# *NCResSys*: A Geospatial Modeling Information System for the Identification of Potential Municipal Water Supply Reservoir Locations across the State of North Carolina

Timothy P. Morrissey

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Approved By:

Dr. Stephen J. Walsh

Dr. Conghe Song

Dr. Xiaodong Chen

## ABSTRACT

TIMOTHY MORRISSEY: NCResSys: A Geospatial Modeling Information System for the Identification of Potential Municipal Water Supply Reservoir Locations across the State of North Carolina
(Under the direction of Dr. Stephen J. Walsh)

The primary objective of this research is the development of a comprehensive, geospatial information system utilizing digital spatial datasets and technologies for the purpose of modeling potential municipal water supply reservoir sites across the State of North Carolina. To achieve this primary goal, a computational information system, ***NCResSys,*** has been designed by applying principles of software engineering, hydrology, and computational geography to conduct hydrologic and terrain analysis across the State in a spatially-explicit, Geographic Information System (GIS) environment. Potential reservoir sites are assessed based on the locational characteristics of physical storage and capacity. The terrain analysis component of this research examines the physical landscape of water storage capacity through a series of recursive algorithms for processing high-volume LiDAR DEM data. This research combines approaches from multiple disciplines in a computational environment to contribute value-added support to the decision-making process for public water supply planning, development, and management.

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# CHAPTER 1: INTRODUCTION

In recent years, the State of North Carolina has experienced drought conditions that have left municipal water supplies at alarmingly low levels across the State. These periods of drought, compounded by regional population growth and economic development, demonstrate the need for a statewide system to assess the potential for expanding municipal water supplies. Such an analysis would assess the spatial pattern and density of population, sensitive and protected environments, terrain conditions, land use and land cover patterns, existing reservoirs and water distribution systems, transportation networks, restricted areas, such as, existing urban centers, and the hydrologic capacity of the State of North Carolina to support additional, potential reservoir sites.

Identification of a potential reservoir site involves the calculation of physical water storage capacity through terrain and hydrologic analysis. These physical capacity measures combined with ancillary data on impacted areas, such as, land-use, demographics, services, aid in the decision-making process of siting potential reservoirs. This research describes the design and implementation of an extensible and comprehensive reservoir identification system, "***NCResSys***," using the extensive inventory of publicly available geospatial data for the State of North Carolina, including highly-accurate, multi-scale, laser-calculated LiDAR (Light Detection and Ranging) elevation data.

### 1.1 Background & Problem Statement

Communities across the State of North Carolina have experienced periods in which public water supply levels have fallen to alarmingly low levels in recent years. The regional drought of 2007 was the worst drought since record keeping began in 1895 (*North carolina drought management advisory council activities report - 2008.*2008). The National Weather Service identified 2007 as the driest year in North Carolina in over 100 years, and the United States Geological Survey (USGS) reported the lowest stream flows in more than 110 years for many of the rivers in the State. These climatic and hydrologic conditions led to many public water supplies reaching record low levels across the State. Along with these climatic conditions, the State has seen rapid population growth and economic development in the past 15 years. With forecasts continuing this population growth trend for years to come (*Population Estimates and Projections - NC | OBSM*, 2009), the already stressed capacity of public water supplies will most likely experience increased levels of demand. The ability of government to maintain adequate water supplies is an essential component of public safety, security, and well-being. The public requires a reliable source of public water supply through variable climatic and population conditions to maintain safety and quality of life. The impacts of drought and population growth on public water supplies throughout the State of North Carolina are clear and the predictions are dire.

The rate of investment in water storage facilities in North Carolina has been in decline since 1965. An analysis of data in the *Inventory of Dams* compiled and maintained by the North Carolina Division of Land Resources shows that 86% of current capacity was in place by 1965, and 96% was in place by 1985. During the period from 1910 to 1965, population in the State increased by 2.6 million people and over 5 million acre feet (MAF) of reservoir storage was constructed. This represents an average of 1.9 acre-feet for each new resident. In the period since 1965, population has increased by over 4.4 million people, while only 0.89 MAF of water storage has been added. This is an investment of 0.19 acre-feet per new resident, 1/10 the rate from 1910 to 1965. Along with this slowdown in water supply development there exist a lack of a systematic process to identify sites where water can be stored specifically for the purpose of municipal water supply, given social and ecological constraints as well as places of compelling need and opportunity.

The most comprehensive study of reservoir sites was primarily for hydroelectric power. Congress directed the United States Army Corps of Engineers (USACE) in the "*Rivers and Harbors Act of 1925*" to identify potential sites for hydroelectric power and to suggest how those sites should be developed to best serve the interests of flood control, irrigation, and navigation, along with hydropower (Northwest Power and Conservation Council, 2012). Some of those sites were subsequently billed as multipurpose reservoirs that include public water supply as a component, but reports did not include sites that would be primarily used for public water supplies.

The stressors on municipal water reserves, both on the supply-side, i.e., climatic conditions, such as, drought, and on the demand-side, i.e., continued population growth and development, coupled with an inability to identify additional storage locations, demonstrates the need for a statewide system to assess the potential for expanding municipal water supplies across the State of North Carolina. This research addresses this need through the creation of a computational, geospatial, information system for the modeling of hydrologic yields, terrain conditions, and potential municipal water supply reservoirs sites across the State of North Carolina. The basic intent is to generate an exploratory, screening tool and analytical approach to conduct statewide analyses of potential reservoir sites across the State of North Carolina, given specific needs and opportunities that link people and the environment in explicit ways to terrain and hydrologic conditions.

### 1.2 Objectives

The primary objective of this research is the development of a comprehensive, geospatial information system utilizing digital spatial datasets and technologies for the purpose of modeling potential municipal water supply reservoir sites across the State of North Carolina. To achieve this primary goal, a computational information system, ***NCResSys,*** has been designed by applying principles of software engineering, hydrology, and computational geography to conduct hydrologic and terrain analysis across the State in a spatially-explicit, Geographic Information System (GIS) environment. Potential reservoir sites are assessed based on the locational characteristics of physical storage and capacity. These physical attributes of terrain and hydrology determine the storage capacity and gross hydrologic yield of a potential reservoir site. This research examines the physical landscape of water storage capacity and supply along with the spatial integration of ancillary data, such as land use and population, to contribute value-added support to the decision-making process for public water supply planning, development, and management. This project will provide an approach to identifying potential sites for public water supply development as well as quantifying and spatially representing the potential impacts – benefitting not only public policy decision-making, but also contributing to public knowledge on water supply and impact. Further, this project will consolidate geospatial data for the State of North Carolina, particularly multi-resolution LiDAR data and other multi-thematic GIS data layers that are integrated into the analytical design and processing approach.

As a comprehensive geospatial modeling information system, ***NCResSys*** can be utilized to aid the various levels of municipal water resource management decision making across the entirety of the State of North Carolina. This research develops an information system that provides statewide analytical coverage in terms of the computation modeling of the physical characteristics of a reservoir, as well as the impact of that reservoir across a myriad of thematic categories, such as population, transportation, etc. As a terrain-based, extensible, computational reservoir identification system, ***NCResSys*** avoids making value judgments of the political feasibility of a potential reservoir location. Instead, this research addresses the need for a systematic process to identify sites to store water for use by public water suppliers. This analytical approach facilitates statewide analyses of potential reservoir sites across the State of North Carolina, in a comprehensive manner that allows for decision-makers and stakeholders to focus on the benefits and impacts of sites that might be developed.

To accomplish these objectives a series of processes and tasks have been created according to the principles of software engineering and geographic information science. The ***NCResSys*** information system was designed and developed according to the object-oriented analysis and design (OOAD) software engineering approach. This iterative development approach allows for the identification of application components as objects containing state (attributes) and behavior (functions). Per this methodology, a series of data modeling exercises will be conducted to identify the 'real-world' components, or objects, that comprise the needed information involved with modeling potential reservoir locations. This methodology provides the informational framework in which to design the computational algorithms to accomplish the objectives of modeling a municipal water supply reservoir. This informational framework is detailed in chapter two of this thesis, but includes components such as River Basin, Catchment, Stream Network, Yield, Reservoir, Dam, etc. Each of these components has attributes (name, area, length, elevation, volume, etc.) and relationships to other components in the system (River Basin contains a Sub River Basin). In the context of a geospatial information system, these informational components include the generic geographical characteristic of location. This facilitates the ability to calculate the measurement of the spatial relationship between components of the ***NCResSys*** (Reservoir at location A intersects with Road Network B). From this information design and architecture a comprehensive database of geospatial data sets will be collected to perform the necessary computational spatial analysis for modeling the physical characteristics and impact of a potential reservoir location.

Utilizing this database as inputs to the ***NCResSys*** a series of computational processes will be conducted according to the principles of the geographic information science. Spatial analysis will be conducted to demarcate areas throughout the State of North Carolina, in which reservoir development would be unfeasible. While this is a very subjective classification, as a baseline of United States National Parks, North Carolina State Parks, and existing urban areas throughout the State are deemed to be “off-limits” for potential reservoir development. Through terrain-bases hydrologic analysis, watershed areas with a calculated drainage area size over 25 square-miles ($mi^2$) outside of these “off-limit” areas will be identified. These areas will serve as the potential area for reservoir location and development. This drainage area size (25 $mi^2$), was determined as an estimate of a threshold size for a municipal water supply reservoir. Within these identified watershed areas, a hydrologic stream network based on terrain will be developed to identify the location of potential dams. This stream network will be traversed for potential dam and reservoir locations, starting at the lowest point, or outlet, of the watershed. A three-dimensional, terrain-based, computational algorithm will be conducted to determine the physical characteristics or surface area and volume of a potential reservoir according to the dam characteristics of location (x,y) and height (z) for each dam site along the stream network. Along with the physical characteristics of capacity at each reservoir location, a representation of the inundated flood area created at the potential dam site will be calculated. This inundated area will be used as input into calculating the impact of this potential reservoir location across a number of thematic data sets. The hydrologic characteristics of gross storage yield will be calculated. Gross storage yield will be determined as a spatially interpolated surface based on historical data from stream gauge record stations located throughout the State of North Carolina. These terrain and hydrologic analyses will provide the physical model of a reservoir at any given location, including volume, surface are, safe yield, and impacted area.

## 1.3. Data Processing and Analysis

### 1.3.1 Data

The primary datasets for the ***NCResSys*** fall into three broad categories: (1) terrain, (2) hydrology, and (3) thematic Socio-Economic. The State of North Carolina has an extensive inventory of publicly available geospatial data. Various state agencies, along with county and municipal governments, provide multi-thematic data freely available to the public. The North Carolina Center for Geographic Information and Analysis (NCCGIA) is a cost-recovery, public agency in North Carolina who is largely responsible for the generation, maintenance, and consolidation of multi-thematic geospatial data for the State of North Carolina.

Terrain, the vertical and horizontal dimension of land surface, is the primary dataset used in this study to identify the physical characteristics of a potential reservoir location. This project utilizes two primary sources for terrain data: the North Carolina Department of Transportation (NC DOT) and the North Carolina Floodplain Mapping Program (NCFMP). NC DOT produces a more generalized Digital Elevation Model (DEM) at the statewide scale with a spatial resolution of $80^{ft}$. The NCFMP produces a more detailed DEM available at the county level with a spatial resolution of $20^{ft}$. The multiple-scale resolution of the terrain data for the State of North Carolina facilitates the design and implementation of the recursive algorithm and general analytical approached developed to site potential reservoir sites in North Carolina. The NCFMP project is a unique partnership between the Federal Emergency Management Agency (FEMA) and the State of North Carolina. North Carolina was the first Cooperating Technical States (CTS) to modernize flood hazard mapping for all communities statewide (State of North Carolina, 2008). As a result of this program, the State has a comprehensive repository of highly accurate LiDAR DEM data sets. LiDAR is a Remote Sensing technique in which extremely dense laser measures of elevation are collected from an altimeter on-bard aircraft or satellite. LiDAR is an active optical sensor in which laser pulses are emitted at an extremely fast rate (up to 25,000 per second) to the Earth's surface along an airborne flight path (Campbell, 2002). The sensor records the precise time of the reflection of the laser as it encounters objects, thus producing a range distance measurement of the object and the sensor. These measurements, along with the other components of the LiDAR sensor (Global Positioning System (GPS) and inertial measurement unit (IMU)) are transformed to measurements of actual three-dimensional points of the reflected object in space (Figure 1).

