/year)

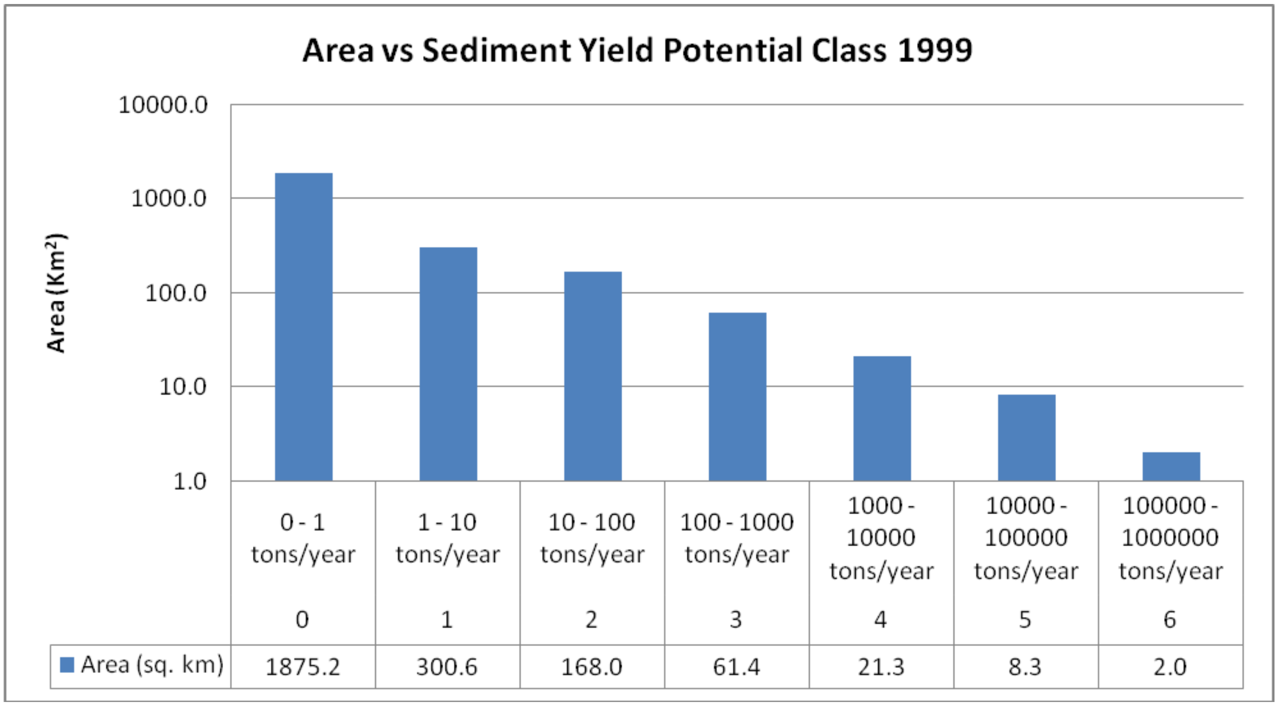
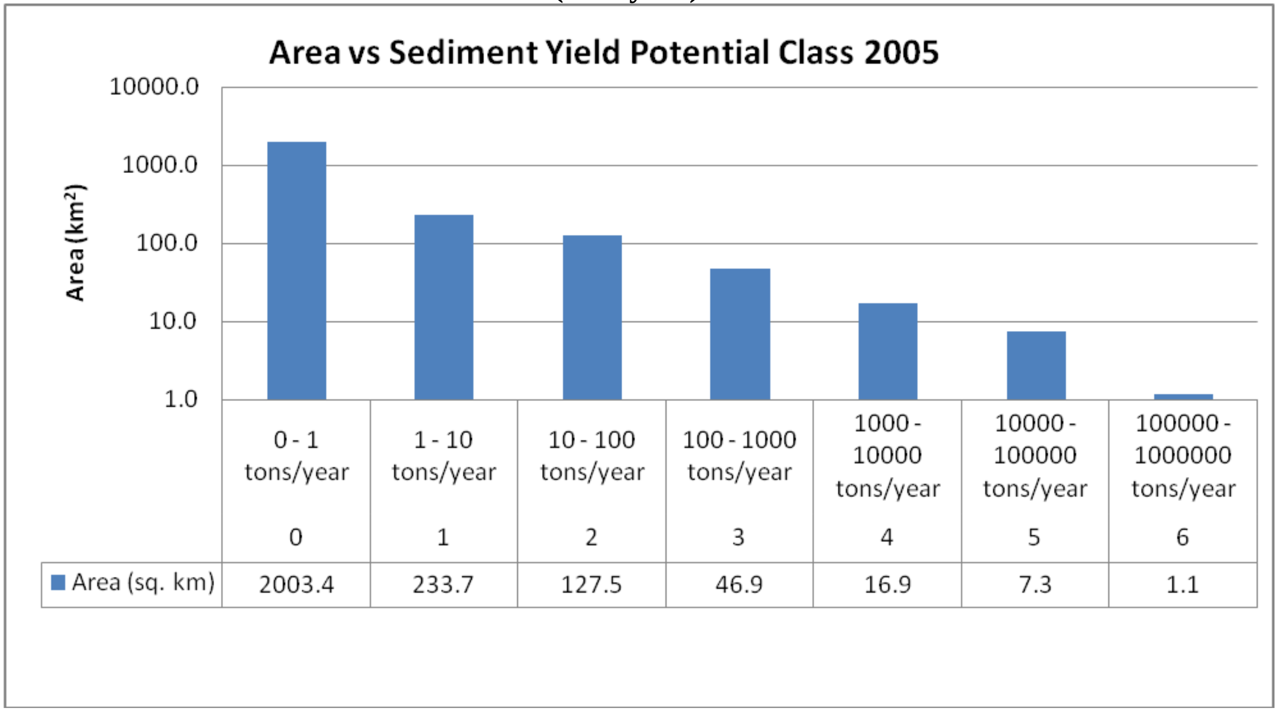
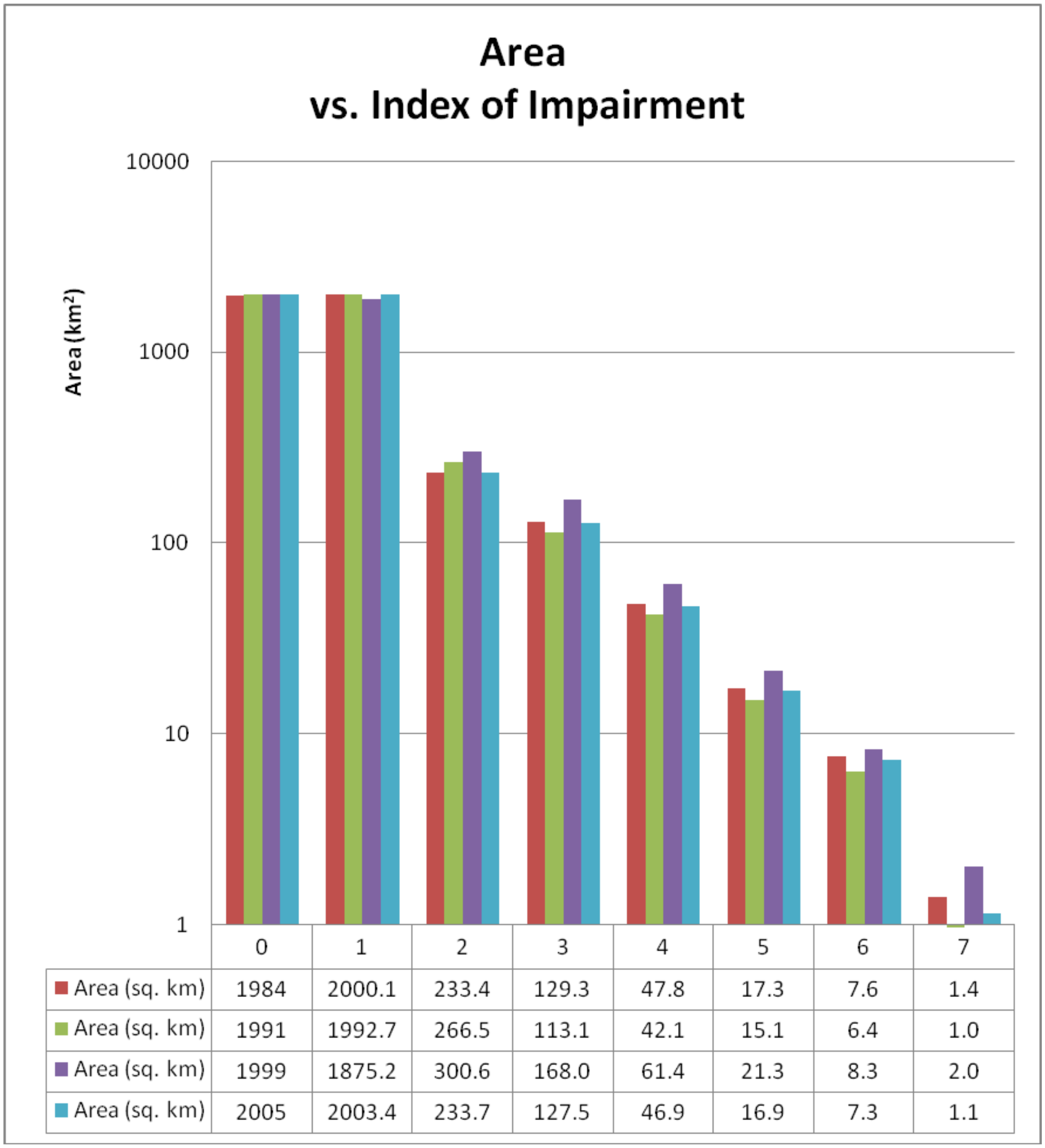


Figure 57: 2005 Area (km^2) vs. Lake Lanier watershed Sediment Yield Potential Class (tons/year)



The high sediment yield classes are noticeably greater for 1984 and 1999 years most likely due to the mainly agricultural nature of the watershed in 1984 and due to increased Pasture/Agriculture class in 1999 which is accompanied by decrease in Forest cover. However, the most sediment deposition prone areas of the watershed with a sediment yield potential of greater than 10^4 tons/year is about 3 percent of the entire watershed area (~ 83 km^2) over the entire period of the study. These regions are mostly along stream banks and flood plains in the watershed. These areas can be queried out from the sediment yield potential maps on ArcGIS and the field measurements of pollutants can be used for calibrating the non-point source modeling of pollutant loads.

Figure 58: 1984 - 2005 Area vs. Index of Impairment



	0	1	2	3	4	5	6	7
🟥 Area (sq. km) 1984	2000.1	233.4	129.3	47.8	17.3	7.6	1.4	
🟩 Area (sq. km) 1991	1992.7	266.5	113.1	42.1	15.1	6.4	1.0	
🟪 Area (sq. km) 1999	1875.2	300.6	168.0	61.4	21.3	8.3	2.0	
🟦 Area (sq. km) 2005	2003.4	233.7	127.5	46.9	16.9	7.3	1.1	

CHAPTER 4

COMPARISON OF 1980's and 1990's EROSION/SEDIMENT YIELD MODELING AND MEASUREMENTS

Validation of modeling results is a critical step that is underestimated or even neglected by many modeling studies. Indeed, validation of spatial models applied to broad geographic areas such as the Lake Lanier watershed may not be viable due to cost and the constraints of field based validation. An alternate method of model validation is to compare results to those of another model. Although there is no guarantee that both model results are accurate, comparisons with previous independent efforts that demonstrate similar results lend a degree of confidence in the assessed model, procedures and results. In addition, if empirical measurements of erosion and sedimentation are available, a good match with modeling results lends credibility to the erosion modeling techniques used in this project and the subsequent sediment modeling that is based on the modeled erosion.