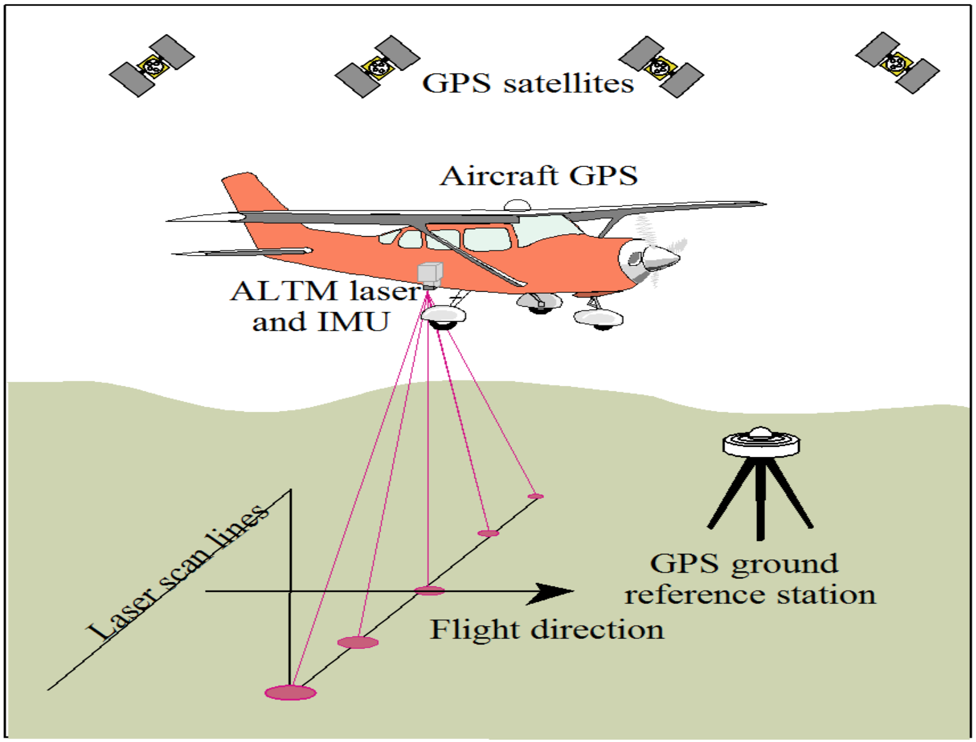



**Figure 1.1 - Airborne LiDAR Collection System**

This produces a highly accurate x, y, z measurement of the Earth's surface, typically with a centimeter-level vertical accuracy with a RMSE of 15 cm (Shan & Toth, 2008). As such, LiDAR is capable of generating very high spatial resolution models of elevation. There are two main types of LiDAR sensor data, full waveform and discrete-return. With waveform, permutations of the reflected laser wave form correspond to interactions with objects in space. Discrete-return LiDAR is represented as a series of return values, from first to last, corresponding to the reflections of the emitted laser pulse as it encounters objects both on and above the ground surface (Figure 2) (Wehr & Lohr, 1999). Multiple return values are capable of detecting several objects in the footprint of the laser path and as such can provide a three-dimensional representation of vegetation structure. Discrete point data is post-processed to produce extremely accurate representations of the Earth's surface. ***NCResSys*** utilizes the discrete-return LiDAR data collected and processed into DEMs by the NCFMP.

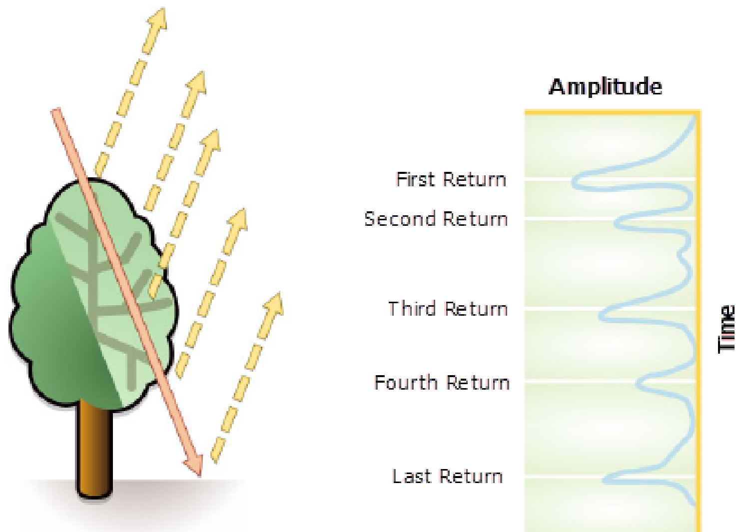



**Figure 1.2 - LiDAR Formats Discrete Return & Full Waveform (ESRI, 2012)**

The spatial resolution of the DEM determines how much ground coverage each pixel represents in terms of a single elevation measure (Woodcock & Strahler, 1987). In this case, the NC DOT DEM contains one elevation value per 80 x $80^{ft}$ of horizontal ground coverage, while the NCFMP DEM contains one elevation value per 20 x $20^{ft}$ of horizontal ground coverage (See Figure 3). Thus, the NCFMP DEM produces a much more detailed and accurate representation of terrain. While LiDAR derived data is highly accurate, it presents tremendous challenges for computational processing of terrain characteristics necessary to model reservoir capacity and potential site selection. This highly accurate elevation data on a statewide scale facilitates the terrain-based hydrologic modeling for the ***NCResSys*** and presents a unique opportunity for water resource system management.

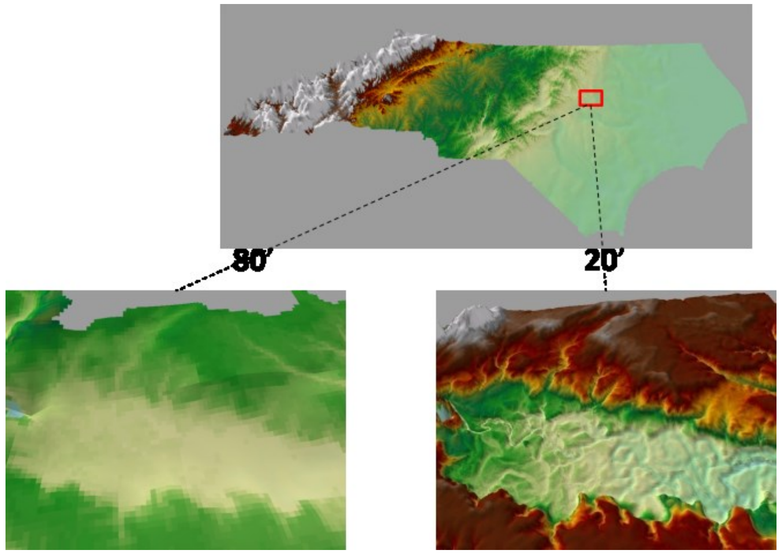



**Figure 1.3: DEM Spatial Resolution - NC DOT 80$^{ft}$ vs. NCFMP 20$^{ft}$.**

Hydrography data sets include the National Hydrography Dataset (NHD+) for coarse scale hydrologic units such as river basin and sub basin. Hydrologic data from the United States Geological Survey (USGS) contains stream flow gauge data that are utilized to characterize stream reach inflow and gross hydrologic yield estimates.

The third category of data, socio-economic, consists of a multitude of various spatially-explicit thematic data sets such as population, municipal and administrative boundaries, road networks, state and federal parklands, and water pollution discharge sites among others that were obtained from NCCGIA. These data are analyzed to address mitigating impacts to potential reservoir site analysis based on the inundation zone created and the parameters of the reservoir.

### 1.3.2 Analysis

The methodology for the **NCResSys** involves a number of techniques including physical terrain analysis, spatial analysis, and software engineering. The process for identifying potential municipal water supply sites involves the calculation of the physical capacity of a reservoir at a given location or dam site. This physical capacity, in terms of volume, is derived from the terrain surrounding the given dam location. Through the analysis of terrain over multiple spatial scales, the following solution provides the ability to model individual reservoir locations using a series of recursive terrain and hydrologic analyses that are based on geographic scale, from coarse (statewide) to fine (reservoir site), explicitly driven from the LiDAR terrain data.

The necessary terrain processing routines for identifying potential municipal water supply sites across the large geographic region of the State of North Carolina requires a novel approach to balance computational efficiency and feasibility, while providing the most accurate models of reservoir capacity and characteristics. As such, the designed solution for identifying potential reservoir sites is a recursive algorithm that utilizes the coarser, $80^{ft}$ DEM over larger geographical areas, such as River Sub Basin (8 digit USGS HUC), to derive smaller watershed boundaries to model potential reservoir sites utilizing the finer-grained $20^{ft}$ DEM. This design results in a solution that utilizes the highly accurate LiDAR-derived terrain data over smaller areas, thus, mitigating the computational constraints of using such a dense and rich data source, while still providing comprehensive statewide exploratory analysis.

Spatial analysis is conducted on the output of the physical reservoir identification to spatially reference the potential inundation zone of the site against the socio-economic datasets. This system is composed of a modular, component driven, object-oriented framework and application developed in the Python programming language.

### 1.4. Structure

This thesis will consist of five chapters. Chapter 1 will include introductory information such as background, problem statement, objectives, and high-level information on data and analysis. Chapter 2 will further detail the study area and data sets analyzed. Chapter 3 will describe the computational algorithms designed and developed to achieve the analytical research objectives. Chapter 4 will discuss the implication, meaning, and impact of this research. Chapter 5 will present the summary, conclusions, and directions for future work.

# CHAPTER 2: STUDY AREA & DATA

This chapter describes the geographic study area and corresponding data sets utilized in the ***NCResSys***, the geospatial modeling information system for identifying potential municipal reservoir locations in the State of North Carolina. The design of the terrain processing algorithms of the ***NCResSys*** produces a data-driven computational geospatial modeling engine that is not constrained by a specific geographic study area. However, the spatial extent of the data sets analyzed in the specific implementation of these computational algorithms in ***NCResSys*** produces the geographic study area bounds, i.e., the State of North Carolina. As such, the study area and data sets are related in a spatially explicit manner, but the geospatial tool that is described can be used for any locale even beyond the State of North Carolina.

## 2.0 Study Area

As the name indicates, ***NCResSys*** is a geospatial modeling information system for the identification of potential municipal water supply reservoir locations across the State of North Carolina. This research describes an information system that provides statewide analytical coverage for the computational modeling of the physical characteristics of a reservoir as well as the implications of a defined reservoir site across a set of multi-thematic data categories. As noted, ***NCResSys*** is a data-driven computational geospatial modeling engine used as a screening tool to assess potential reservoir sites in the State of North Carolina in which the spatial extent of the input data characterizes the study area under analysis. While the terrain-based computational algorithms have been designed to process data regardless of location, the specific implementation of the ***NCResSys*** utilizes spatial data for the State of North Carolina. While, the information system is comprehensive in providing statewide analysis for the modeling of municipal reservoir sites, a prototype area was selected to demonstrate the capabilities of the ***NCResSys***. This prototype area has varying terrain, hydrologic, and dynamic socio-economic conditions to test the tool. Based on projected population growth numbers (Office of State Budget & Management, 2009).

Durham, Johnston, and Wake counties are expected to grow tremendously over the next 29 years, 81%, 135%, and 154% respectively. As Figure 2.1 shows, these counties are located in the Upper Neuse sub-basin of the Neuse River basin. The high likelihood of increased water supply demands due to the projected population growth within this area is expected to place tremendous stress on existing water supplies and, thus, this demonstration site represents an area of great importance and opportunity for identifying potential reservoir sites.

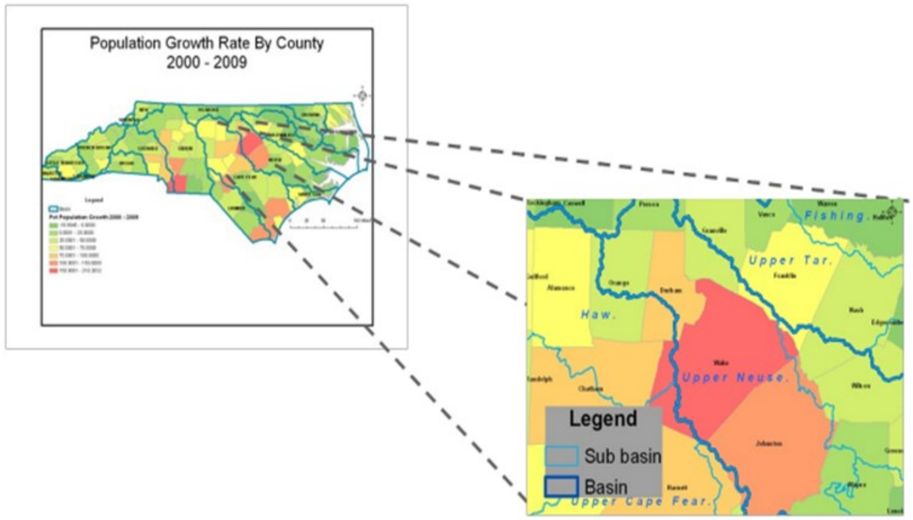



**Figure 2.4 - NCResSys Prototype Area - Population Growth**

## 2.1 Data

By designing the ***NCResSys*** information system according to the software engineering principles and data modeling methodology of Object-Oriented Analysis & Design (OOAD) an informational data framework has been created based on what the “real world” components, or objects, that comprise the needed information involved with modeling potential reservoir locations. The application of OOAD principles to spatial information systems is not new (Herring, 1992; Raper & Livingstone, 1995; Tang, Adams, & Usery, 1996; Worboys, 1994), but it does present a systematic approach to designing any type of information system (Johnson & Hardgrave, 1999; Johnson, 2002; Sangwan, Neill, Bass, & El Houda, 2008). This data design and architecture provides the framework for the physical data storage model, as well as the basis for the computational algorithm development for modeling a water supply reservoir (Booch et al., 2008). Through the OOAD methodology, three broad categories of information have been identified as imperative when modeling the abstract characteristics and behaviors associated with the development of a municipal water supply reservoir. These categories of information include the following: (1) terrain, (2) hydrology, and (3) multi-thematic socio-economic conditions. Together, these site descriptors or analytical dimensions form the logical data model for developing the ***NCResSys***. The spatially explicit environment in which this information system functions is a key component in the logical data model. As such, the generic geographic characteristic of location is associated with each component of the data model. By providing an inherent characteristic of location in each component of the data model, the spatial relationship between components can be analyzed in the context of a GIS (Milne, Milton, & Smith, 1993; Raper & Livingstone, 1995) .