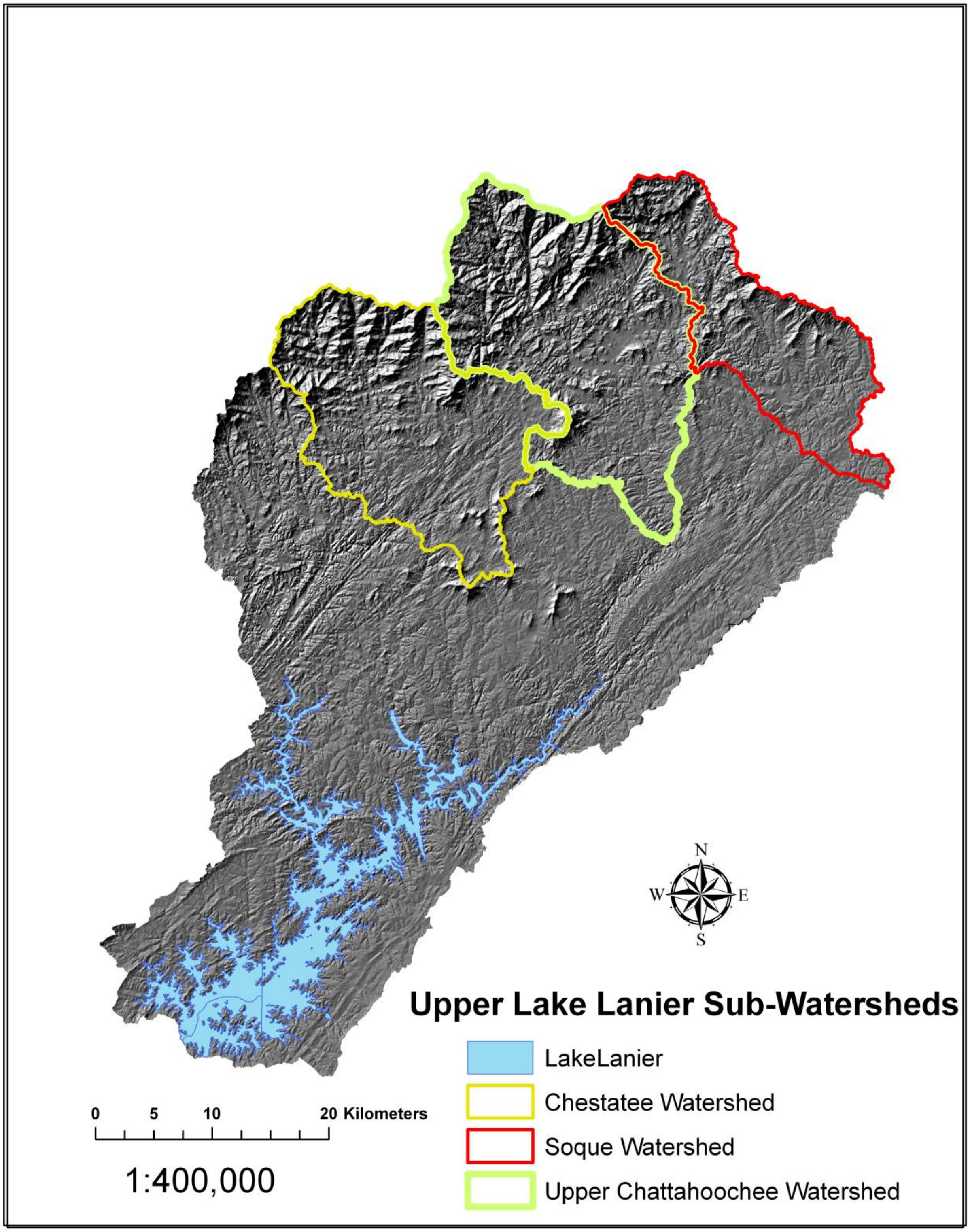
Faye et al. (1980) published a definitive study of erosion and sedimentation in the upper watersheds of Lake Lanier in the late 1970's. This study established a baseline for both the USLE based erosion modeling and sediment discharge measurements in this important water body. The only other sediment discharge measurements into Lake Lanier have been made by Leigh et al. (1998). A favorable comparison of the results of this USLE modeling with the both the work of Faye et al. (1980) and Leigh et al. (1998) will further validate this study.

Comparison of 1984 Erosion Modeling in Three Sub-watersheds of the Lake Lanier watershed with Faye et al. (1980)

Faye et al. (1980) did not have access to modern geospatial data and tools. Therefore, the thoroughness and scope of their work on both the upper and middle Chattahoochee River Basin is a testimony to their careful consideration of the issues and meticulous attention to detail. As a part of their work, Faye et al. studied erosion and sedimentation in the primary upper sub-watersheds that feed Lake Lanier; namely the Upper Chattahoochee, the Chestatee and the Soque Watersheds. Their relative sizes and proximity to each other are shown in Figure 59. These sub-watersheds cover an area of 984 km^2 which is 36.5 percent of the entire Lake Lanier watershed. They contain most of the source waters of Lake Lanier and the Chattahoochee River and also include the steepest terrain in the entire watershed. Terrain relief is the single most important variable in the modeling of erosion processes as the USLE has a quadratic dependence on the slope. This makes the erosion and sediment yield estimates of these sub-watersheds all the more relevant.

The erosion and sediment USLE modeling and sediment discharge measurements by Faye et al. (1980) were completed in the late 1970's and published in 1980. Although the aim of this study was to compare remote sensing based non-point erosion modeling estimates with results from Faye et al., the earliest cloud free multispectral imagery available for this area was acquired on two days in September 1984 by the Landsat MSS instrument. Therefore, the comparison of non-point modeling for 1984 with Faye et al.'s results assumes that no significant land cover change took place in the watershed from the late 1970's to 1984. This is a reasonable assumption because the study area was primarily an agricultural watershed at that time.

Figure 59: The Upper Sub-Watersheds of Lake Lanier Studied by Faye et al. (1980)



These two adjacent September 1984 images of the watershed area were mosaiced, clipped, histogram equalized and color balanced to produce a seamless image of the study area for the extraction of the 1984 land cover.

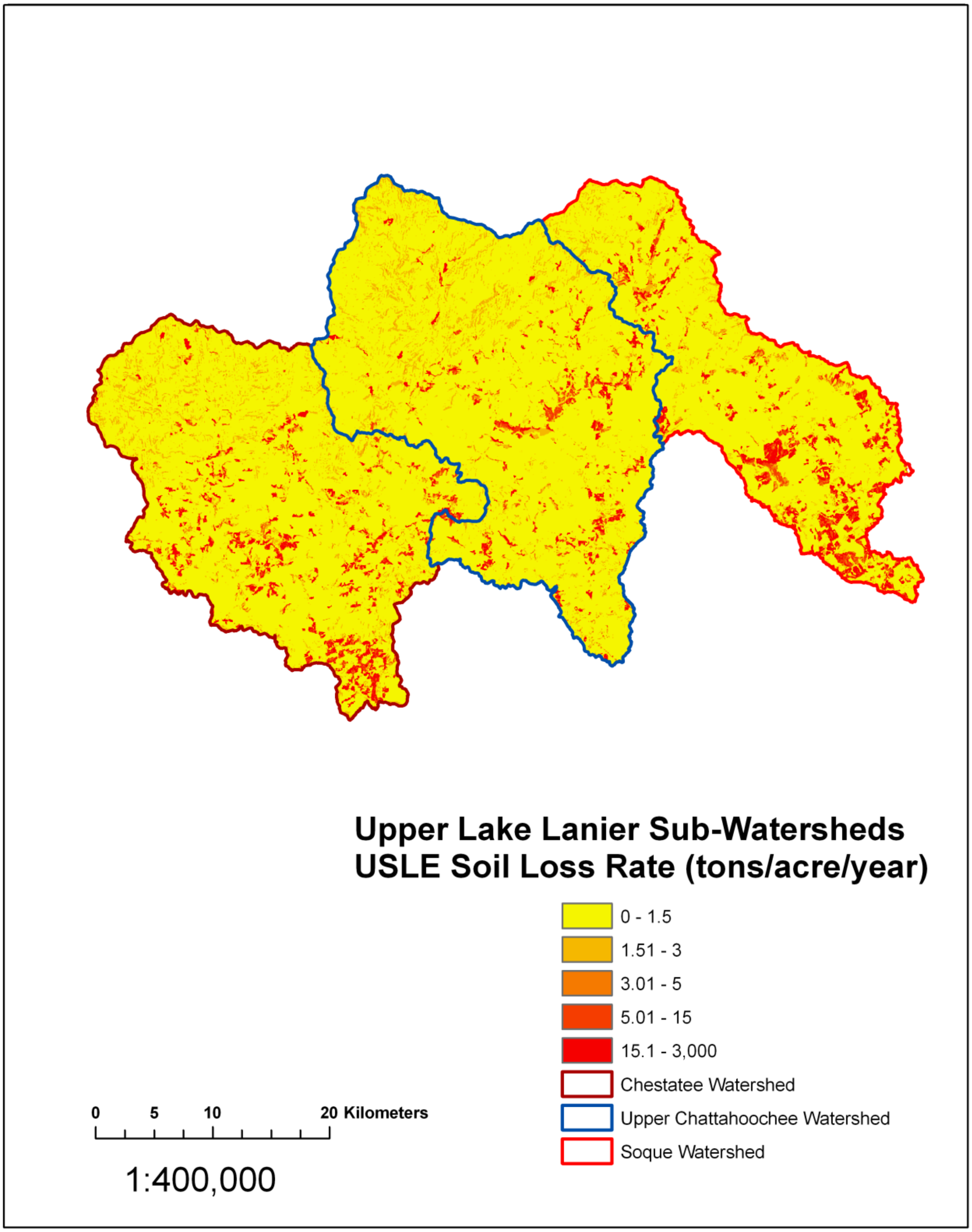
In their USLE modeling study, Faye et al. did not have access to detailed DEM's and land cover maps. They, therefore, lumped the watersheds into regions of relatively similar slope and land cover and summed up the USLE calculations for these lumped 'elements' in the watershed landscape. In this remote-sensing based spatially distributed USLE modeling, the land cover, soil and slope is reasonably well known for every 30 m x 30 m grid cell. This allowance for spatial heterogeneity of Earth surface features should result in a more accurate description of the watershed soil erosion, as described by the USLE.

The spatially distributed USLE soil loss rates for these three Upper Lake Lanier sub-watersheds were calculated (Figure 60). The comparison of USLE erosion results obtained by Faye et al. and erosion results by this spatially distributed USLE modeling are shown in Table 11. Although the average and the total erosion values obtained by Faye et al. are systematically a little over two times larger than the erosion values obtained in this remote sensing based spatially distributed project, the relative estimates of the Chestatee Watershed having the greatest total erosion and the Chattahoochee Watershed having the lowest average erosion were the same for both approaches. Differences in absolute erosion estimates are likely due to lumped vs. distributed model and the fact that Faye et al. used the low resolution soil maps of the late 1970's, while this study used higher resolution (1:12,000 to 1:63,000) SSURGO soil data which is a result of recently completed surveys. Nonetheless, the similarity in relative erosion estimates lends both credibility and continuity in this type of a USLE modeling study for this watershed.

Table 11: Comparison of Distributed Erosion Modeling in Three Lake Lanier Sub-Watersheds Compared to Erosion Modeling by Faye et al. (1980)

	Upper Chattahoochee	Chestatee	Soque
Watershed Area Pixel (30m x 30m) Count	447272	386263	258613
Watershed Area	402.5 Km^2 9.95 x 10^4 Acres 155.4 $Mile^2$	347.6 Km^2 8.59 x 10^4 Acres 134.3 $Mile^2$	232.8 Km^2 5.75 x 10^4 Acres 89.9 $Mile^2$
Faye et al. USLE Model Total Erosion (1976)	3.05 x 10^5 Tons/Year	6.13 x 10^5 Tons/Year	4.82 x 10^5 Tons/Year
Faye et al. USLE Model Soil Loss Rate (1980)	3.06 Tons/Acre/Year	7.14 Tons/Acre/Year	8.38 Tons/Acre/Year
Spatially Distributed USLE Model Total Erosion (1984)	1.79 x 10^5 Tons/Year	2.28 x 10^5 Tons/Year	1.57 x 10^5 Tons/Year
Spatially Distributed USLE Model Soil Loss Rate (1984)	1.78 Tons/Acre/Year/	2.63 Tons/Acre/Year	2.70 Tons/Acre/Year

Figure 60: USLE Erosion in the 1984 Upper Chattahoochee, Chestatee and Soque Watersheds



Comparison of Sediment Discharge Based on 1984 USLE Modeling Results and Sediment Measurements by Faye et al. (1980) and Leigh (1998)

Faye et al. (1980) made estimates of sediment discharge into the Chattahoocee and the Chestatee Rivers for the late 1970's (Table 12). These sediment estimates were based on correlating measured suspended sediment concentration per unit volume of water to measured flow rates of volume per second of the Chattahoochee and the Chestatee Rivers by Faye et al. (1980).

Table 12: Measurement Based Sediment Discharge Estimates to Lake Lanier by Faye et al. (1980)

	Upper Chattahoochee	Chestatee	Soque
Suspended Sediment Discharge (Pg 55, Faye et al. Table 22)	43000 tons/yr	52300 tons/yr	43200 tons/yr
Average Annual Unmeasured Sediment Discharge (Pg 67, Faye et al., Table 25)	21200 tons/yr	21300 tons/yr	----------------
Average Annual Total Sediment Discharge (Pg 67, Faye et al., Table 25)	64200 tons/yr	73600 tons/yr	-----------------

Note: the Unmeasured and Total Sediment Discharge for Soque was not reported by Faye et al. (1980)

The total sediment discharge into the Chattahoochee and the Chestatee Rivers around 1980 as estimated by Faye et al., is compared to the estimates based on the spatially distributed 1984 USLE based erosion modeling and a lumped area based SDR, for these sub-watersheds (Table 13). It is apparent that the sediment discharge estimates based on Faye et al.'s empirically based approach and the spatially distributed non-point source USLE modeling approach are within 40 percent of each other. This comparison of the sediment discharge estimated using two different approaches lends greater credibility to the drainage area based erosion and sediment modeling method.

Table 13: Comparison of Sediment Discharge from Non-point source Modeling Results with Sediment Discharge Measurements of Faye et al. (1980) in Upper Sub-watersheds

	1984 USLE Non-point source Modeling				**Faye et al. (1980) Measurements**	**Modeling Error**
	Modeled Total Erosion (tons/year)	Watersed Area (km^2)	Area based SDR (from Fig. 36)	Modeled Sediment Discharge (tons)	Measured Sediment Discharge (tons)	Percent Difference (relative to measured Discharge)
Upper Chattahoochee	795,000	348	0.1	79,500	64,200	+23.8 %
Chestatee	1,020,000	403	0.1	102,000	73, 600	+38.5%
Soque	698,000	233	0.12	83,760		

Note: No sediment discharge results were reported for the Soque watershed by Faye et al.