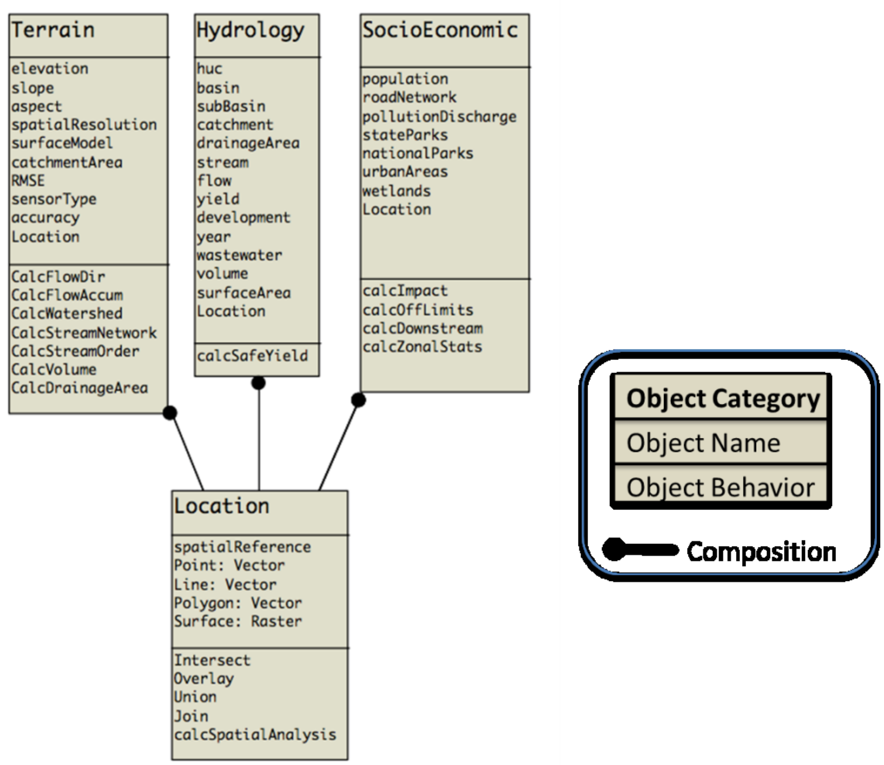



**Figure 5.2: *NCResSys* Logical Object Model**

As Figure 2 indicates, adhering to the data modeling principles of the OOAD methodology produces the informational framework of attributes and behaviors for the components involved IN computationally modeling a municipal water supply reservoir. Each broad information category (i.e., terrain, hydrology, socio-economic descriptors) is further broken down into the logical objects, including associated attributes (nouns) and behaviors (verbs) that serve as the basis for the data and algorithms of the ***NCResSys*.**

From this logical data model, a comprehensive database of geospatial data sets was developed. This database facilitates the analytical goals of modeling water supply reservoirs in a dynamic and spatially explicit manner at a regional scale. The State of North Carolina has an extensive inventory of publicly available geospatial data. Various state agencies, along with county and municipal governments, provide multi-thematic data freely available to the public. ***NCResSys*** utilizes two primary sources for terrain data: the North Carolina Department of Transportation (NC DOT) and the North Carolina Floodplain Mapping Program (NCFMP) (State of North Carolina, 2008). Hydrography data sets include the National Hydrography Dataset (NHD+) for coarse scale hydrologic units such as river basin and sub basin (U.S. Geological Survey, 2012a). Hydrologic data from the United States Geological Survey (USGS) contains stream flow gauge data that are utilized to characterize stream reach inflow and gross hydrologic yield estimates. Terrain and hydrologic data are interrelated in the context of geospatial modeling, as the physical properties of water over a change in terrain per a given area adhere to the laws of gravity (Jenson, 1991). The North Carolina Center for Geographic Information and Analysis

(NCCGIA) is a cost-recovery, public agency in North Carolina who is largely responsible for the generation, maintenance, and consolidation of multi-thematic geospatial data for the State of North Carolina (NC Center for Geographic Information & Analysis, 2010). A number of the socioeconomic thematic data sets were provided from the NCCGIA.

### 2.2 Terrain

Terrain, the vertical and horizontal dimension of land surface, is the primary data set used in this study to identify the physical characteristics of a potential reservoir location. While a land surface coverage can change over time, the baseline surface terrain is considered a static dataset. As such, the ***NCResSys*** derives the physical characteristics of a potential reservoir location based on the static terrain data. These characteristics, such as volume and surface area, form the logical basis of what a reservoir *is* and changes in terrain determine how damning, inundating, and developing a location can be quantified and spatially analyzed against the other logical data categories, i.e., hydrology and socio-economic conditions ((Woolard & Colby, 2002).

As previously mentioned, ***NCResSys*** utilizes two primary sources for terrain data. Each of these data sources represents terrain as a Digital Elevation Model (DEM). In a DEM, elevation is represented as a regular grid of continuous cells, each containing a single elevation value for that cell. The spatial resolution of the DEM determines how much ground coverage each cell represents in terms of this single elevation measure. For example, a DEM with an $80^{ft}$ spatial resolution will contain a regular grid of cells, with each cell containing a singular value of elevation that is representative of the $80^{ft}$ of land surface at that specific location. In contrast, a $20^{ft}$ spatial resolution DEM will contain a single elevation value for every $20^{ft}$ of land surface coverage (Woodcock & Strahler, 1987). Thus, as Figure 3 indicates, a $20^{ft}$ DEM contains a much higher density of elevation values for a given area. In fact, for the same area of land surface, a $20^{ft}$ DEM will contain a square of squares, or *n* to the $4^{th}$ power ($n^4$), the amount of elevation values as the $80^{ft}$ DEM (Figure 3).

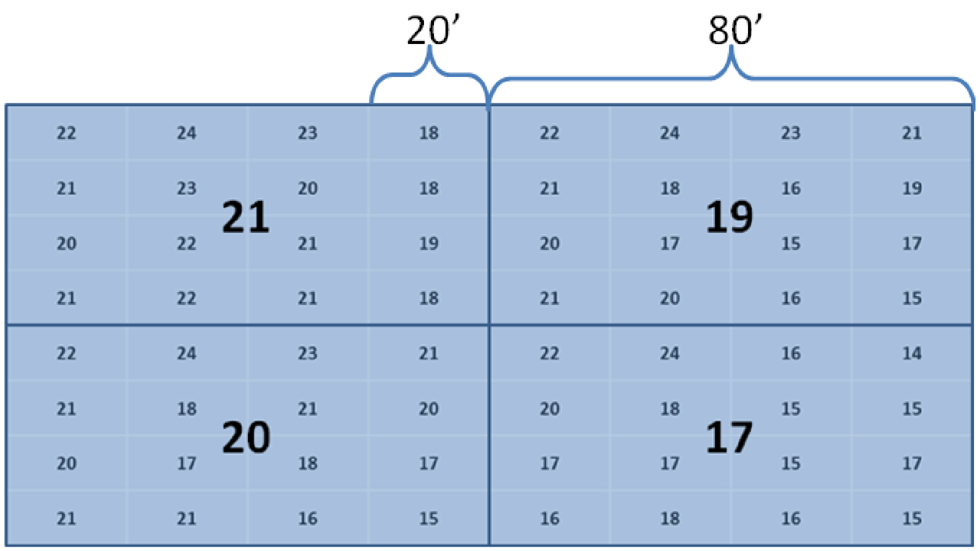



**Figure 2.6 - Amount of Information $20^{ft}$ vs. $80^{ft}$ DEM**

In practical terms for the ***NCResSys***, this means that a $20^{ft}$ DEM produces a much denser data set of terrain in which to model reservoir locations. Figure 4 shows how this difference in spatial resolution of the input terrain data set produces vastly different visual representations of changes in elevation over smaller geographic areas. At the coarser $80^{ft}$ spatial resolution changes in terrain are not captured in as much detail as the $20^{ft}$ DEM. Utilizing finer scaled DEM terrain may help to identify potential reservoir locations and drainage basins that might not have been identified at the coarser scale (Marks & Bates, 2000). However, the increase in data volume from the $20^{ft}$ DEM also equates to increased complexities when computationally processing the terrain data over larger geographic areas. These challenges are detailed in Chapter 3.

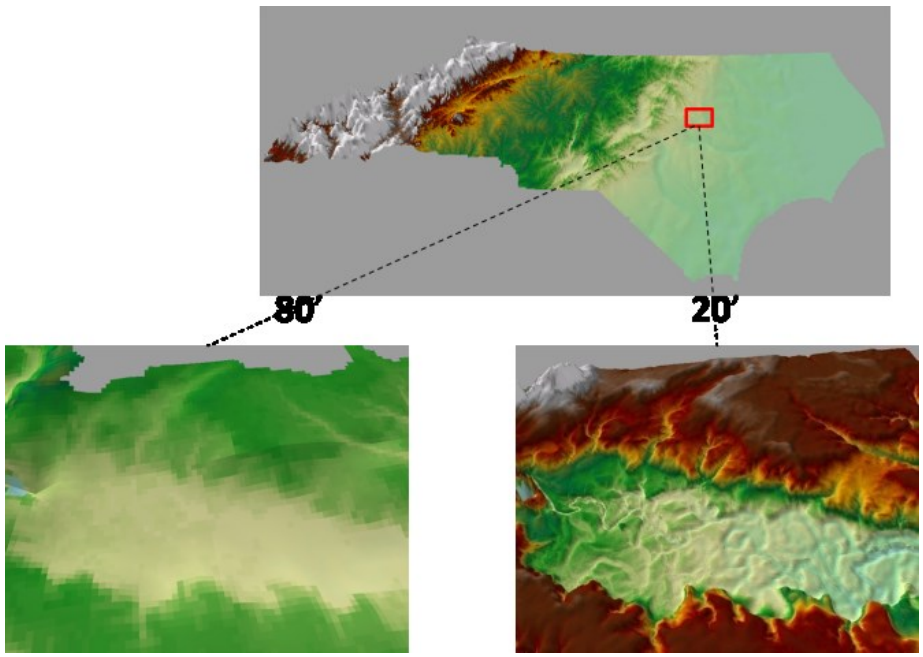



**Figure 2.7 - Elevation Differences $80^{ft}$ vs. $20^{ft}$ in North Carolina**

The terrain data utilized in the ***NCResSys*** consists of the DEMs that have been derived from the remote sensing technique known as LiDAR, i.e., Light Detection and Ranging. This technique is similar to RADAR (Radio Detection and Ranging), in which radio waves are emitted from a sensor with the return permutations of the waveform being calculated (Wehr & Lohr, 1999). With LiDAR, focused, coherent light, or lasers, are actively directed upon a surface, with the permutations of either the light waveform or path indicating a unit of measurement (Shan & Toth, 2008). The State of North Carolina has a comprehensive repository of these highly accurate LiDAR DEM data sets. LiDAR is a remote sensing measurement technique in which extremely dense laser measures of elevation are collected from an altimeter on-board an aircraft or satellite (Shan & Toth, 2008). LiDAR is an active optical sensor in which laser pulses are emitted at an extremely fast rate (up to 25,000 per second) to the Earth's surface along an airborne flight path. The sensor records the precise time of the reflection of the laser as it encounters objects, thus producing a range distance measurement of the object and the sensor. This produces a highly accurate x, y, z measurement of the Earth's surface, typically with a centimeter-level vertical accuracy with a RMSE of 15 cm (Campbell, 2002). As such, LiDAR is capable of generating very high spatial resolution models of elevation (Marks & Bates, 2000). There are two main types of LiDAR sensor data, full waveform and discrete-return. With waveform, permutations of the reflected laser wave form correspond to interactions with objects in space. Discrete-return LiDAR is represented as a series of return values, from first to last, corresponding to the reflections of the emitted laser pulse as it encounters objects both on and above-the-ground surface (Baltsavias, 1999). Multiple return values are capable of detecting several objects in the footprint of the laser path and, as such, can provide a three-dimensional representation of vegetation structure. Discrete point data is post-processed to produce extremely accurate representations of the Earth's surface.

As previously mentioned, the ***NCResSys***, utilizes LiDAR derived DEMs from two sources: NCFMP and NC DOT. These data sources are representations of discrete-return LiDAR data that has been collected and processed into DEMs at the $80^{ft}$ and $20^{ft}$ spatial resolutions. NC DOT produces a more generalized Digital Elevation Model (DEM) at the statewide scale with a spatial resolution of $80^{ft}$. The NCFMP produces a more detailed DEM available at the county level with a spatial resolution of $20^{ft}$. The multiple-scale resolution of the terrain data for the State of North Carolina facilitates the design and implementation of the recursive algorithm and general analytical approached developed to site potential reservoir sites in North Carolina, as detailed in Chapter 3. As previously mentioned, the spatial resolution of the DEM determines how much ground coverage each pixel represents in terms of a single elevation measure. In this case, the NC DOT DEM contains one elevation value per $80^{ft}$ x $80^{ft}$ of horizontal ground coverage, while the NCFMP DEM contains one elevation value per $20^{ft}$ x $20^{ft}$ of horizontal ground coverage. Thus, the NCFMP DEM produces a much more detailed and accurate representation of terrain. While LiDAR derived data are highly accurate, it presents tremendous challenges for computational processing of terrain characteristics necessary to model reservoir capacity and potential site selection. This highly accurate elevation data on a statewide scale facilitates the terrain-based hydrologic modeling for the ***NCResSys*** and presents a unique opportunity for water resource system management.

### 2.3 Hydrology

Hydrology and terrain are closely related when spatially modeling the physical capacity of a potential reservoir location. The logical organization of land area in the

United States can be categorized through the United States Geologic Survey's (USGS) Hydrologic Unit Code (HUC) designation. The USGS demarcates the US into successively smaller hydrologic units that are classified into four levels: region, sub-region, accounting units, and cataloging (U.S. Geological Survey, 2012c). Each of these smaller units is identified through its HUC designation. For example, the Upper Neuse River area of North Carolina is hydrologically identified according to the USGS schema as an 8-digit cataloging unit or HUC-8, "03020201" (Seaber, Kapinos, & Knapp, 1994). This is deconstructed through the hierarchy of HUCs, by region (03, South Atlantic-Gulf, HUC-2), sub-region (0302, Neuse-Pamlico, HUC-4), accounting unit (030202, Neuse, HUC-6) and finally by cataloging unit (03020201, Upper Neuse, HUC-8). Each of these HUCs is aggregated by area and drainage basin. Areas within each of these HUCs will drain to the same ultimate location, given the terrain within the HUC.

The demarcation of the state of North Carolina into HUCs by the USGS serves as the hydrologic starting point for the ***NCResSys.*** As detailed in Chapter 3, the HUC-6 and HUC-8 data are utilized as inputs to the ***NCResSys*** terrain processing algorithms to hydrologically and intelligently delineate appropriate boundary extents for computing the dense $20^{ft}$ DEMs. The USGS has identified 18 accounting units (HUC-6) and 56 cataloging units (HUC-8) throughout North Carolina (Figure 5).

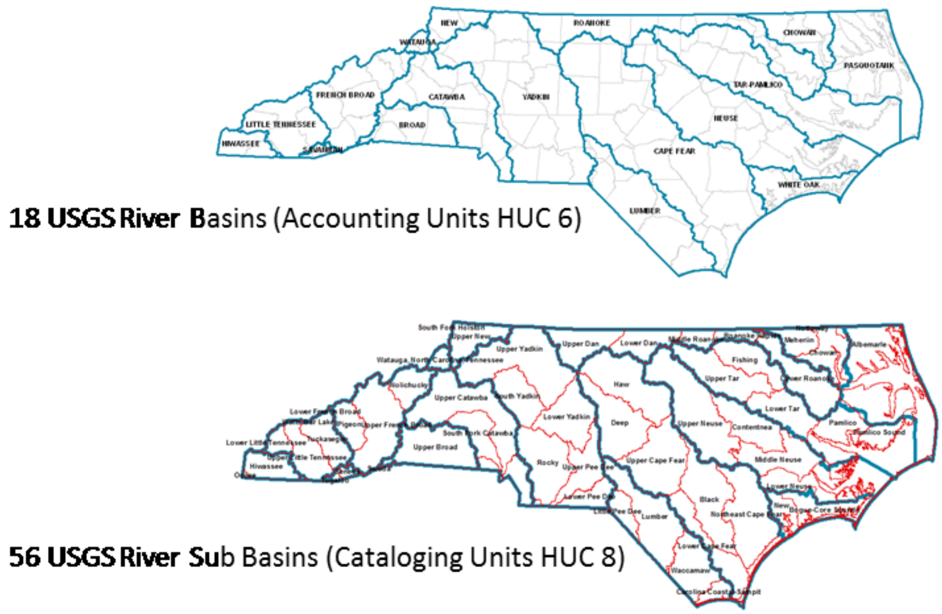



**Figure 2.8 - USGS Hydrologic Unit Code areas North Carolina**

Along with the HUC boundary data from the USGS, dynamic stream gauge data are utilized to calculate a measure of the yield from the potential reservoir location. This is a dynamic data source, as the stream gauge recordings are variable over time, based on the precipitation patterns throughout the recording period (U.S. Geological Survey, 2012b). As such, these data are calculated in a separate process from the terrain analysis processing engine, which is operating on data that are static over time. The aggregation of stream gauge recording stations over time produces the hydrologic record of a given area.

These hydrologic records are composed of precipitation measures over time as recorded by USGS stream gauge network. Data from 118 USGS stream gauges located across North Carolina is utilized to characterize stream reach inflow parameters of a potential reservoir location. Data from each of the 118 stream gauges serves as the computational input to determine the safe yield, or the maximum uniform rate of withdrawal from an impoundment over the historical record of stream flows for each gauge location. Spatially interpolating a continuous surface from the 118 stream gauges provides a measure of precipitation, as well as safe yield, over time and time for the entire State of North Carolina.

### 2.4 Socio-Economic

The third category of data, socio-economic, consists of a multitude of various spatially-explicit thematic data sets. These data are dynamic in nature and thus is utilized to identify, characterize, and quantify the development impacts of a potential reservoir location across the various themes. Based on the dynamic computational design of the ***NCResSys,*** any geo-referenced data set can be analyzed in a spatially explicit manner against the modeled reservoir. Due to the highly dynamic nature of these types of data this are key, as not only can new geo-referenced data be added for analysis, newer versions of thematic data can also be evaluated and inserted into the data system.

A number of thematic categories have been identified through the data modeling process as important with regards to the identification of potential reservoir development. These data sets serve as the baseline for characterizing the impact of potential reservoir development. Various spatially-explicit thematic data sets such as population totals, municipal and administrative boundaries, road networks, state and federal parklands, and water pollution discharge sites, among others, were obtained from NCCGIA and used in this project (Figure 6). These data are analyzed to address mitigating impacts to potential reservoir site locations based on the inundation zone created and the parameters of the reservoir. Along with the hydrologic measures of HUC and yield, these various thematic datasets are analyzed for the potential reservoir flood inundation zone in a spatially explicit manner, thus identifying, characterizing, and quantifying the impacts at that location, such as, percent of land use inundated, length and type of roads inundated, and proportion of the parklands inundated when the flooding of land at a specified location to a set of reservoir specifications (Goodchild et al., 1992).

In addition to the dynamic socio-economic data conditions impacted by the potential reservoir flood inundation zone, the spatial context of the surrounding catchment area can be analyzed to situate the suitability of a location. For example, economically, ecologically, and culturally sensitive areas that are located within the larger catchment area of a potential reservoir location can be spatially identified. This provides an indication of not only the directly impacted location of the potential reservoir flood zone, but also the larger impact based on the spatial relationship. The footprint of a potential reservoir location can be identified based on the spatial relationships between the physical and socio-economic conditions.

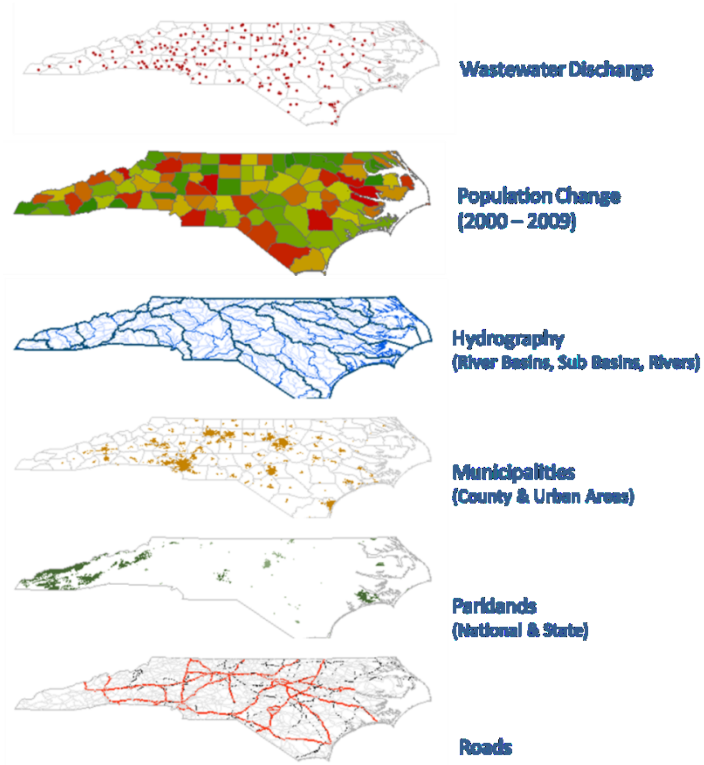



**Figure 2.9 - Socioeconomic Data sets NCResSys**

### 2.6 Conclusions

Utilizing the Object-Orient Analysis & Design methodology of software engineering, the logical data model representing terrain, hydrologic, and socio-economic objects involved with modeling potential reservoir locations was created. From this logical data model, the data sets were procured from various sources to form the physical data model used by the ***NCResSys.*** The terrain object model involves multi-scale LiDAR DEM data, the main focus of the computational engine developed in this application. Terrain, along with hydrologic and socio-economic data, is identified in the logical object models that form the computational components of the ***NCResSys*** have been designed.

# CHAPTER 3: METHODS & ANALYSIS

This chapter describes the analytical approaches and general methods of the ***NCResSys***, the geospatial modeling information system for identifying potential municipal reservoir locations in the State of North Carolina. The overall system level design for the ***NCResSys*** employs a number of techniques from various disciplines such as software engineering, three-dimensional terrain processing, and spatial analysis. Continuing from the conceptual, logical, and physical data modeling processes of the Object-Oriented Analysis & Design (OOAD) software engineering methodology, described in Chapter 2 of this document, data-driven application components and algorithms have been designed to computationally model the development of potential reservoir locations in a spatially explicit manner. Each of the system level components of the ***NCResSys*** is described, as well as the overall system architecture and technical implementation details.

The methodology for the ***NCResSys*** involves a number of techniques including physical terrain analysis, spatial analysis, and software engineering. Potential reservoir locations are identified through their physical capacity and general characteristics, such as surface area and volume, utilizing multi-scale terrain data. This geospatial modeling methodology involves a series of recursive terrain and hydrologic analyses based on geographic scale, from coarse (statewide) to fine (reservoir site), explicitly driven from LIDAR terrain data. This application involves constant or static datasets, as well as dynamic data elements. Terrain data were chosen as the driver of all analyses due to its static nature. Spatial analysis is conducted on the output of the physical reservoir identification to spatially reference the potential inundation zone of the site against the socio-economic datasets.

As Chapter 2 detailed, through the OOAD data modeling process, three logical data component, subject areas were identified: terrain, hydrologic, and socio-economic. Location was also identified as a key component of modeling potential reservoirs in a spatially explicit manner. Building upon this informational data model, the computational algorithms and components were designed and implemented to analyze the primary data components of terrain, hydrology, and socio-economic conditions. This chapter details the software engineering elements of the technical architecture, design, and development of the ***NCResSys***, as well as the analytical processing algorithms computed for the terrain, hydrologic, and socio-economic data layers, producing the comprehensive geospatial modeling information system for identifying potential municipal reservoir locations in the State of North Carolina, or ***NCResSys.***

### 3.1 Technical Design & System Architecture

The computational processing of the ***NCResSys*** involves the design and development of a comprehensive system, facilitating the recursive terrain analysis as part of the spatially modeling of potential reservoir locations. This system is composed of a modular, component driven, object-oriented framework and applications developed in the Python programming language. A high-level system diagram is shown in Figure 1.