In their study, Faye et al. also made measurements of the sediment discharge into Lake Lanier via the Chattahoochee River, its tributary the Soque River, and the Chestatee Rivers, which accounts for 73 percent of the total water inflow into Lake Lanier. In addition, an average annual unmeasured sediment discharge was estimated by Faye et al. to obtain an empirically based estimate of the total sediment input into Lake Lanier in the early 1980's. Therefore, the total sediment measured inflow of sediment in 1984 into Lake Lanier is around 140,000 tons/year from these three rivers. It would therefore be reasonable to include proportionally additional sediment discharge due to the remaining 27 percent inflow into Lake Lanier. Therefore, estimates of the annual sediment input into Lake Lanier were upwards of 200,000 tons per year in the early 1980’s. Leigh (1998) used techniques similar to Faye et al. (1980) to calculate the sediment discharge into Lake Lanier from the Chattahoochee and the Chestatee Rivers in the mid 1990’s to be 256,000 tons/year (Table 14). The sediment discharge estimates into Lake Lanier from both the empirically based methods and the non-point source modeling approach, for 1984 and 1999, compare very well with each other. This further validates this spatially distributed non-point source erosion and sedimentation study, and lends confidence to the sediment discharge results from 1991, 1992, 2001 and 2005 as well.

Table 14: Comparison of Non-point source Modeling with Measurements of Faye et al. (1980) for Sediment Discharge to Lake Lanier in Late 1970’s and Leigh (1998) in Mid 1990’s

	Sediment Input from Entire Watershed from Modeled non-point source USLE Erosion and Lumped Watershed SDR of 0.1	Measured Sediment Input by Faye et al. in 1980 (pg 67) (from Chattahoochee and Chestatee only)	Measured Sediment Input by Leigh (1990) (from Chattahoochee and Chestatee only)
1984 (STATSGO)	188000 tons/year	138000 tons/year (from 73 percent of Lake Lanier Watershed)	
1984 (SSURGO)	145,000 tons/year		
1991 (SSURGO)	95,400 tons/year		
1992 (SSURGO and NLCD)	172,000 tons/year		
1999 (SSURGO)	233,000 tons/year		256,000 tons/year (from 73 percent of inflow into Lake Lanier)
2001 (SSURGO and NLCD)	203,000 tons/year		
2005 (SSURGO)	137,000 tons/year		

The non-point source USLE modeling for the entire Lake Lanier watershed calculated the 1984 total erosion to be 1.45 x 10^6 tons/year (SSURGO) and 1.88 x 10^6 tons/year (STATSGO). By taking a ratio of the total annual modeled soil erosion with the total annual measured sediment for the early 1980's, we get a watershed wide SDR in a range of 0.14 based on SSURGO and 0.11 based on STATSGO. Referring to the drainage area vs. SDR graph, for a watershed with an area 2.7 x 10^9 meter^2 (2693 km^2) the SDR should be around 0.1 or lower (Figure 45). This means that there is a concordance between this non-point source 1984 USLE modeling and sediment measurements by Faye et al. (1980) in the late 1970's and Leigh (1998) in the mid 1990's. The matching of results from different approaches also validates this non-point source modeling approach for each of the years after 1984. A level of confidence is thus gained for this remote sensing based non-point source erosion modeling. This approach can be very useful for determining spatial and temporal trends in erosion and sediment yield in the Lake Lanier watershed and can help optimize erosion and sedimentation remediation efforts in this important watershed.

CHAPTER 5

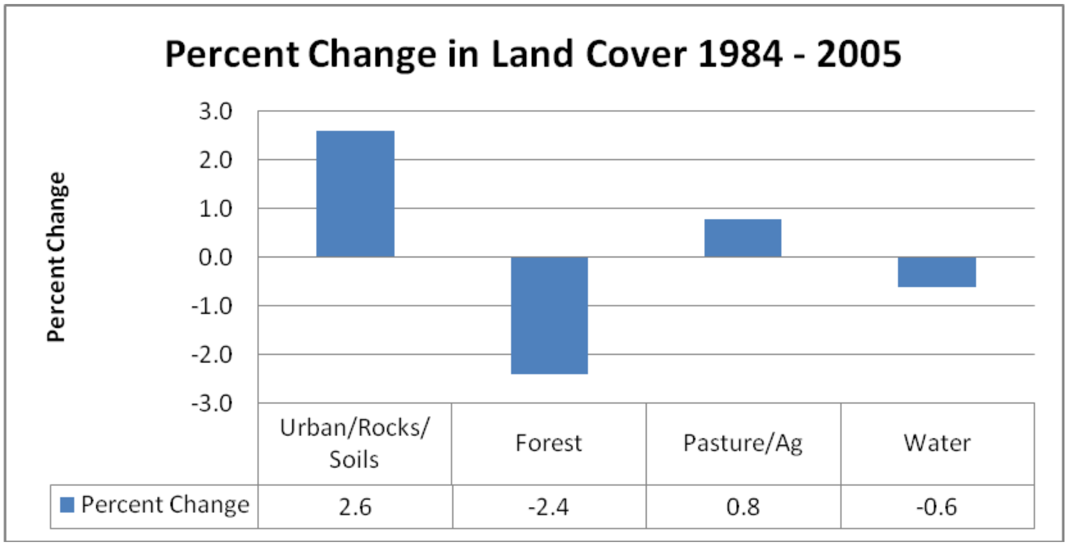
ANALYSIS AND IMPLICATIONS OF RESULTS

The 1984, 1991 and 1999 remote sensing based non-point source modeling approach resulted in erosion and sedimentation estimates relatively comparable to both the modeling and empirical methods of Faye et al. (1980) and empirical methods of Leigh (1998). The USLE soil loss rates and subsequent sediment yield modeling was repeated for 1999 and 2005. This allowed the identification of the areas with high erosion potential and high sedimentation potential, and provided spatial trends over time. This knowledge is essential for the emplacement of effective soil conservation measures. The change in soil loss rates is primarily dependant on land cover change. Land cover change leading to increasing urbanization can have a major impact on soil loss rates and consequent sediment discharge into Lake Lanier. The upslope sediment loading on the stream banks of the Lake Lanier watershed can be analyzed to identify the steam segments most susceptible to sedimentation. These issues will be examined in the following sections.

Land Cover Change and Erosion

Trends in erosion and sediment yield potential for the Lake Lanier watershed over the 21-year study period are largely dependent on changes in land cover within the watershed. The total land cover change from 1984 to 2005 was about 6 percent (Figure 61). In general, the forest/tree cover has decreased by about 2.4 percent and the pasture/agriculture has increased by about 0.8 percent. This is accompanied by an increase in urban/rocks/soils of about 2.6 percent. In addition, the extent of water area in the watershed has decreased by 0.6 percent. This could be due to changes in the level of Lake Lanier which is regulated by the U.S. Army Corps of Engineers. Therefore, it would be reasonable to assume that the total land-cover change was about 6 percent (62.4 square miles) of the watershed area. It is also reasonable to assume that the land was denuded to bare soil in the process of change of land cover, the bulk of which is due to urbanization. The average slope for urbanized areas is usually low and for forests can be higher. So, for about 3 percent (31.2 square miles ~ 20000 acres) of the land-cover change to urban, we will assume a smaller slope of 10 percent. For the forest and pasture/agriculture change of about 3 percent of watershed area, we will assume a higher 25 percent slope. The average upslope drainage area for a pixel in this watershed is 105 (30 m x 30 m) pixels and so it would be reasonable to assume an average flow length of roughly 3000 m (~10000 feet), terminating in a stream or water body. This gives approximate length-slope LS factors of about 4 for urban and about 20 for forest and pasture/agriculture, as determined from the graph that correlates flow length and slope to the LS factor in Wischmeier and Smith (1978). The average soil erodibility k-factor for the Lake Lanier watershed is 0.224.

Figure 61: Graph of the Change in Land Cover between 1984 and 2005



	Urban/Rocks/ Soils	Forest	Pasture/Ag	Water
🟦 Percent Change	2.6	-2.4	0.8	-0.6

A USLE calculation then yields an estimate as follows;

For change to urban,

$E_1 = R\ K\ LS\ C\ P = 340 \times 0.224 \times 4 \times 0.5 \times 1 = 152$ ***tons/acre/year***

Erosion yield 152 tons/acre/year x 20000 acres = 3.0×10^6 ***tons/yar***

For change from forest and pasture/agriculture,

$E_2 = R\ K\ LS\ C\ P = 340 \times 0.224 \times 20 \times 0.5 \times 1 = 762$ ***tons/acre/year***

Erosion yield 762 tons/acre/year x 20000 acres = 15.0×10^6 ***tons/year***

Total Erosion yield due to land-cover change from 1984 to 2005 = 18.0×10^6 ***tons/year***

However, this erosion will be spread out over the 21-year period between 1984 and 2005, giving an additional erosion yield of at least 1.0 x 10^6 tons per year. With a sediment delivery ratio (SDR) of approximately 0.1, at least an additional 100,000 tons of sediment per year flows into Lake Lanier due to anthropogenic land cover change activities. This means that natural erosion has been augmented by human induced land cover change, and can almost double the 2005 modeled sediment discharge in Lake Lanier to about 237,000 tons/year.

Deviation of Spatial Distribution of Modeled Erosion from Soil Loss Tolerance in the Lake Lanier Watershed

Soil is created by the weathering of geologic material and deposition of organic matter due to vegetation. Soil is then eroded, transported and deposited by forces exerted by water, wind and gravity. As discussed in the introductory chapter, soil loss tolerance or the T-factor, has been defined by the NRCS in the National Resources Inventory (NRI 2003). A SSURGO soil database

T-factor for the Lake Lanier watershed is shown in Figure 9. A tolerable soil loss rate is a function of climate, geologic underlayment, vegetation and terrain characteristics. In order to sustain future higher populations, the preservation of agricultural productivity of valuable farm land is a critical imperative. Therefore, the regions where the soil erosion exceeds the soil loss tolerances are the primary regions where soil conservation efforts must be deployed.

In order to assess the deviation of the spatially distributed soil loss rate from the spatially distributed SSURGO soil loss tolerance, the T-factor layer was subtracted from the modeled USLE soil erosion for 1984, 1991, 1999 and 2005. This results in spatial data layers that represent the deviation of soil erosion from the soil loss tolerances for the years of this study. The areas in need of soil conservation efforts are clearly identifiable and it is also apparent that in most of the watershed the soil loss rate is below the soil loss tolerance. The annually averaged deviations of modeled soil erosion from the soil loss tolerance show that non-point source USLE soil loss rate exceeded the soil erosion tolerances in 13 to 20 percent of the watershed area, for the period of this study (Table 15).

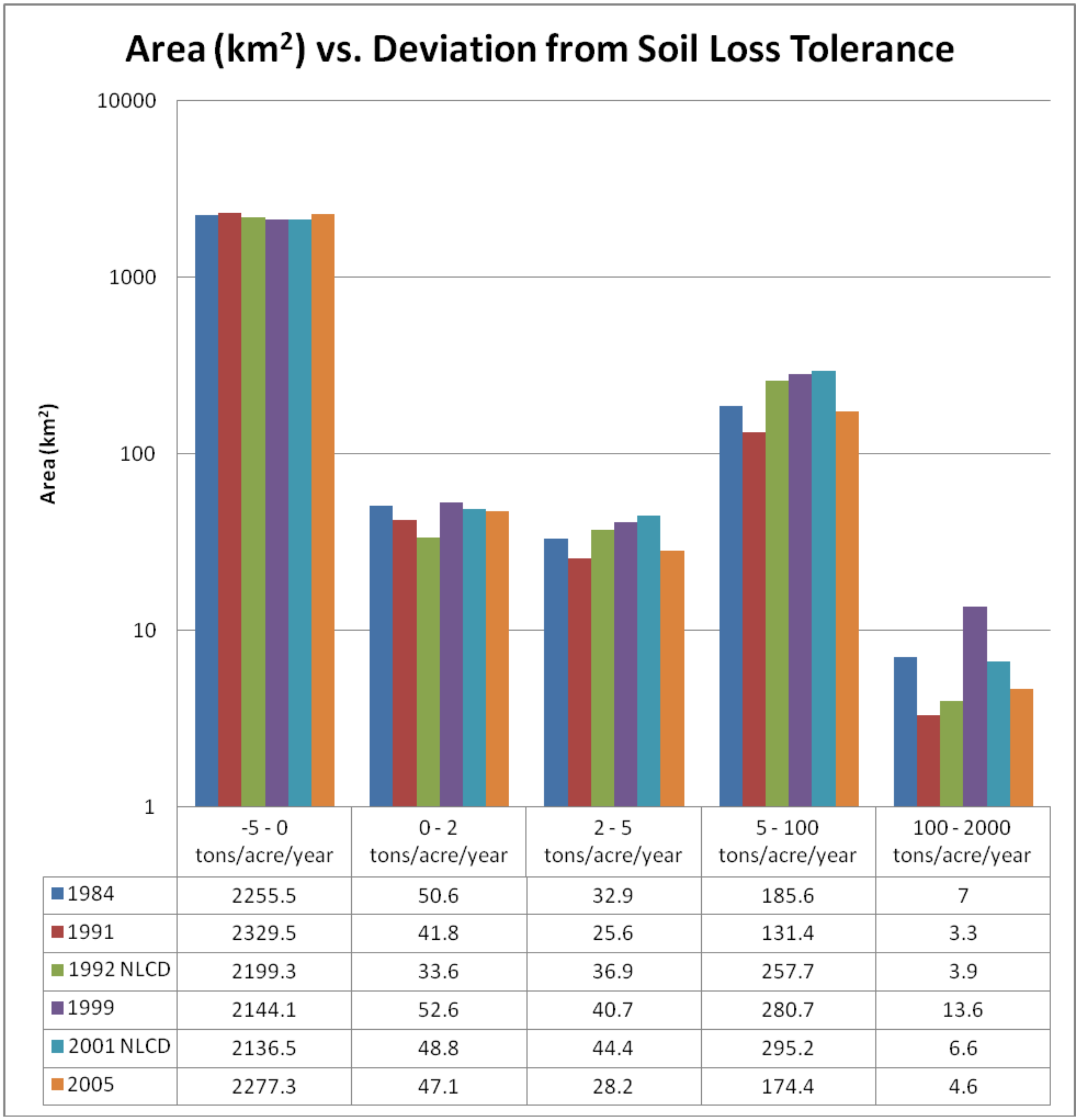
It is apparent that the annual average soil loss rate in the Lake Lanier watershed is roughly 1 to 3 tons/acre/year below the soil loss tolerance, for the years of this study. Both improved soil conservation efforts and the increase of impervious surfaces due to urban growth result in lower erosion. However, increased impervious surface also increases the runoff velocity and thereby increases erosion due to stream scour. Greater urbanization also increases non-point source pollutant transport to the water bodies and the quantification of these effects is an active area of research.

Table 15: Average Deviation of Soil Erosion from Soil Loss Tolerance for 1984, 1991, 1992 1999, 2001 and 2005

Year	Average Deviation tons/acre/year	Standard Deviation tons/acre/year	Percent Watershed Area Impaired by Soil Loss	Percent Watershed Area with Acceptable Erosion
1984	-2.57	14.3	14.9	85.1
1991	-3.37	10.4	12.1	87.9
1992 NLCD	-0.17	16.7	18.3	81.7
1999	-1.08	18.6	19.9	80.1
2001 NLCD	-0.94	15.4	20.7	79.3
2005	-2.70	11.9	14.1	85.9

The histograms for the areas of the deviation of soil loss erosion from the allowable tolerance classes provide a measure of the areas in which the erosion exceeds or is less than the soil loss rate needed to maintain the soil productivity indefinitely (Figure 62). For the time period of this study, on the average, 85 percent (2250 km^2) of the watershed area has soil loss rates below the soil loss tolerance. This means about 15 percent (400 km^2) of the watershed has erosion above the soil loss tolerance. The percentage of watershed area exceeding the erosion tolerance remains approximately the same over the years of this study. Therefore the increase in erosion impairment happens in the regions where the erosion is already above the soil loss tolerance. It is noteworthy that the deviation from the soil erosion tolerance by the soil loss rate calculated using the 1992 and 2001 NLCD LULC follows the same histogram as for the Landsat image derived LULC for the other years of this study. This confirms the utility of the Landsat derived LULC for non-point source soil erosion studies such as this. The spatial locations of erosion impairment are identifiable on the deviation from soil loss tolerance maps and provide essential information for targeting soil conservation efforts (Figure 63 through Figure 68).

Figure 62: Histogram of Area vs. Deviation of Modeled 1984, 1991, 1992 (NLCD), 1999, 2001 (NLCD) and 2005 USLE Soil Erosion Rate from Soil Loss Tolerance T-factor



	-5 - 0 tons/acre/year	0 - 2 tons/acre/year	2 - 5 tons/acre/year	5 - 100 tons/acre/year	100 - 2000 tons/acre/year
1984	2255.5	50.6	32.9	185.6	7
1991	2329.5	41.8	25.6	131.4	3.3
1992 NLCD	2199.3	33.6	36.9	257.7	3.9
1999	2144.1	52.6	40.7	280.7	13.6
2001 NLCD	2136.5	48.8	44.4	295.2	6.6
2005	2277.3	47.1	28.2	174.4	4.6

Figure 63: Deviation of Modeled 1984 Erosion Rate from Soil Loss Tolerance T-factor Close Up

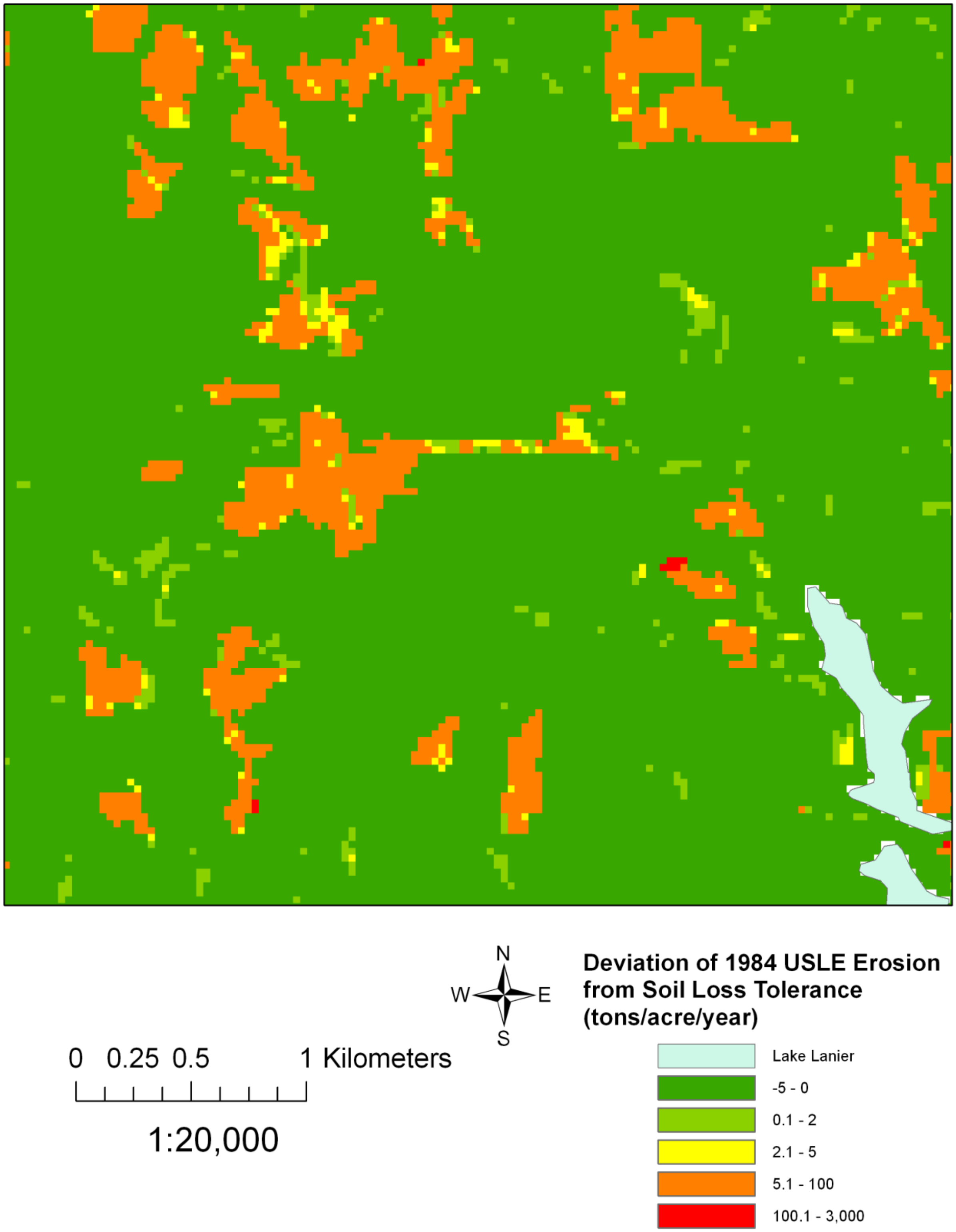


Figure 64: Deviation of Modeled 1991 Erosion Rate from Soil Loss Tolerance T-factor Close Up

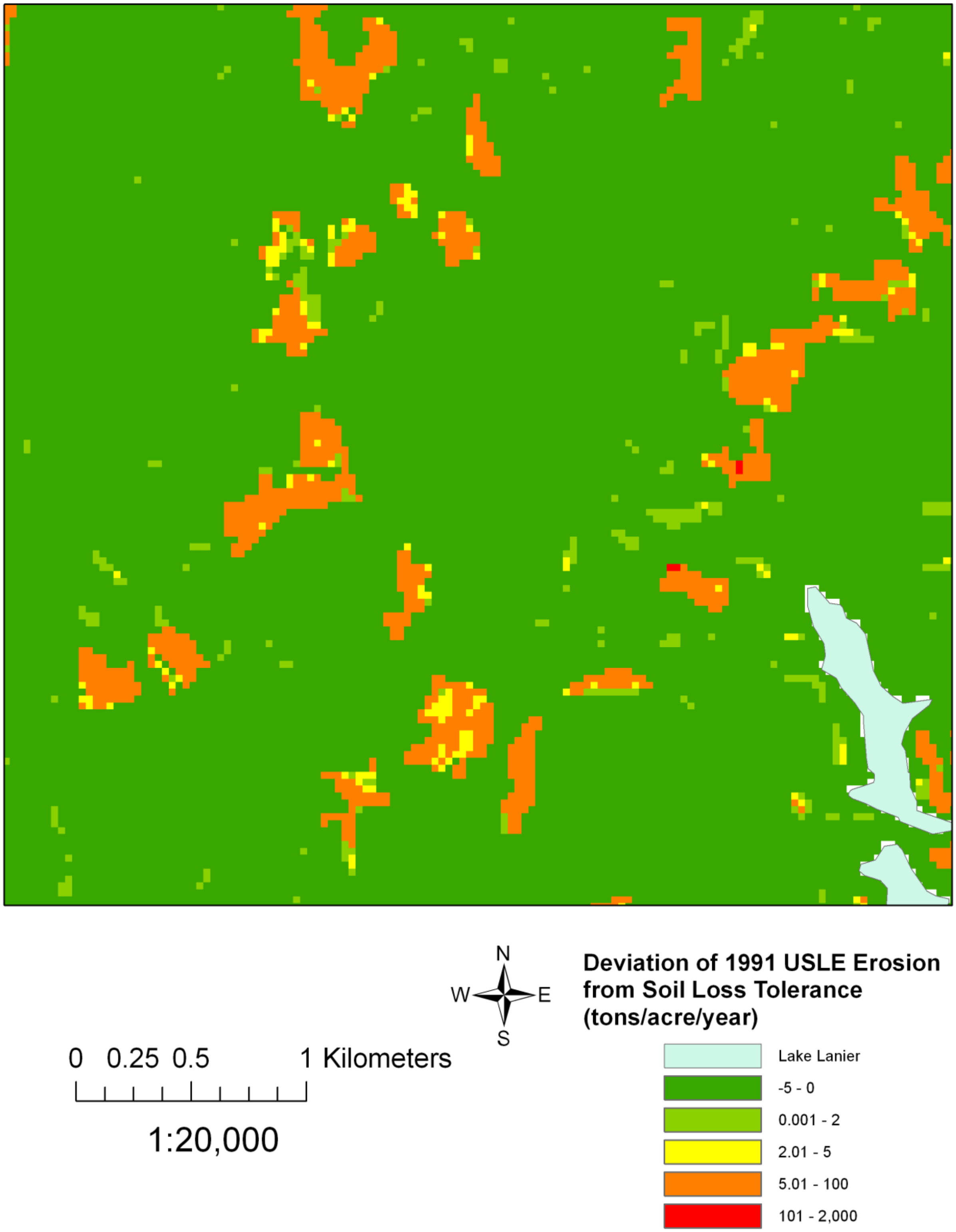


Figure 65: Deviation of Modeled 1992 Erosion Rate (NLCD Based) from Soil Loss Tolerance T-factor Close Up

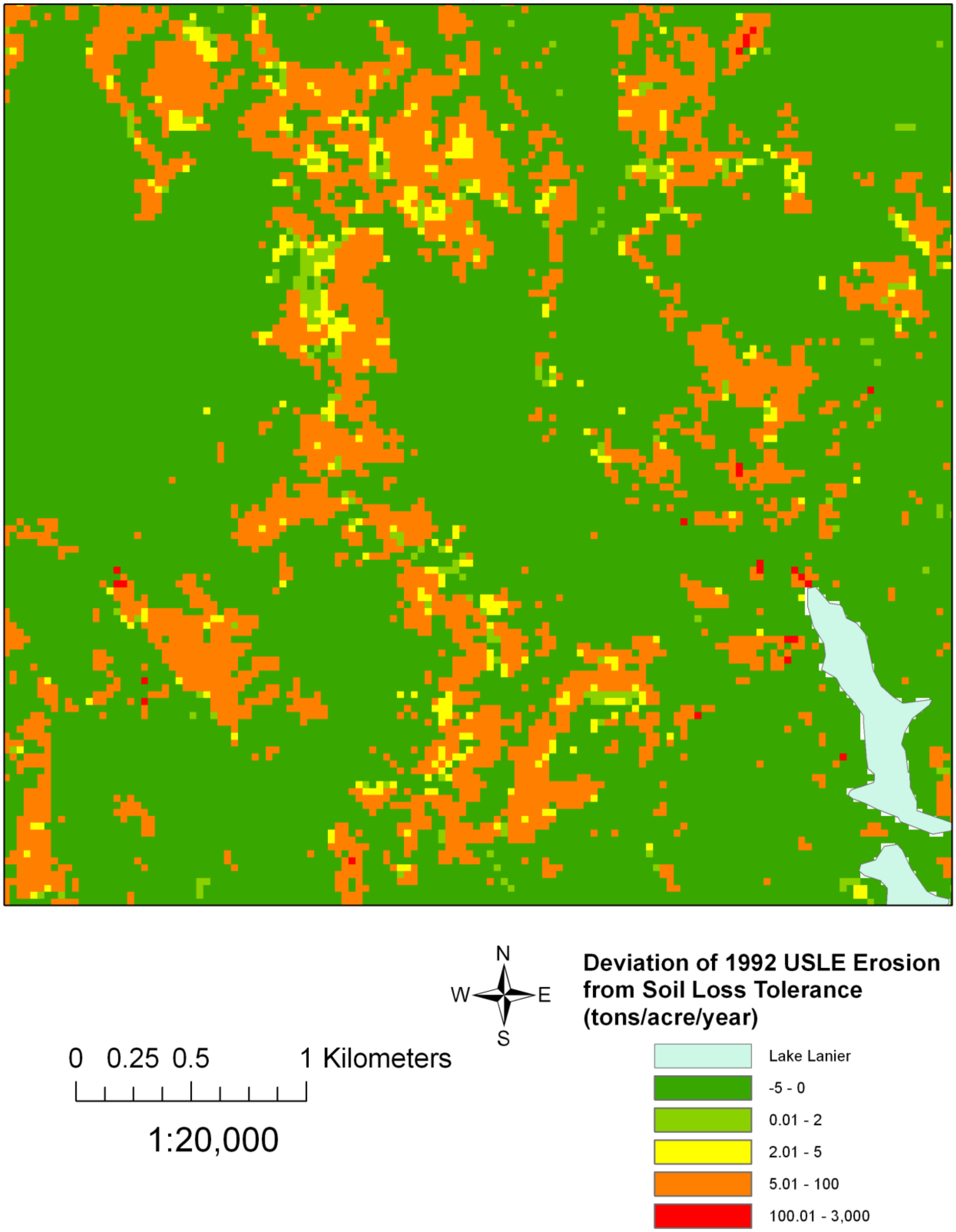


Figure 66: Deviation of Modeled 1999 Erosion Rate from Soil Loss Tolerance T-factor Close Up