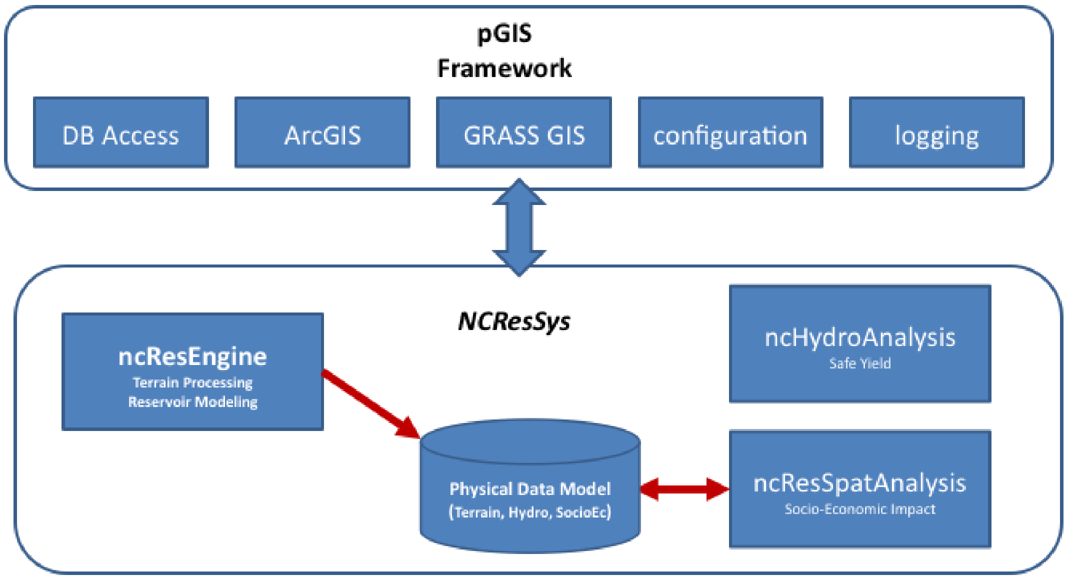



**Figure 3.10 - NCResSys Technical Architecture**

To address the data intensive processing challenges associated with high-density terrain analysis, ***NCResSys*** was designed as an implementation of the pGIS geospatial analysis framework (Morrissey, 2010b). pGIS is an abstract processing framework developed in the Python programming language that incorporates the capabilities of multiple GIS systems, and extends those systems in a customizable and configurable framework for geospatial analysis and modeling implementations. pGIS provides modular implementation of the ArcGIS geoprocessing and GRASS GIS libraries in an application framework allowing for seamless inter-system processing, allowing the implemented application access to the strengths of each GIS system. Along with this inter-GIS capability, pGIS provides modular and extensible functionality of the Python programming language, such as configurations, logging, email, file system management, data access, web output and visualizations, among others. ***NCResSys*** is a reference implementation of the pGIS framework that is thematically geared towards three-dimensional, multi-scale, terrain analysis (Morrissey, 2010a). This framework allows the ability to design and develop the above solution as a robust application that utilizes the computational efficiency of the binary raster processing of GRASS GIS for the terrain and hydrologic processing, while also utilizing the geographic transformations, vector processing, and display strengths of ArcGIS (Chairat & Delleur, 1993; Guo Xian-chun, Luo Ding-gui, Zou Shi-lin, Li Da-jun, & Zheng Wan-qing, 2009; Neteler & Mitasova, 2002). The pGIS framework provides abstraction between the computational processing libraries for performing spatially explicit analysis, such as GRASS GIS Python package (i.e., grass. script) and the specific implementation theme of the ***NCResSys***.

System architecture and overall technical design was created through the OOAD approach for the design of system level components at multiple levels. The creation of UML diagrams such as system diagrams, object models, and processing flow charts were conducted through the OOAD methodology, from the high level architecture down to the individual terrain-processing algorithms (Dobing & Parsons, 2005). As described in Chapter 2, the three logical categories of information for the ***NCResSys:*** terrain, hydrography, and socio-economic, form the base of the computational analysis components in the overall system design. Each of these components performs specific spatial computational analysis on data within the three information domains. The components interact with other data and analyses through interfaces designed as part of the OOAD process. The process of modeling the individual components through UML object models diagrams and algorithm processing flow charts for the physical terrain analysis component are discussed below. The relationships of the hydro and socio economic components are also detailed. The high-level system diagram (Figure 2) provides the design connection between the logical data model and the computational system level components.

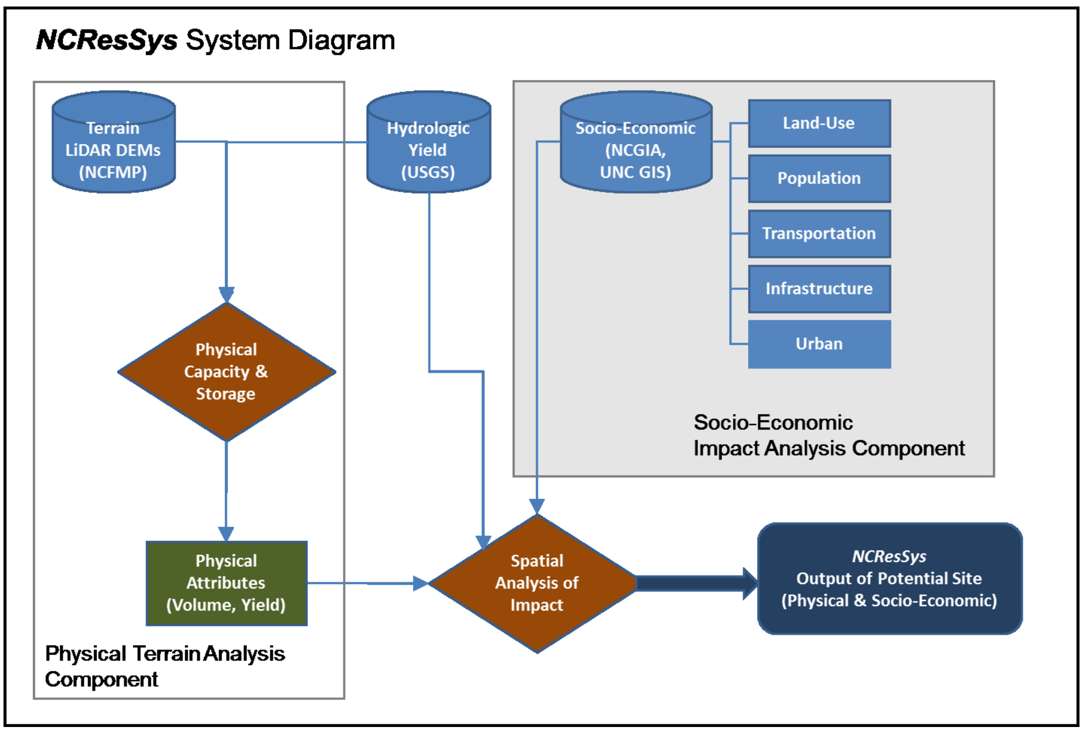



**Figure 3.11 - *NCResSys* System Design Diagram**

### 3.2 Terrain Analysis

The methodology for designing the terrain component of the ***NCResSys*** involves a number of techniques including physical terrain analysis, spatial analysis, and software engineering. Potential reservoir locations are identified through their physical capacity and general characteristics, such as surface area and volume, utilizing multi-scale terrain data (Band, 1986; More, Grayson, & Ladson, 1991). This geospatial modeling methodology involves a series of recursive terrain and hydrologic analysis based on geographic scale, from coarse (statewide) to fine (reservoir site), explicitly driven from terrain data. The logical information objects for the terrain-processing component of ***NCResSys*** are technically implemented via the creation of specific instances of these objects. UML object model diagrams help to identify the attributes, behaviors, and relationships of the logical objects (Figure 3). These objects are computationally processed via Python classes with attributes, methods, and relationships that comprise the terrain processing analysis component.

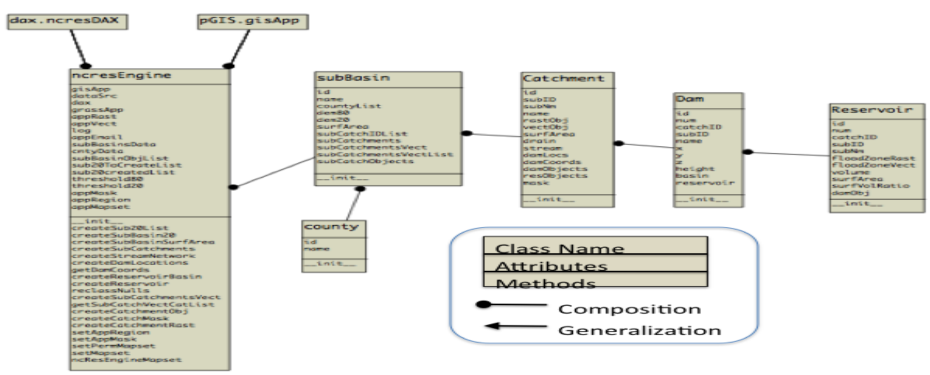



**Figure 3.12 - NCResSys Terrain Processing Component Object Model UML Diagram**

The necessary terrain processing routines for identifying potential municipal water supply sites across the large geographic region of the State of North Carolina requires a novel approach to balance computational efficiency and feasibility, while providing the most accurate models of reservoir capacity and characteristics. The

LiDAR elevation data sets utilized in the ***NCResSys*** present an extremely dense data source that, while is increasingly accurate than other DEM data sources, presents computational challenges for processing terrain-driven hydrologic characteristics, especially at scale (Band, Patterson, Nemani, & Running, 1993; Hopkinson, Hayashi, & Peddle, 2009; Marks & Bates, 2000). As such, the designed solution for identifying potential reservoir sites is a recursive algorithm that utilizes the coarser, $80^{ft}$ DEM over larger geographical areas, such as River Sub Basin (8 digit USGS HUC), to derive smaller watershed boundaries to model potential reservoir sites utilizing the finer-grained $20^{ft}$ DEM. This design results in a solution that utilizes the highly accurate LiDAR-derived terrain data over smaller areas, thus, mitigating the computational constraints of using such a dense and rich data source, while still providing comprehensive statewide analysis. Previous research efforts in the State of North Carolina have shown the value and challenges of utilizing LiDAR derived DEM data for performing terrain analysis (Mitasova, Drake, Bernstein, & Harmon, 2004; Mitasova, Overton, & Harmon, 2005; Mitasova, Overton, Recalde, Bernstein, & Freeman, 2009). The enhanced data capabilities of the available LiDAR data for conducting terrain analysis present a unique opportunity for modeling reservoir capacity across the State.

There are two main recursive algorithms that were designed to perform the terrain analysis for utilizing the multi-scale LiDAR elevation data to model potential water supply reservoirs (Figure 4). The Sub-Catchment Processing algorithm recursively performs multi-scale LiDAR DEM terrain analysis on smaller geographic hydrologic unit boundaries to identify smaller drainage areas for more finely grained reservoir modeling. The Reservoir Modeling Processing algorithm performs fine-grained terrain analysis for modeling the physical capacity of a reservoir at given dam characteristics such as location and height. These algorithms form the computational and analytical processing for the terrain analysis component of the ***NCResSys*** information system.

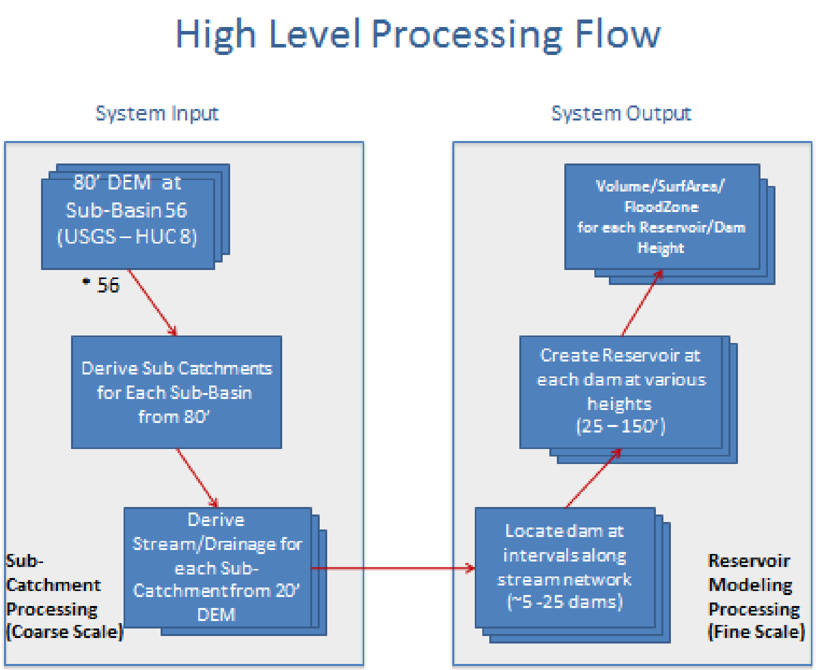



**Figure 3.13 - NCResSys Terrain Processing Component High Level Processing Flow**

### 3.2.1 Sub-Catchment Processing

The Sub-Catchment processing algorithm is a terrain-data driven computational routine that recursively calculates smaller geographic drainage areas in which to model a potential reservoir. This algorithm utilizes multi-scale LiDAR DEM data to balance computational efficiency with accuracy regarding DEM resolution at the appropriate scale. The UML diagram of the Sub-Catchment Terrain processing flow chart details the computational routines involved in this algorithm (Figure 3.5). Python code has been developed according to the specification of the Terrain Processing object model (Figure 3.3) and this processing flow chart (Figure 3.5) (GRASS Development Team, 2008; Neteler & Mitasova, 2002). The Sub-Catchment Terrain Processing Algorithm flow chart details the recursive computational analysis of raster DEM data into smaller Sub-Catchment areas for fine-grained detailed analysis. Utilizing the GRASS raster processing engine, the hydrologic characteristics, such as flow direction, flow accumulation, watershed basin, drainage area, and stream network can be derived. By computationally controlling the processing area of interest, or masking, high density DEM data can be processed over increasingly smaller areas. This provides the balance between computational feasibility and accuracy. The details of this computational processing algorithm are described below.