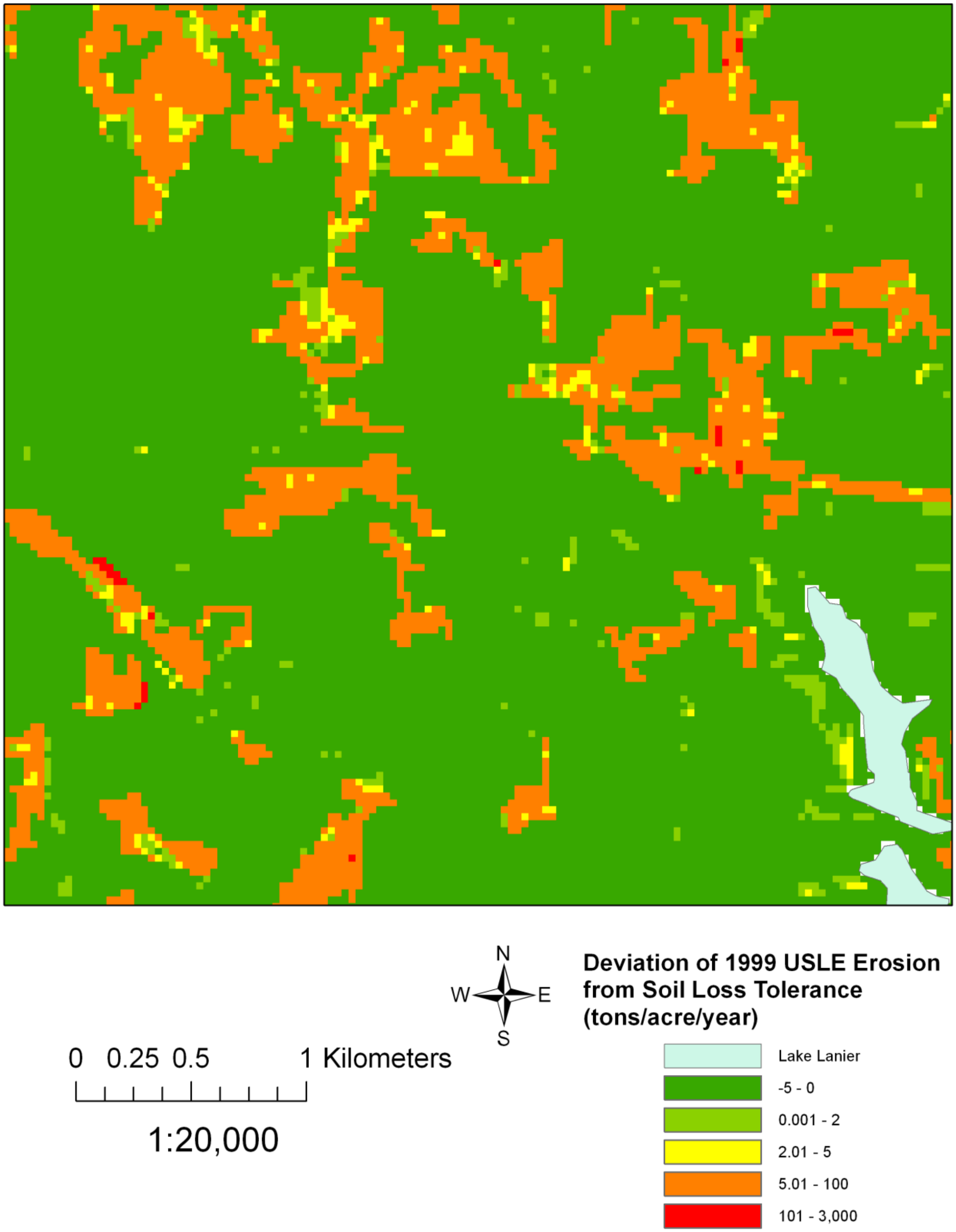


Figure 67: Deviation of Modeled 2001 Erosion Rate (NLCD based) from Soil Loss Tolerance T-factor Close Up

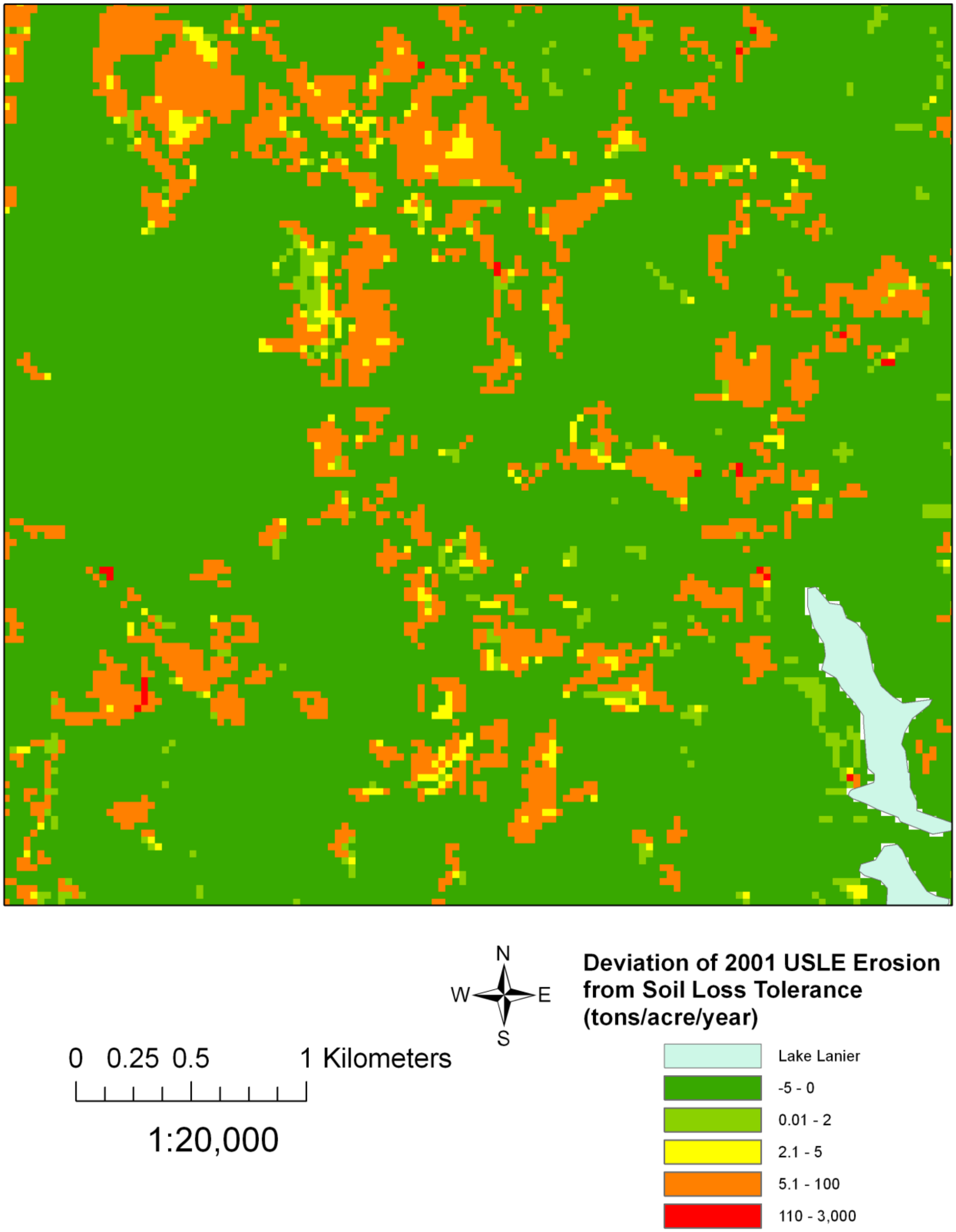
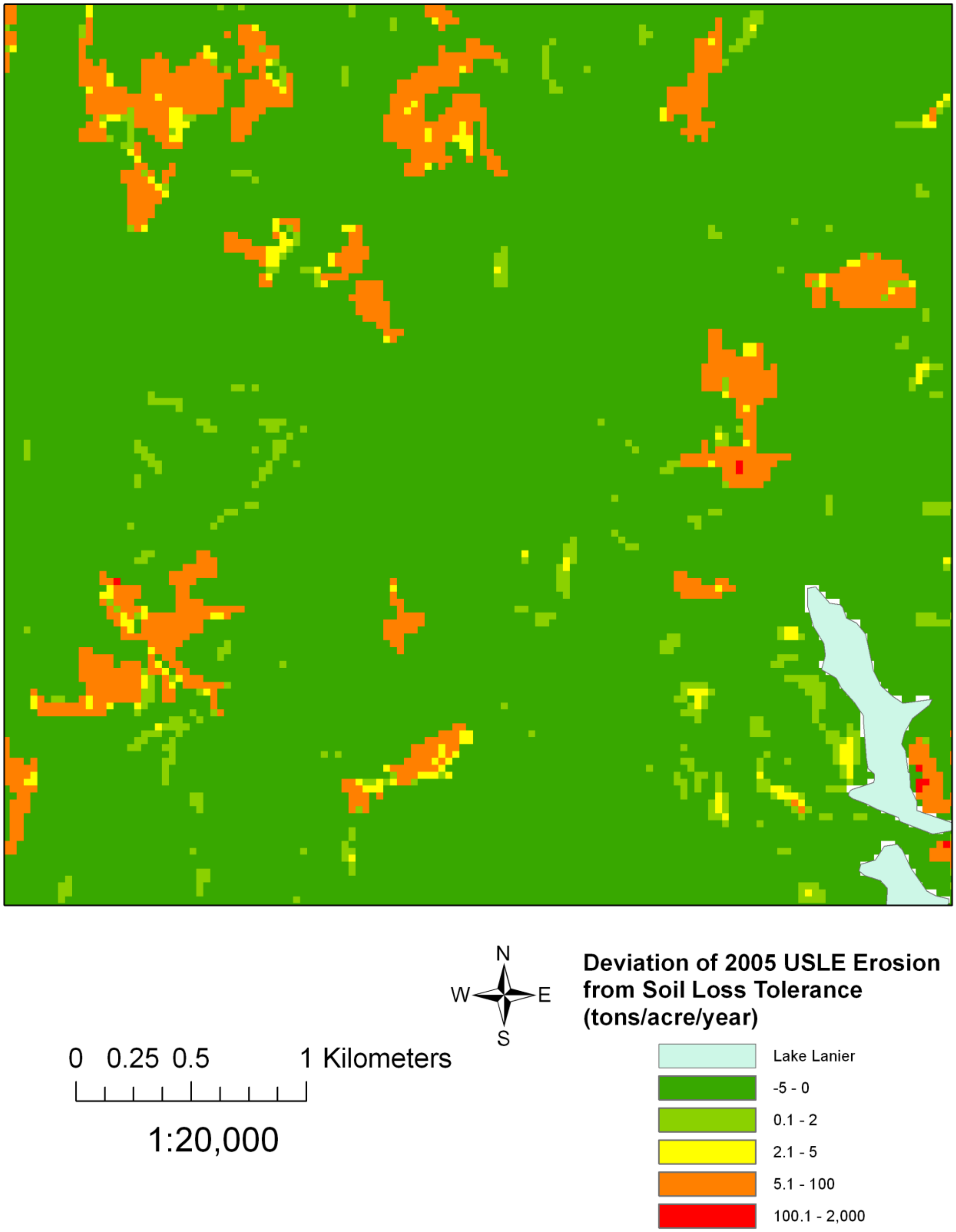


Figure 68: Deviation of Modeled 2005 Erosion Rate from Soil Loss Tolerance T-factor Close Up



Lake Lanier Watershed Stream Bank Sediment Yield Potential Analysis

The identification of stream segments that are particularly vulnerable to sediment loading is an important goal in soil conservation efforts. The Lake Lanier watershed soil sediment yield potential map can be processed using GIS techniques to spatially query the sediment yield potential within a 15-m stream buffer on each side of the stream. This means that the sediment yield potential on the 30-m (98.4 ft) pixel that is roughly centered on the stream, was clipped out allowing a visualization of the regions of the stream network that are least and most susceptible to sediment input. The total count of grid cells within this 30-m wide buffer is 76628, which is equivalent to an area of 69.0 km^2 (26.7 $miles^2$ = 1.71x 10^4 acres or 2.6 percent of watershed area) (Table 16). It is noteworthy that the total sediment potential queried within a 30-m buffer around the stream comprises 2.6 percent of the watershed area, but contains about 2/3 of the total sediment yield potential. This is to be expected as the stream network is the terminus of the surface water flow and hence the foci of sediment deposition. Interestingly, the average sediment yield potential per pixel within the stream-bank buffer is about 22 times greater than the sediment potential average for the entire watershed.