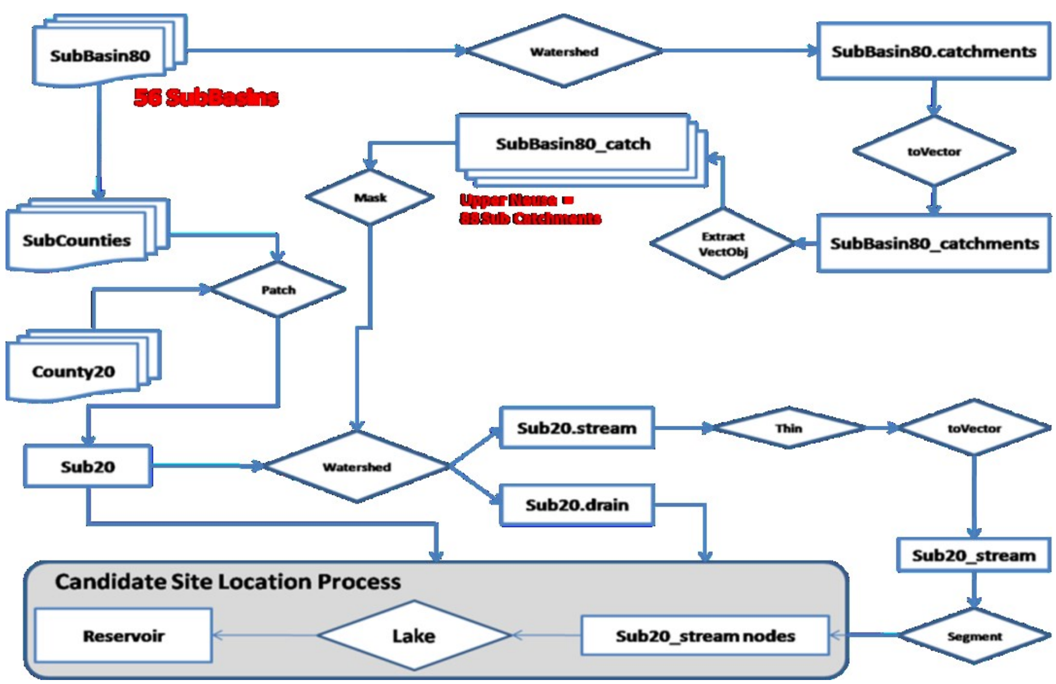



**Figure 3.14 - NCResSys Sub-Catchment Terrain Analysis Processing Algorithm**

#### 3.2.1.1 Reservoir Catchment Delineation

The process of deriving catchments for potential reservoir sites across the State is a series of computational routines that start at the macro, statewide scale and become recursively finer-grained at the individual potential reservoir site. The State of North Carolina contains 18 River Basins (HUC 6) and 56 River Sub Basins (HUC 8) as defined by the United States Geological Survey (USGS) (Figure 6).

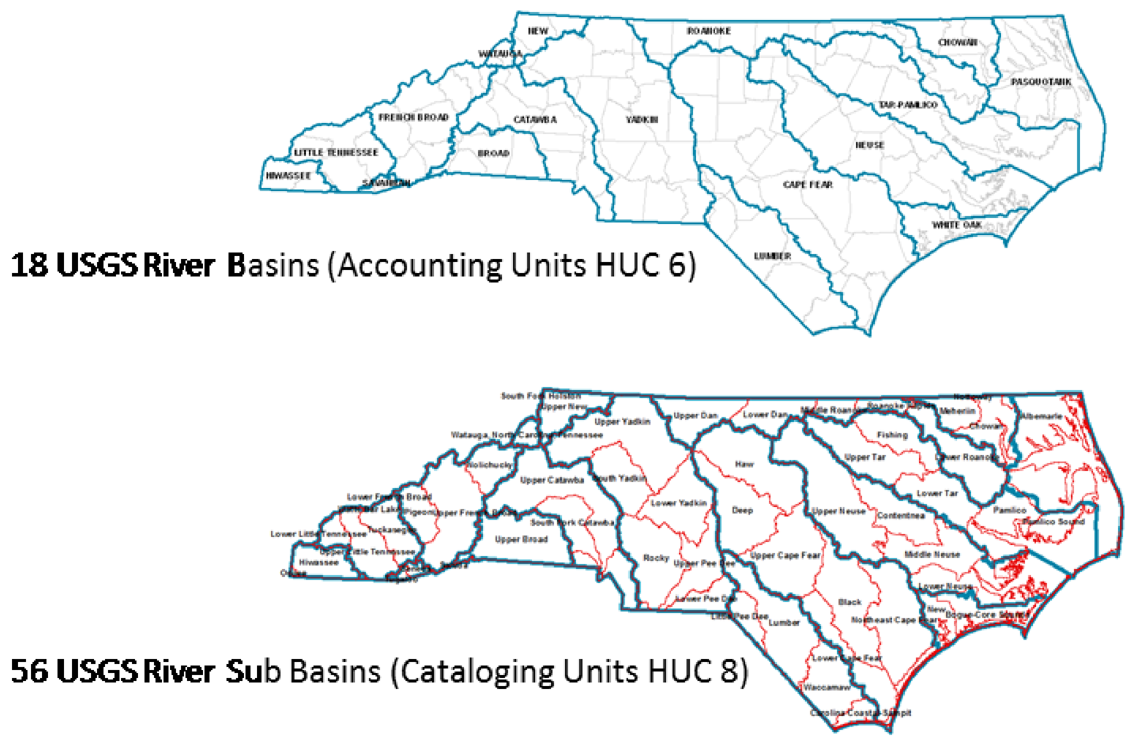



**Figure 3.15 - USGS River Basins and River Sub Basins of North Carolina.**

The contiguous statewide terrain data, provided by the NC DOT at 80$^{ft}$ spatial resolution, is spatially partitioned by the 56 separate River Sub Basin boundaries.

This results in 56 terrain data models at $80^{ft}$ spatial resolution, one for each River Sub Basin (SubBasin80) (Figure 7).

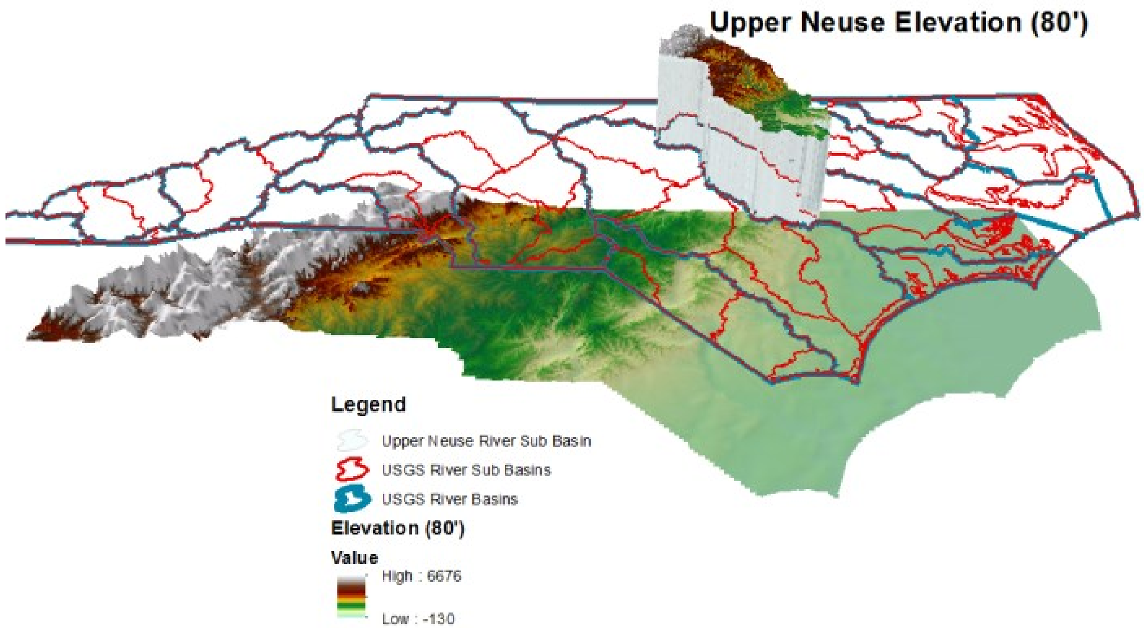



**Figure 3.16 - Spatially partitioning statewide $80^{ft}$ DEM by the 56 USGS Sub Basins.**

Each of the 56 River Sub Basins are further spatially partitioned by performing hydrologic catchment analysis on each corresponding River Sub Basin $80^{ft}$ terrain model. Catchments within each River Sub Basin (Sub-Catchments) are computed by performing an $A^T$ Least-Cost Search algorithm on the SubBasin80 DEM. This computational terrain analysis determines hydrologic parameters such as drainage direction, flow accumulation, and catchment basin through pixel-by-pixel calculations of slope and area across the SubBasin80 DEM (Hengl & Reuter, 2008; Tarboton, 1997). The pertinent output of this terrain analysis is the delineation of catchment basins' boundaries (Sub-Catchments) at a finer scale than the River Sub

Basin that are characterized by drainage area size for further analysis (Figure 8) (Band, 1986). The number of Sub-Catchments produced for each River Sub Basin through this computation varies, dependent upon the characteristics of size (area) and relief (slope) of the input SubBasin80 DEM.

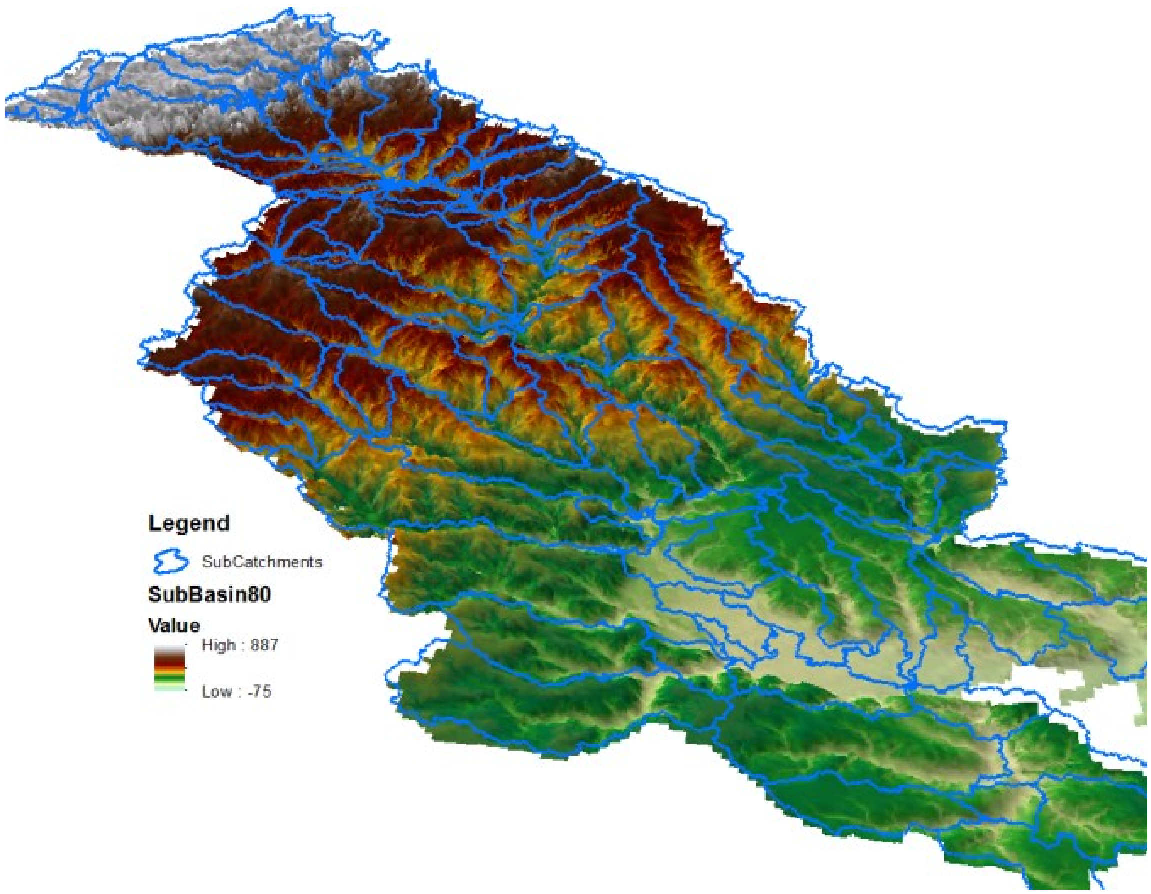



**Figure 3.17 - Terrain-derived River Sub Basin catchments (Sub-Catchments).**

The finer scale catchments derived from the terrain data serve as boundaries for more detailed hydrologic analysis and reservoir modeling, utilizing the highly accurate 20ft DEM data. Sub-Catchments that do not meet a configurable minimum threshold for drainage area size (e.g., 20 $mi^2$) are filtered from further processing and analysis. Each of these resulting Sub-Catchments represents a spatial boundary at the computationally efficient and feasible scale necessary for the detailed terrain-driven hydrologic analysis at the $20^{ft}$ spatial resolution.