An analysis of the histogram distributions of stream bank sediment yield potential over the time period of investigation also gives a measure of the overall health of the stream networks. A histogram of the sediment yield potential may be viewed as a sedimentation ‘spectrum’, the characteristics of which are indicative of the watershed stream susceptibility to sediment deposition. The histogram plot of the logarithm of the pixel count for each sediment potential class is particularly sensitive to changes in sediment loads on the stream network.

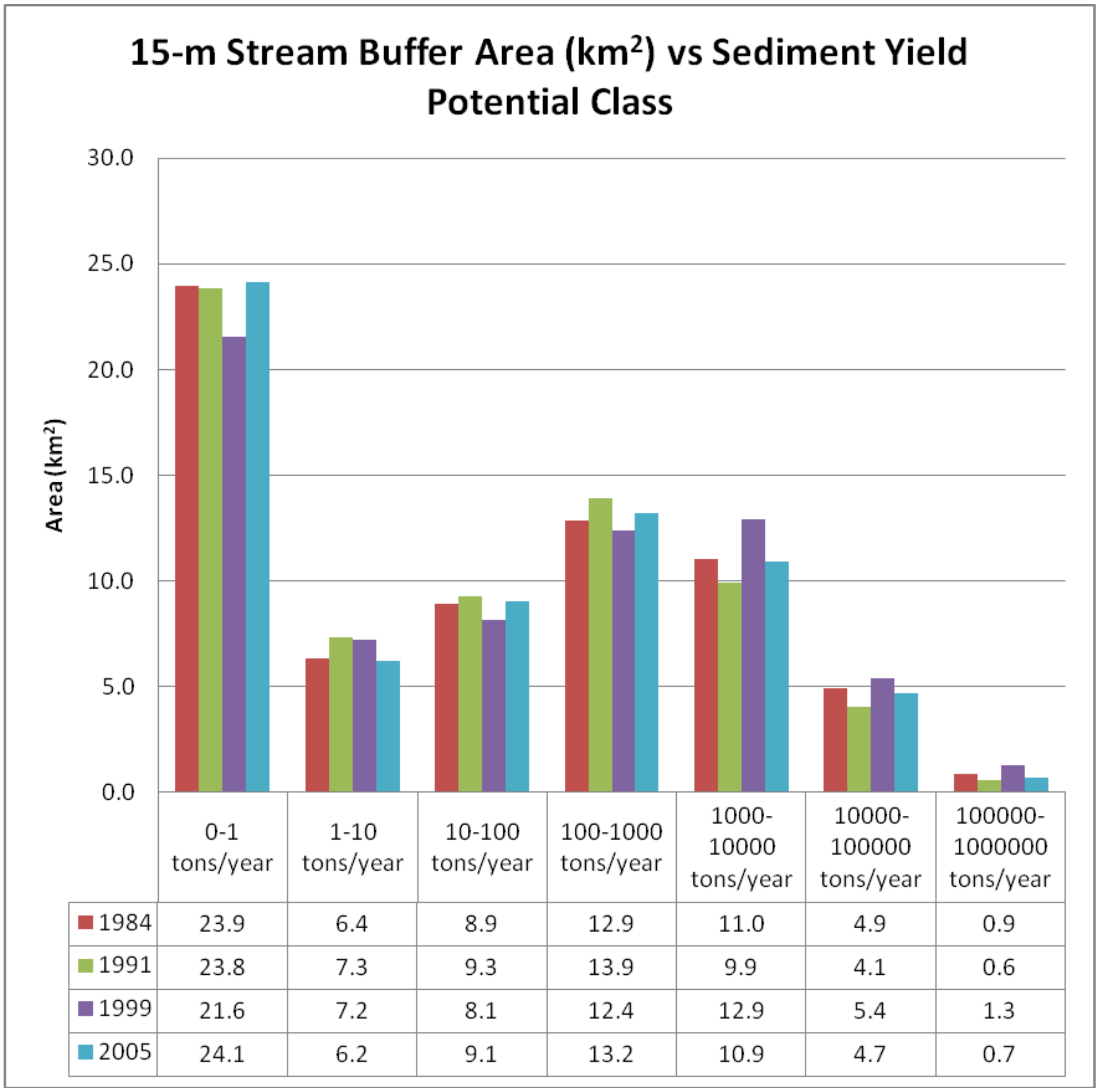
Table 16: Sediment Yield Potential within a 15-m Buffer around Lake Lanier Streams/Rivers

	Max (tons/year)	Sum (tons/year)	Average (tons/year)	Standard Deviation
1984	639,600	467,100,100	6096	35500
1991	428,710	302,970,000	3954	23187
1999	993,000	668,300,000	8721	54450
2005	615,900	393,600,000	5136	31470
Total Area for Lake Lanier watershed 15-m stream buffer is 69.0 km^2				

This is clearly illustrated by the histograms for the Area vs. Sediment Yield Potential within a 15-m buffer about the streams (Figure 69). The shift of the histogram distribution towards greater watershed area with a large sediment yield potential in 1984 and 1999 is particularly evident. This is due to the large increase in pasture/agriculture class since the early 1990's, accompanied by a large decrease in the forest cover. Both of these land-cover changes greatly contribute to erosion and sedimentation. Conversely, the skew of the distribution towards lesser sedimentation in 1991 is evident upon close inspection, as well.

The sediment yield potential classes are expressed in factors of ten. In this watershed the maximum sediment yield potential (total upslope sediment) for a grid cell is within 10^6 tons/year. Therefore, the logarithm of the sediment yield potential values for each class, ranging from 10^0 ton/year to 10^6 tons/year, will be a number ranging from 0 to 6. These numbers can serve as an index of stream sediment impairment, indicating progressively greater sediment deposition.

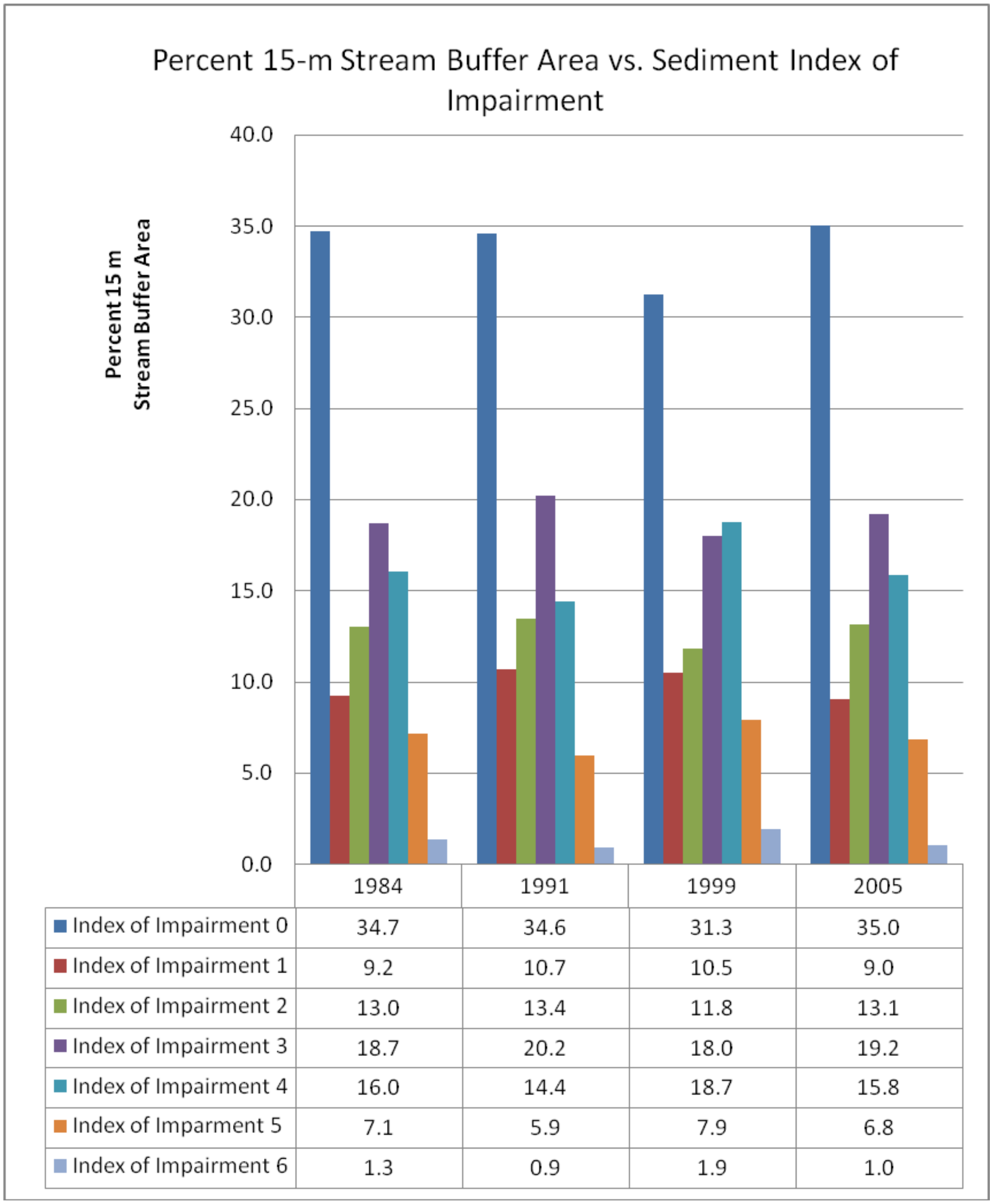
Figure 69: Area within a 15-m Buffer vs. Stream Bank Sediment Yield Potential Class



	0-1 tons/year	1-10 tons/year	10-100 tons/year	100-1000 tons/year	1000-10000 tons/year	10000-100000 tons/year	100000-1000000 tons/year
🟥 1984	23.9	6.4	8.9	12.9	11.0	4.9	0.9
🟩 1991	23.8	7.3	9.3	13.9	9.9	4.1	0.6
🟪 1999	21.6	7.2	8.1	12.4	12.9	5.4	1.3
🟦 2005	24.1	6.2	9.1	13.2	10.9	4.7	0.7

The increased sediment load on the streams in 1999 is apparent as a larger percentage of the stream buffer area has indices of impairment 4, 5 and 6, relative to the other years (Figure 70). As discussed earlier, this is due to the increase in erosion due to the drought that was extant in 1999. The stream bank sediment yield potential for the close-up portion of the watershed is shown in Figure 71 through Figure 74, for 1984 through 2005, respectively. This allows for the direct spatial identification of the parts of the stream network most vulnerable to sediment inflow.

Figure 70: Percent 15-m Stream Buffer Area vs. Index of Impairment



	1984	1991	1999	2005
🟦 Index of Impairment 0	34.7	34.6	31.3	35.0
🟥 Index of Impairment 1	9.2	10.7	10.5	9.0
🟩 Index of Impairment 2	13.0	13.4	11.8	13.1
🟪 Index of Impairment 3	18.7	20.2	18.0	19.2
🟦 Index of Impairment 4	16.0	14.4	18.7	15.8
🟧 Index of Imparment 5	7.1	5.9	7.9	6.8
🟦 Index of Impairment 6	1.3	0.9	1.9	1.0