#### 3.2.1.2 Reservoir Catchment Terrain Data

The processing of each Sub-Catchment contained within each SubBasin80 continues with analysis of the administrative county boundaries intersecting with the Sub-Catchment. Spatial analysis is performed on the Sub-Catchment area vector representation to identify the counties in which the Sub-Catchment is located. The fine-grained 20ft terrain data are organized at the county-level; thus a Sub-Catchment may be located in more than one county, which requires an amalgamation of county-level DEMs into a single DEM of all intersecting counties, resulting in a tremendous volume of data at the county or multiple county-level at this spatial resolution. The single or multiple county-level DEM data are spatially partitioned, or “clipped”, by the boundary of the Sub-Catchment area vector. This results in the highly accurate terrain dataset (SubCatchment20) at $20^{ft}$ spatial resolution that is bounded by the geographic scale necessary for computationally feasible and efficient modeling of individual reservoir locations (Figure 9).

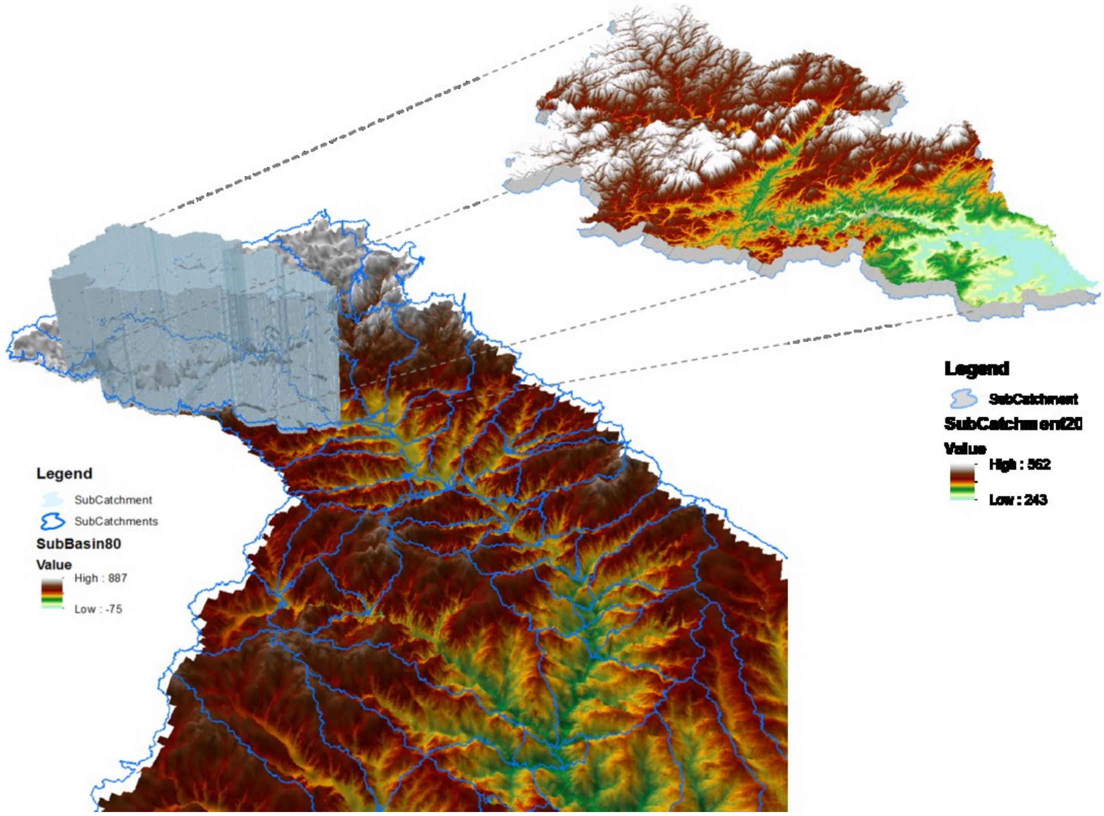



**Figure 3.18: Sub-Catchment boundary used to create 20ft terrain dataset (SubCatchment20).**

### 3.2.2 Reservoir Modeling

The reservoir modeling, computational routines involve iterative terrain-based hydrologic analysis, along with network analysis to produce sets of potential dam and reservoir locations and characteristics. Utilizing the previously created terrain dataset (SubCatchment20), the necessary hydrologic datasets are derived, such as stream network and catchment outlet point, and the physical characteristics of volume and surface area of a reservoir are modeled at a given location or dam site. Traversing the stream network for possible dam locations, as well as iterating over a range of dam heights, provides a robust reservoir-modeling algorithm by providing configurable scenarios of possible development. At each dam location, inundation routines are computed per dam location and height parameters are sent to the algorithm. The physical characteristics of volume and surface area, as well as the inundation flood impact zone, are computed per each dam location along the stream network. The UML diagram of the Reservoir Modeling processing flow chart details the computational routines involved in this algorithm (Figure 3.10). Python code has been developed according to the specification of the Terrain Processing object model (Figure 3) and this processing flow chart (Figure 3.10) (GRASS Development Team, 2008; Neteler & Mitasova, 2002). The Reservoir Modeling Terrain Processing Algorithm flow chart details the computational analysis of derived stream networks into potential reservoir locations and characteristics. By computationally modeling potential dam locations along a derived stream network alternate scenarios of dam characteristics and thus reservoir characteristics can be computed. This provides a robust algorithm for computationally modeling multiple reservoir locations along a stream network. The details of this computational processing algorithm are described below.

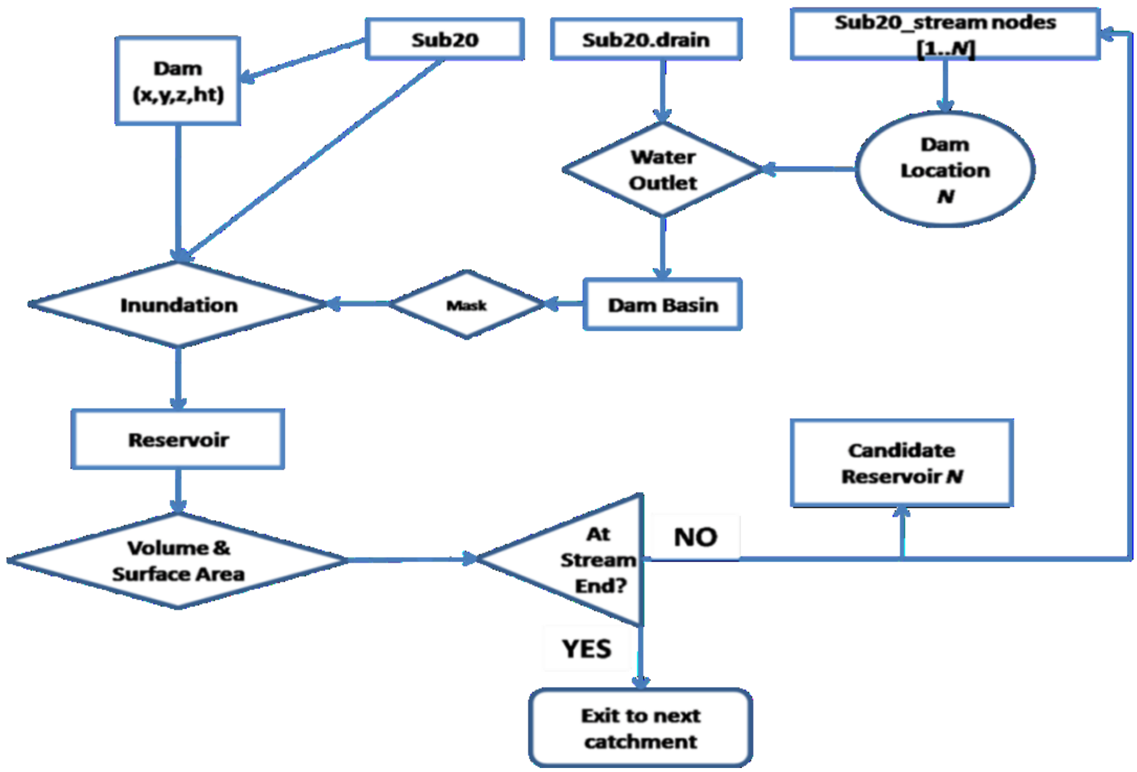



**Figure 3.19 - NCResSys Reservoir Modeling Terrain Analysis Processing Algorithm**

### 3.2.2.1 Stream Network Derivation

Each SubCatchment20 terrain dataset provides the input to the computational processing routines for modeling the spatial and physical characteristics of a potential reservoir location. Using the SubCatchment20 terrain dataset as input, a stream network and water outflow points are computed for each Sub-Catchment. The computational algorithms for deriving the terrain-based stream network and water outflow points are based on the same $A^T$ Least-Cost Search algorithm utilized for creating the Sub-Catchments from the coarser SubBasin80 terrain dataset, mentioned previously. While this computational terrain analysis determines the same hydrologic parameters through pixel by pixel calculations of slope and area across the dataset, it is now performed on the finer-grained $20^{ft}$ terrain dataset (SubCatchment20). This recursion of terrain-based hydrologic analysis at varying spatial scales and spatial resolutions allows for the computationally efficient and accurate solution for modeling reservoir potential at the statewide scale. The pertinent output of this computational terrain analysis is the derivation of a stream network (Sub-Catchment Stream), as well as outflow point for the Sub-Catchment area (Ocallaghan & Mark, 1984; Tarboton, Bras, & Rodriguez-Iturbe, 1991).

#### 3.2.2.2 Stream Network Analysis – Dam Locating

The creation of the stream network, Sub-Catchment Stream, affords the ability to perform network analysis by creating a linear-referenced network in which a set of nodes can be created. These nodes along the linear network represent potential dam locations along the Sub-Catchment Stream. Starting at the derived catchment outlet point of the Sub-Catchment Stream, the stream is computationally traversed, demarcating potential dam locations at a configurable distance (e.g., every 1 mile) along the stream network. In essence, we are traveling upstream from the mouth of the stream and placing dam locations at a given interval that can be configured as an input parameter to the algorithm. The output of this network analysis is a set of points, containing coordinate information (X,Y) that represents potential dam locations (Figure 11). The algorithm queries the terrain dataset (SubCatchment20) for the given elevation value at that given dam location. This results in the location of a set of potential dam sites in three-dimensional space (X,Y,Z) along the Sub-Catchment Stream. The drainage area for each dam location is calculated using the dam location coordinates and the SubCatchment20 terrain data set. The number of potential dam locations on a stream network is highly dependent on the terrain of the given area and the characteristics of size (area) and relief (slope) in the given Sub-Catchment.