Figure 71: 1984 Stream Bank Sediment Yield Potential Close Up

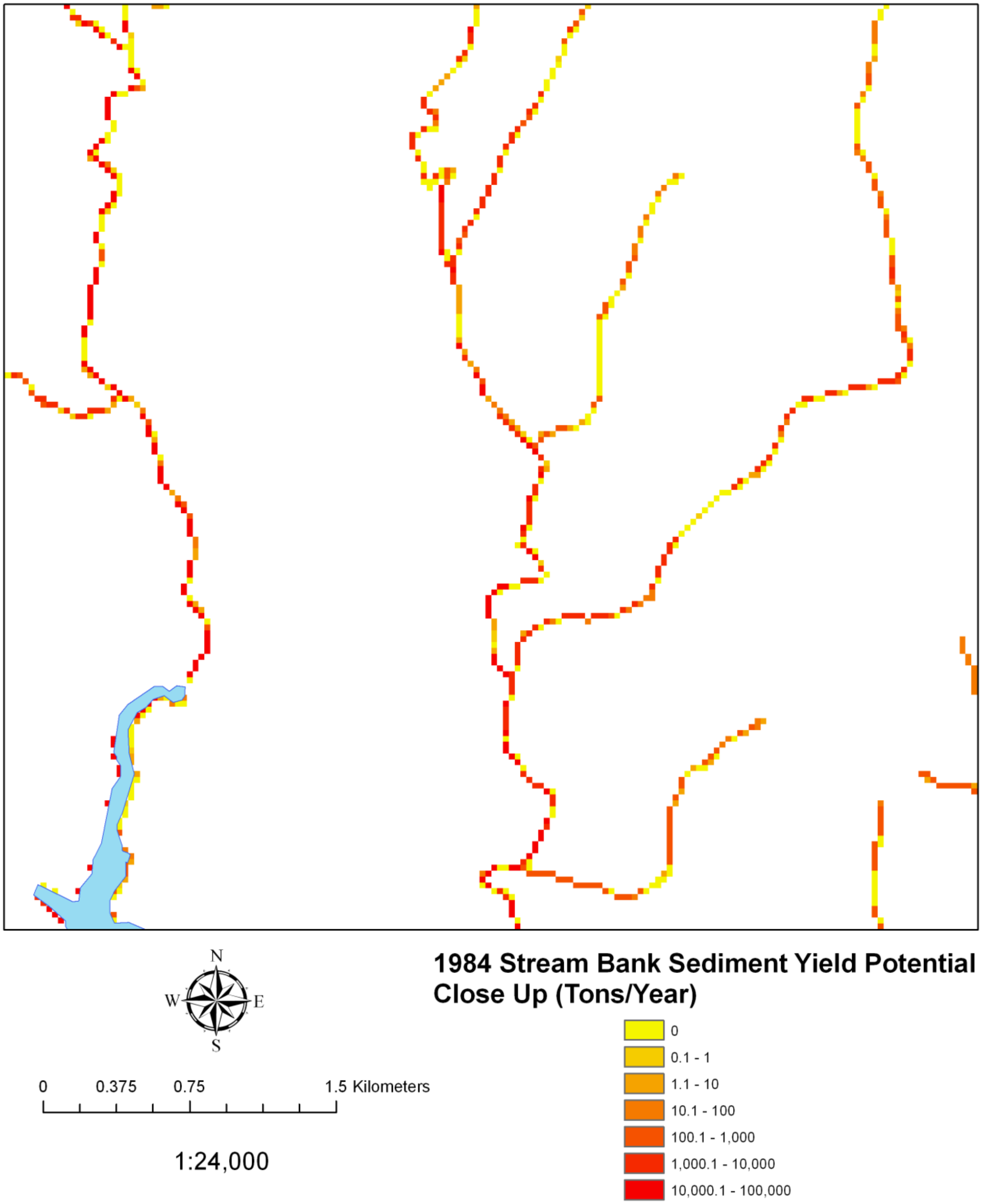


Figure 72: 1991 Stream Bank Sediment Yield Potential Close Up

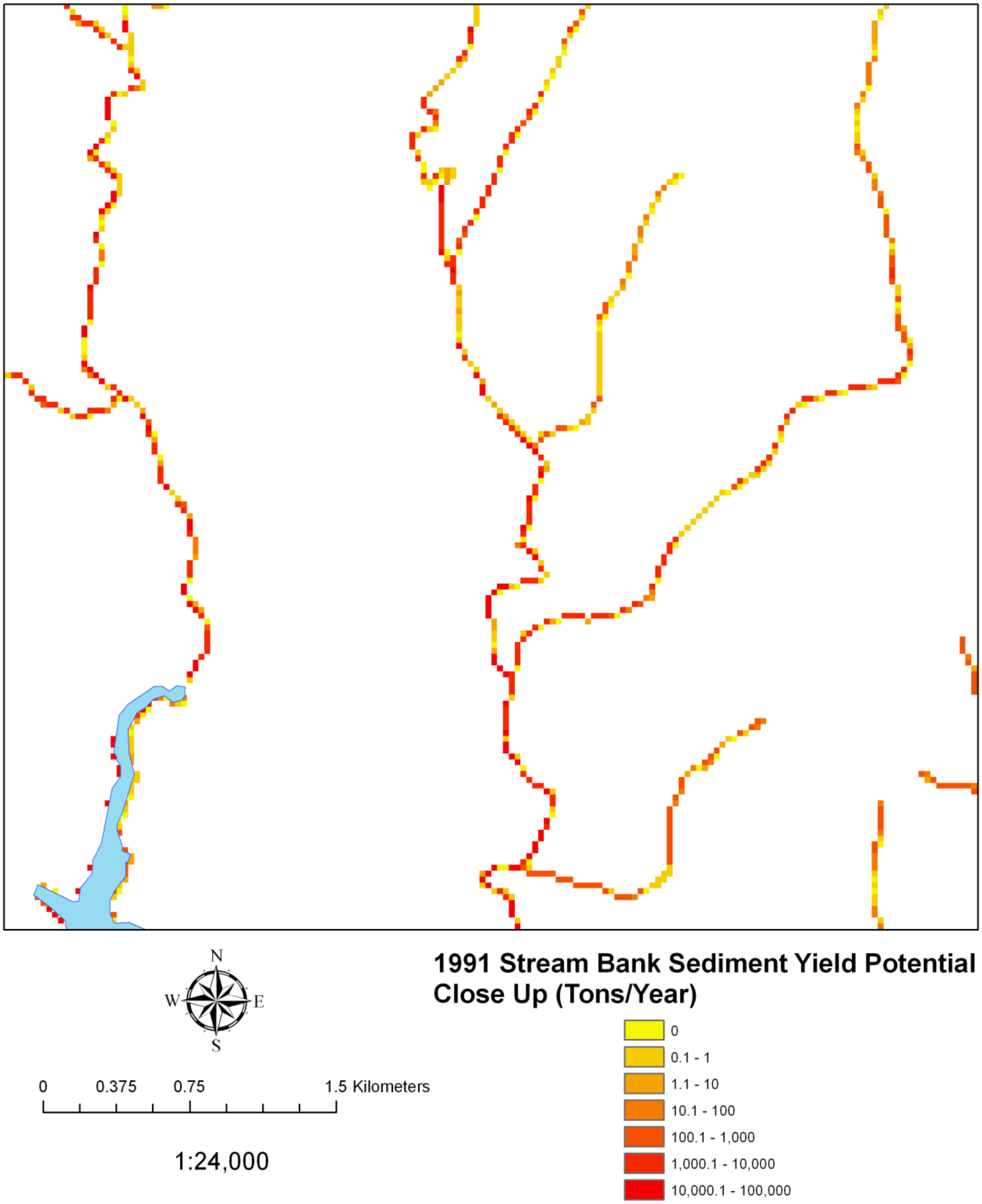


Figure 73: 1999 Stream Bank Sediment Yield Potential Close Up

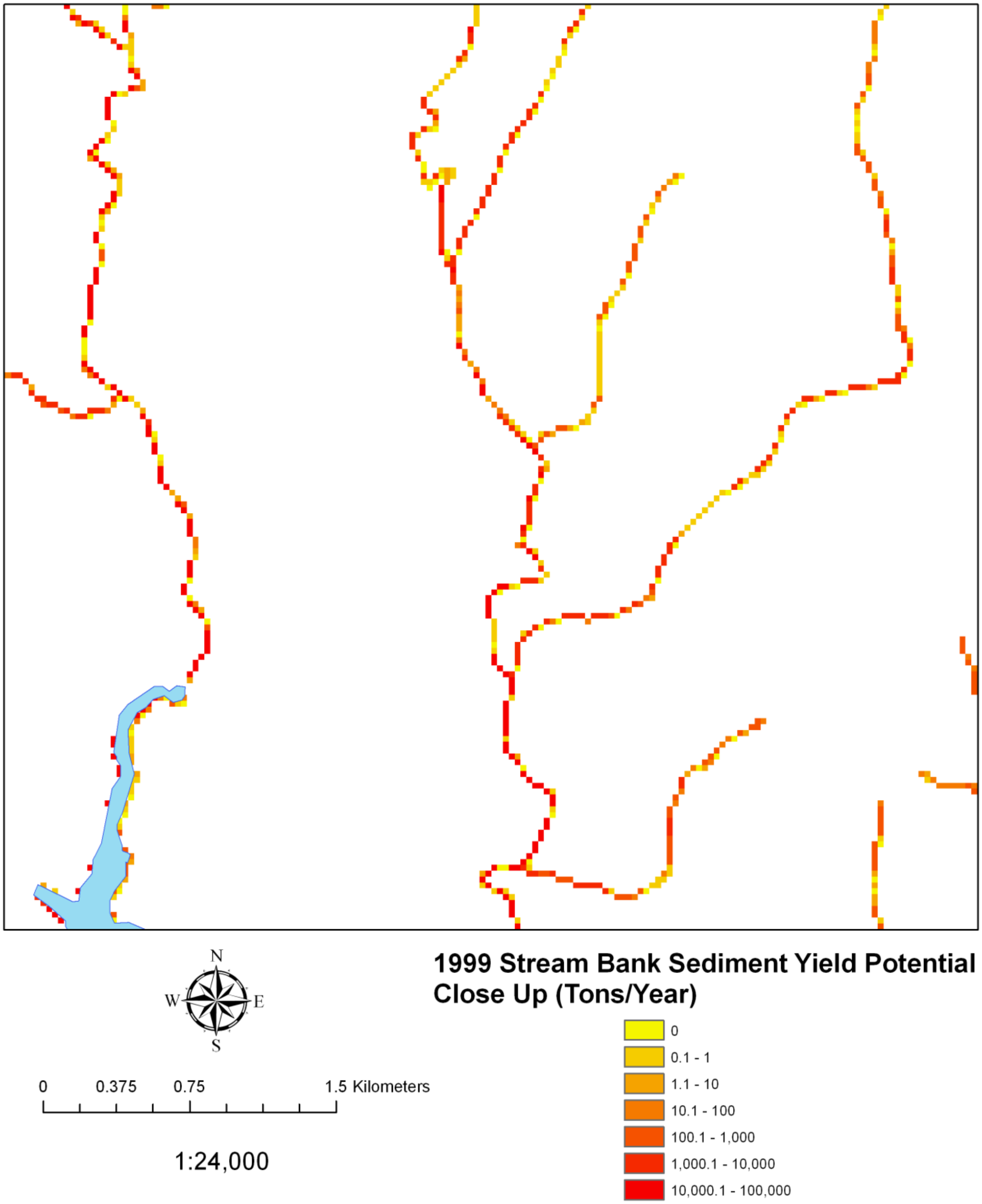
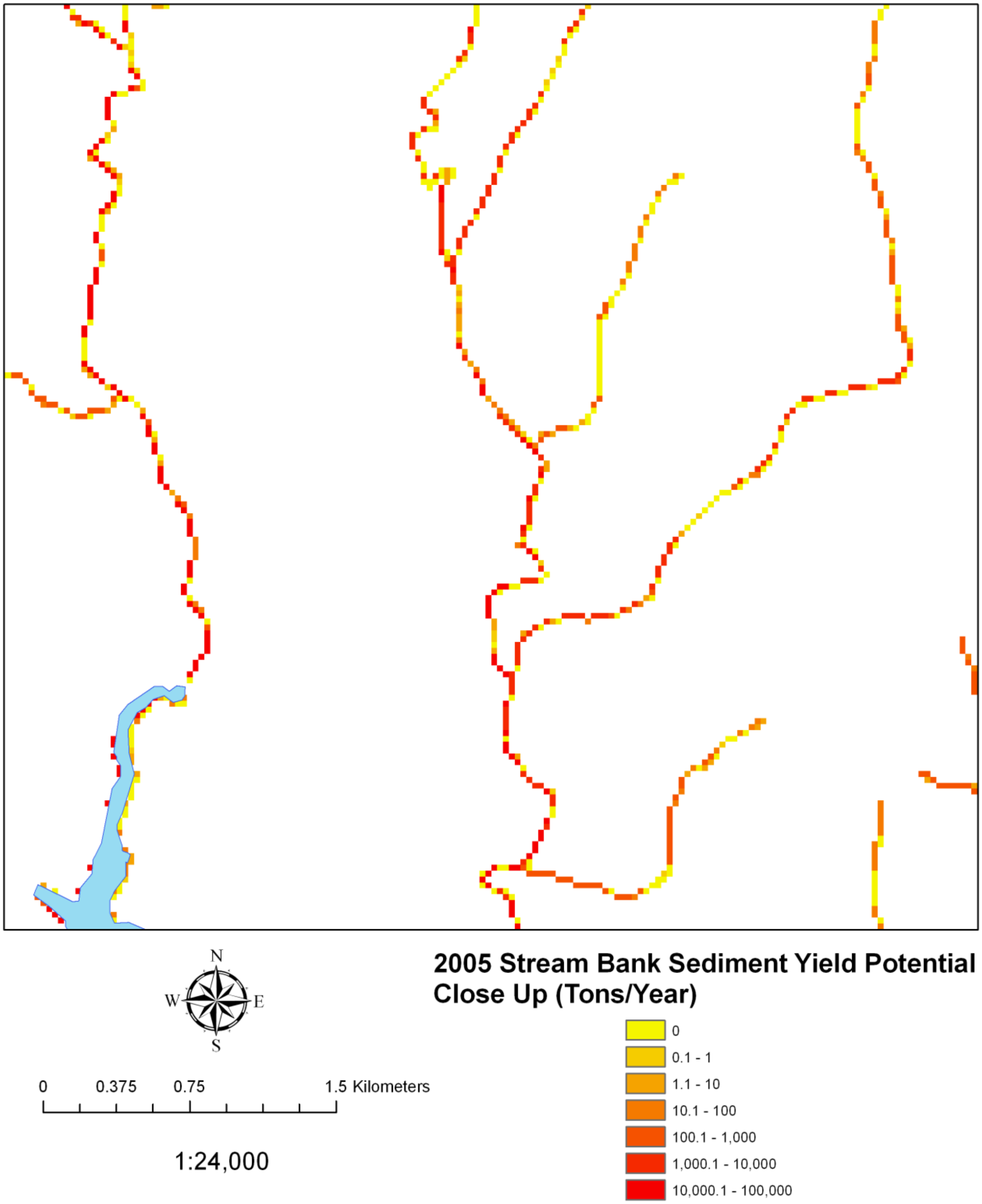


Figure 74: 2005 Stream Bank Sediment Yield Potential Close Up



Implications for Environmental Law and Total Maximum Daily Loads (TMDLs)

In 1996, the EPA was taken to court by the Sierra Club for failing to make Georgia comply with the Clean Water Act in the development and implementation of Total Maximum Daily Load (TMDL's) for the State (CWA 1972, EPA 2005). Younos et al. (2005) outline the origins and status of the Clean Water Act and the history of its relationship with TMDL's. Keyes and Radcliffe (2002) head a Technical Advisory Group (TAG) which is charged with developing protocols for sediment TMDL's for the State of Georgia. Sediment in streams is directly related to the Index of Biotic Integrity (IBI) and large amounts of sediment in streams in the Etowah Basin have been correlated to a low IBI (Leigh et al. 2002, Walters 2002). The IBI was shown to be consistently low when the Suspended Sediment Concentration under base-flow conditions exceeded 10 mg/L.

Essential to the implementation of the TMDL's is the *a priori* identification of the streams most susceptible to higher sediment loads. The explicit identification of streambanks with the greatest sediment loading is essential to the proper emplacement of Best Management Practices (BMP's) to keep the streams within TMDL standards. This can be accomplished using the area SDR based sediment modeling approach that identifies the stretches of the streams that need the most attention to alleviate sedimentation in this very large watershed. Furthermore, this model can be calibrated with measurement of the sediment outflow from stream-banks that have the greatest upslope loading. Indeed, there is a need for more research on empirically quantifying suspended sediment concentrations in the streams in the Lake Lanier watershed to both complement and calibrate this modeling approach. The spatially distributed drainage area based

SDR approach for sediment yield modeling has the advantage of rapidly characterizing large watershed erosion and sedimentation patterns without needing extensive field-based data. This type of spatially explicit information can be very useful for the development of realistic, effective and enforceable TMDL standards in the North Georgia/Southern Appalachia watersheds.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Erosion and sedimentation are fundamental processes that cause changes in the physical morphology of the terrain. This in turn impacts the productivity of soil, biotic processes and water quality. Sediments provide a transport mechanism for chemicals introduced into the environment due to human activities including agricultural waste, herbicides, pesticides and the plethora of chemicals released by increasing human presence. Knowledge of the spatial distribution of the sedimentation potential at the watershed scale and the time evolution of these spatial distributions is essential to understanding the extent and impact of non-point source pollution that is transported by surficial hydrology on the terrain. Currently, the Lake Lanier watershed has about 4 million inhabitants and due to its proximity to Atlanta and the natural beauty of the area, it is a rapidly urbanizing watershed. The population in the Atlanta Metropolitan Area grew by 20.5 percent from 2000 to 2006, which is the fastest growth rate in the Nation (Demographica 2007). Based on this growth rate it is expected that in the next few decades, the population dependent on the waters of Lake Lanier may increase several fold. This will bring a considerable land cover change and a dramatically increased non-point source pollution loading on the lake. Since this lake is the predominant source of water supply to the Atlanta region, its sustained well being is of critical economic importance to the state of Georgia.

The USLE is an empirically derived mathematical relationship to predict the average annual soil loss rates due to water erosion per unit area. The USLE was developed in test plots that had a length of 72.6 ft. In this raster-based GIS modeling, the USLE based erosion is calculated for

30 m x 30 m grid cells, and the average length of flow across each cell is taken to be 30 meters or 98.4 ft. Therefore, the entire watershed is segmented into grid cells approximately the size of the original USLE test plots such that the use of this empirical correlation is within the constraints of the experimental design of the USLE. This proposition is borne out by the favorable comparison of the sediment predicted for 1984 by this modeling study and the sediment measurements by Faye et al. in the early 1980's, and Leigh et al. in 1990's, as discussed in the Chapter 4.

GIS modeling of large, mesoscale watersheds such as the Lake Lanier watershed (1040 miles^2 or 2693 km^2) comes with its attendant challenges and opportunities. Mesoscale watersheds typically have linear dimensions on the order of a few hundred kilometers (Krysanova 1998a), such as the Lake Lanier watershed. The rapid emergence of powerful software tools and ubiquitous rapid computing has made GIS modeling of large watershed characteristics come of age. Fast computing, large storage memory, broadband networks and high resolution displays make geographic data processing and display a powerful tool for land resource management. The increasing availability of extensive, high resolution and web accessible image, terrain and thematic data is giving a great impetus to modeling Earth surface physical and/or social phenomena. Large area geographic computing, however, can push hardware, software and broadband Internet to its limits. In order to do this erosion and sediment modeling study, several different GIS data layers totaling approximately 10 Giga-bytes were needed. The processing of these GIS layers required the knowledge of image processing, remote sensing, spatial analysis and soil databases.

This project demonstrates the viability of spatially distributed erosion and sedimentation modeling for a mesoscale watershed such as the Lake Lanier watershed. Lake Sidney Lanier is the primary source of water for the metropolitan Atlanta area. The USLE based spatially distributed erosion and sedimentation in the Lake Lanier watershed was determined for 1984, 1991, 1992, 1999, 2001 and 2005. This modeling shows the erosion 'hot-spots' in the watershed, their proximity to streams and their time evolution over the period of this study. This 21-year time period has seen a major change in land cover in the southern portion of this watershed. About 15 percent of the watershed area has soil loss rates in excess of the soil loss tolerances, identifying regions where soil conservation efforts needed the most. The spatially distributed sedimentation model is based on an empirically derived watershed area vs. sediment delivery ratio (SDR) relationship. USLE based erosion modeling provides the supply grid of eroded soil that is available to the sediment transport process. The sedimentation model provides a spatial distribution of the sediment deposition potential at every 30-m pixel, which is indicative of the total upslope drainage area loading of eroded soil at that location. The querying of the sediment yield potential in the vicinity of the streams identifies the stream segments that are the most vulnerable to sediment input and associated pollutants. An ‘index of impairment’ by sediment deposition is proposed, which can be used as a heuristic to identify and rank regions with the greatest to least sediment deposition potential. Calibration of this non-point source modeling with actual sediment measurement of sediment discharge into streams at particular locations, can help in the effort to define and implement sediment TMDL's.

The rapid land cover change fuelled by urbanization in the Lake Lanier watershed has created a dynamic urban-rural interface that has consequences for water quality and quantity in the region. One important consideration concerning the urbanization of the watershed is the increase in impervious area, which increases the surface flow energy. The net total surface erosion in urban areas as predicted by the USLE may be less, but the stream scour increases and leads to an increased net actual erosion. Therefore, as the urbanization in the watershed increases, not only will there be increased sediment due to the ‘pulses’ invoked by land cover change, the erosion due to stream scour can increase as well. The sheet erosion based sediment delivery to Lake Lanier over the period of this study is roughly 150,000 tons/year with roughly an additional 100,000 tons/year due to land cover change, as discussed in Chapter 5. There may be an additional amount due to stream scour and bank erosion that is not modeled in this study. Therefore, the annual average sediment input into Lake Lanier is estimated to be in excess of 250,000 tons per year in 1984, according to this study. This is similar to the estimate of Faye et al. in 1980, stated as a ‘background’ rate of 214,000 tons/year to a maximum of about 400,000 tons/year. This validation lends more confidence to the sediment discharge modeled for the other years of this study. The sediment discharge estimated from the non-point source modeling for the 21-year period of the study varies between 100,000 and 200,000 tons/year

According to the calculations in this study, Lake Lanier has had a steady input of sediment at the rate of over 250,000 tons/year. If we assume it to be 300,000 tons/year in order to account for shoreline erosion, and accept that 1 acre-foot volume of sediment weighs about 2430 tons, the total volume of sediment input into the lake is about 125 acre-ft/year. Faye et al. estimate the sediment input to be a maximum of about 400 acre-ft/year in 1980. As the volume of the Lake is 1.92×10^6 acre-ft, at the rate estimated by Faye et al., Lake Lanier can be filled completely in 4800 years. The U.S Army Corps of Engineers (USACE) that manages Lake Lanier has estimated in the early 1990’s based on some bathymetry studies that 2000 acre-ft of sediment is coming into the Lake annually (Rogers 2007). There are questions about this study as to whether the sediment inflow of the measured sediment is ‘flocking’ and not ‘packed’, giving a false higher estimate of sediment input. However, assuming this value to be true, Lake Lanier will be completely filled with sediment in approximately 960 years.

Estimates of ‘lifetime’ of Lake Lanier can be misleading, however, as the lake water quality can plummet much sooner, and compromise the utility of the lake for drinking and recreation. A projected several-fold growth in population in the watershed over the next four decades can create strains on the Lake Lanier watershed ecosystems in unpredictable ways. Lo et al. (2005) have performed studies of the change in land cover in the metropolitan Atlanta area including the region around Lake Lanier based on cellular automata models. His studies show that the urbanization driven by the current growth regulations and policy will lead to the entire region around Lake Lanier becoming mostly urbanized in the coming four decades. Runoff from urbanized watersheds contains more chemicals and heavy metals that can severely degrade water quality. There is also an increased risk of bacterial contamination from an increasing number of septic tanks in the vicinity of streams and at the edge of Lake Lanier. This highlights the imperative for planned growth based on scientific data that minimizes the impairment of the lake as a source of drinking water.

The sediment model developed for this study was modified to calculate the sediment potential using a cell attribute based SDR in the manner similar to Vieth (2002). The sedimentation modeling with a cell attribute based SDR resulted in sediment yield potential within 50 percent of the area-based SDR modeling results. They also showed a very similar spatial distribution of sediment deposition potential and clearly pointed to the viability of SDR modeling using detailed local attributes of individual grid cells, as has also been done by Fraser (1998, 1999). With the increasing availability of higher spatial resolution geospatial data, it is expected that robust models operating with detailed initial data will begin to give results for both erosion and sediment delivery to the water bodies that are commensurate with actual measurements. This will help facilitate the formulation and implementation of environmental law and public policy that promotes a science-based management of our water bodies and their watersheds.

Accurate high spatial resolution land cover information for large watershed modeling remains the data layer that is the least available and is, therefore, a limiting factor in erosion/sediment yield predictions. The production of higher spatial resolution land cover maps of the Lake Lanier watershed is a research direction that should be pursued to try to bring the erosion and sediment modeling closer to ground measurements. This will involve building a collection of cloud free multispectral satellite imagery at 1-m to 10-m resolution for a test plot within the portion of Hall County that is in the Lake Lanier watershed and includes the Gainesville area. New image object based processing techniques embodied in the software like Definiens can be brought to bear on high resolution multispectral imagery to extract more detailed land cover at potentially higher accuracy. In addition to spectral signatures, image segmentation and fuzzy classification can be based on contextual data about objects such as texture, shape, proximity and spatial coincidence with ancillary GIS thematic data.

As 10-m DEM's are now becoming available for many areas in the U.S. , exploring the effects of scale and terrain detail on modeling soil processes on large watersheds will be an interesting question to pursue. Soil erosion is most sensitive to the slope of the terrain as it is dependent on a quadratic expression in slope (i.e. slope squared), in the USLE. Ultimately, the spatial resolution of the DEM is the greatest limiting factor in modeling soil erosion and sedimentation processes, which are based on surface water runoff. In the event that high accuracy LIDAR data becomes available within the Lake Lanier watershed with post spacing of 1 to 3-m and vertical accuracies of about +/- 0.1-m, further studies should explore fine scale erosion/sedimentation modeling. This must be done in conjunction with field based validation.

All of the modeling discussed thus far pertains to erosion and sedimentation averaged over the entire year. It is now becoming possible to model erosion and sedimentation for a particular rainfall event. This involves the use of NEXRAD radar data which gives the spatial detail of the energy delivered by the rainfall on the terrain. This information can be used by either an empirical model such as the USLE or other non-point source models such as AGNPS or SWAT to calculate the time dependant sediment outflow at the mouth of a small test watershed. Real time sensors at the mouth of this watershed can measure the stream flow rates and turbidity, which can be correlated to the real time sediment outflow. The model can then be calibrated and refined by comparison to actual measurements. Such calibrated models will become very useful tools for managing erosion and sedimentation through best management practices, public policy and quantifiable environmental law.

In order to have accurate models of spatially distributed erosion and sedimentation, it is necessary to have a program of systematic sediment measurement in the sub-watersheds of Lake Lanier. A database of sediment inflow at strategically placed points in streams and rivers in the watershed would be essential to calibrate non-point source erosion and sedimentation models in this watershed. Insights gained in this process can be applied to modeling erosion and sedimentation in other watersheds in the southern piedmont with similar physiographic features and land cover.

This study fulfils the need for a detailed spatially distributed description of land cover, soil erosion and sedimentation using recently available geospatial data downloadable with high speed internet, rapid computing and powerful off-the-shelf geospatial software. The 21-year period of this study provides a spatially explicit description of soil erosion and sediment deposition patterns in the rapidly developing Lake Lanier watershed. It provides the foundation for similar non-point source studies in the future that will make use of higher spatial, spectral and temporal resolution geospatial data.

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APPENDICIES

Appendix A: Description of Acronyms

AGNPS – Agricultural Non Point Source

ACF - Apalachicola-Flint-Chattahoochee

AOI – Area of Interest

CWA – Clean Water Act

DEM – Digital Elevation Model

DOQQ – Digital Ortho Quarter Quad

EPA – Environmental Protection Agency

ESRI – Environmental Systems Research Institute, Inc.

FSA – Farm Service Agency

GIS – Geographical Information Science

GLOVIS – Global

LS – Length-Slope

LULC – Landuse/Land Cover

MSS – Multi-Spectral Scanner

NED – National Elevation Data

NRI – National Resource Inventory

NRCS – National Resource Conservation Service

NIR – Near Infra Red

NLCD – National Land Cover Data

RUSLE – Revised Universal Soil Equation

SDR – Sediment Delivery Ratio

SSURGO – Soil Survey Geographic

STATSGO - State Soil Geographic

SWAT – Source Water Assessment Tool

SERCC – South Eastern Regional Climate Center

TMDL – Total Maximum Daily Loads

TM – Thematic Mapper

USACE – United States Army Corps of Engineers

USDA – United States Department of Agriculture

USGS – United States Geological Survey

USLE – Universal Soil Loss Equation

VPython – Visual Python

WEPP – Water Erosion Prediction Project

WRS-2 – World Reference System - 2

WQS – Water Quality Standards