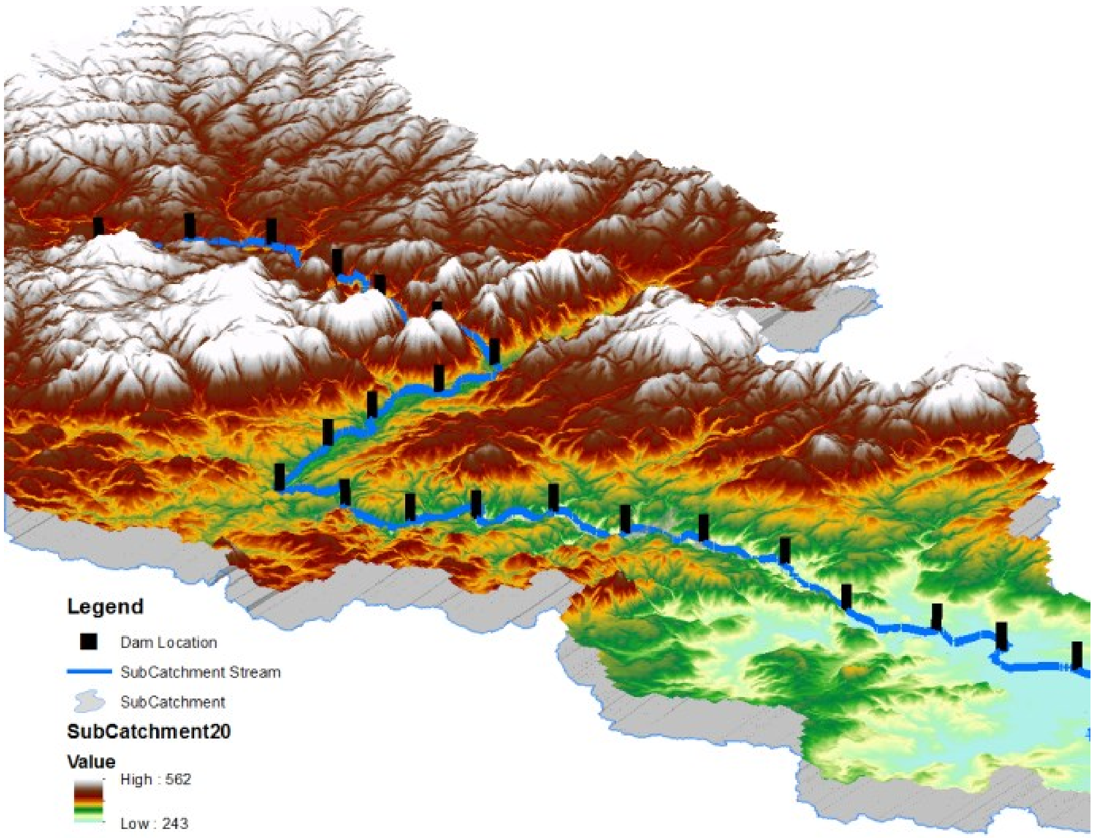



**Figure 3.20 - Terrain-derived stream network (Sub-Catchment Stream) and Dam Locations every 1 mile along Stream**

### 3.2.2.3 Iterative Reservoir Inundation

The final computational step in modeling potential reservoir sites involves the inundation of the surrounding terrain to a certain elevation level, coincident with the height of the reservoir's dam. Based on the above dam location/stream network analysis, a set of three-dimensional dam location coordinates (X,Y,Z) were derived.

These coordinates provide the starting point for a computational routine to inundate the surrounding terrain to a certain water level. The terrain-based hydrologic inundation algorithm uses a 3 x 3 moving cell window to identify all the cells in the SubCatchment20 terrain dataset that are below the specified water level. This 3 X 3 roving window provides the focal neighborhood analysis required to determine terrain-based hydrologic analysis, such as volume analysis. Expanding the focal neighborhood window would result in an increase in the computational processing effort that would negatively impact the feasibility of using high-resolution DEM data. The elevation value specified as the water level for reservoir inundation is a calculation of the z-coordinate value of the dam location and the configurable dam height (De Smith, Goodchild, & Longley, 2007; Grass Development Team, 2008; Hengl & Reuter, 2008; Neteler & Mitasova, 2002). Using a configurable set of dam heights (e.g., every $25^{ft}$ from $50\text{-}150^{ft}$) as input parameters into this computational routine, the process affords an iterative model reservoir inundation derivation against a variety of dam height scenarios at any given dam location (Figure 12). For each of the computational iterations of dam height, the spatial characteristics of surface area and volume are calculated for the modeled reservoir inundation zone.

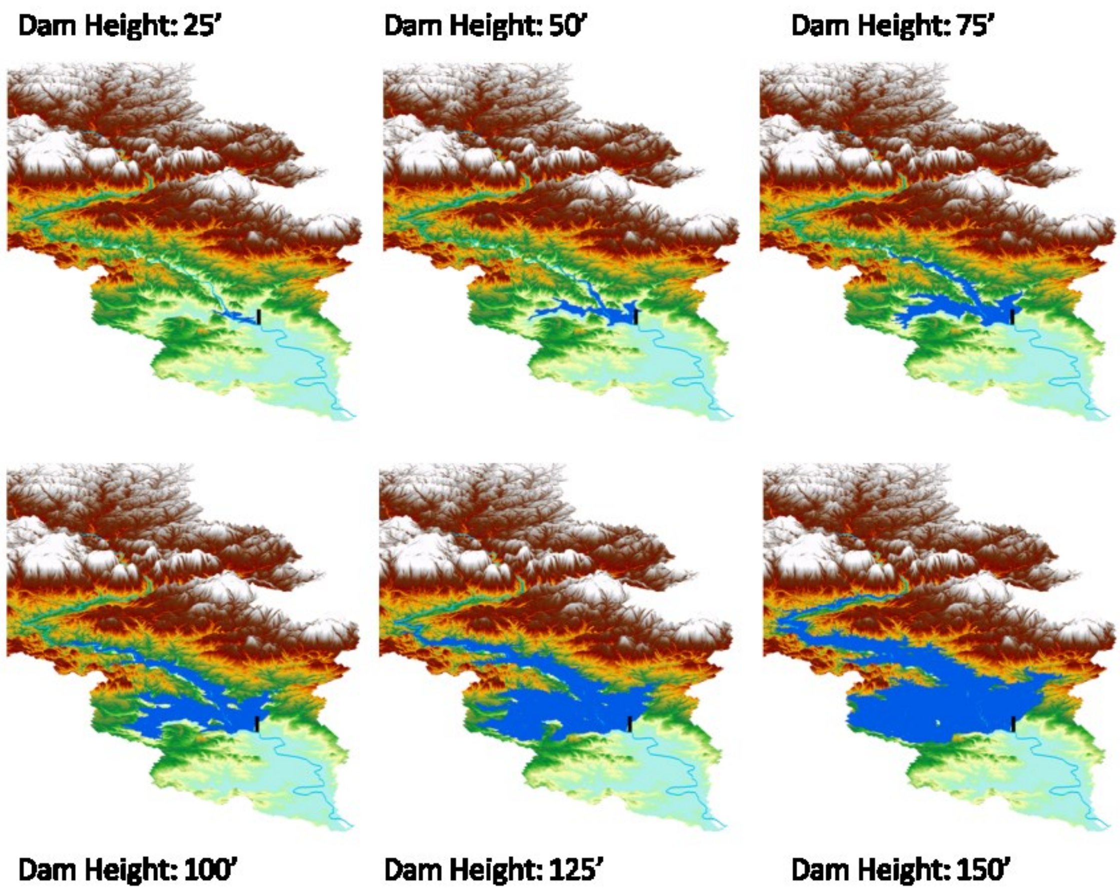



**Figure 3.21 - Reservoir inundation modeling at 1 Dam Location, varying Heights from $25^{ft}$ to $150^{ft}$.**

The results of this computational processing is a robust reservoir modeling algorithm that provides the ability to vary the scenarios of dam location and height, while utilizing highly accurate terrain datasets to determine the physical capacity and spatial implications of the potential reservoir site.

The process for identifying potential municipal water supply sites involves the calculation of the physical capacity of a reservoir at a given location or dam site. This physical capacity, in terms of volume, is derived from the terrain surrounding the given dam location. Through the analysis of terrain over multiple spatial scales, ***NCResSys*** provides the ability to model individual reservoir locations. The extensive computational processing required to analyze the necessary terrain-derived hydrologic parameters at the statewide scale is detailed, including the recursive algorithm that was implemented to balance the computational efficiency and feasibility with data density and accuracy. The resulting solution allows the spatial modeling and analysis of potential reservoir locations throughout the State of North Carolina.

### 3.3 Hydrologic Analysis

The methodology for conducting the hydrologic analysis involves techniques from physical hydrology as well as spatial analysis and interpolation. In the context of the ***NCResSys,*** essential components of hydrologic analysis, such as sub-catchment identification, stream network analysis, and reservoir volumetric, are computed in the terrain analysis components and are detailed in the previous section of this chapter. As such, this section on hydrologic analysis concentrates on the system-level component for determining the potential safe yield characteristic of any potential reservoir location throughout the State of North Carolina. The level of detail for this hydrologic analysis in the context of the ***NCResSys*** focuses on the entity relationship between the hydrologic analysis component as the computation of safe yield for areas throughout the State and the terrain analysis system-level component described in the previous chapter. Due to the overall architecture and design of the ***NCResSys,*** the hydrologic analysis component is independent of the terrain analysis component and thus interacts through computational interfaces and relationships.

### 3.3.1 Safe Yield Analysis

The hydrologic analysis system-level component of the ***NCResSys*** utilizes a methodology for calculating the safe yield characteristic of a potential reservoir location, developed by Dr. David Moreau (Moreau, 2009), UNC Department of City and Regional Planning for this research. The safe yield characteristic of a reservoir location is defined as the maximum uniform rate of withdrawal from an impoundment over the historical record of stream flows, such that the frequency with which the impoundment runs dry is equal to or less than a given value. The historical record of stream flow data is composed of a a subset of all the United States Geological Survey (water.usgs.gov) stream flow gauge stations throughout North Carolina that meet the following criteria: drainage area of at least 25 sq. mi., and a historic record covering at least 25 years of measurements. This includes 103 USGS stream flow gauging stations distributed throughout the State. Yields were estimated with annual frequencies of being dry equal to 0.05, 0.33, 0.25, and 0.20 (Moreau, 2009). Yields at those annual failure probabilities have been traditionally referred to as the 20-, 30-, 40-, and 50-year “safe yields.” Estimates of those values at each gage were made for impoundments ranging in size from 2 percent to 40 percent of the average annual volume of flow. The size of impoundment is subsequently referred to as the “level of development”. The safe yield characteristic of a given stream location then is a computed value that represents the rate of withdrawal for a given failure probability (“safe yield”) at a given percentage of annual impoundment volume (“level of development”). This yield characteristic for a given stream reach is computed as a calculation dependent on the historical daily stream records for inflow, the modeled capacity of impoundment volume (“level of development”), and the failure frequency probability (“safe yield”) given a withdrawal rate (Figure 13).

$$S_0 = \text{reservoir capacity}$$

$$V_t = S_{t-1} + \text{inflow} - \text{withdrawal}$$

$$S_t = \begin{cases} \text{capacity} & \text{if } V_t > \text{capacity} \\ V_t & \text{if } 0 \leq V_t \leq \text{capacity} \\ 0 & \text{if } V_t < 0 \end{cases}$$

**Figure 3.22 - Safe Yield Analysis Calculation (Moreau, 2009)**

Where Vt is trial value for the volume of storage on day t and St is the actual value of end-of-day storage on day t. In other words, for each day of the year, the algorithm calculates a trial value of end-of-day storage as the starting storage plus inflow from the stream minus withdrawal (Hornberger, Raffensperger, Wiberg, & Eshleman, 1998). If that trial value exceeds capacity, water will spill downstream and the reservoir will remain full. Storage cannot be negative, so if the trial value is negative, it signals that the reservoir has run dry. If a reservoir runs dry on at least one day in any year, that year is counted as a failure. If there are multiple days within a year in which a reservoir runs dry, it is calculated as a single annual failure. A sample of the calculated yield characteristics for the 103 USGS gages is shown in Figure 14.

| | | | | | | | | Level of Development as Percent of Mean Annual Volume | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gage No. | Name | Lat | Long | D.A. | # Yrs | Avg Q | | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 | 40 |
| 2053200 | POTECASI CREEK NEAR UN | 36.37083 | -77.0256 | 225 | 51 | 0.910 | 20-Yr | 7.14 | 11.16 | 15.05 | 19.08 | 22.96 | 26.63 | 29.63 | 32.49 | 35.49 | 38.35 | 41.21 | 44.08 | 46.74 | 49.38 | 52.01 | 54.65 | 57.29 | 59.95 | 62.48 | 65.00 |
| | | | | | | | 30-Yr | 6.63 | 10.23 | 13.68 | 17.13 | 20.58 | 23.75 | 26.60 | 29.53 | 32.45 | 35.38 | 38.30 | 41.15 | 43.55 | 46.13 | 48.63 | 51.20 | 53.78 | 56.18 | 58.50 | 60.90 |
| | | | | | | | 40-Yr | 6.09 | 9.48 | 12.51 | 15.53 | 18.56 | 21.63 | 24.26 | 27.08 | 29.90 | 32.72 | 35.54 | 38.18 | 40.79 | 43.47 | 45.97 | 48.65 | 51.33 | 53.94 | 56.38 | 58.99 |
| | | | | | | | 50-Yr | 5.78 | 9.04 | 11.81 | 14.58 | 17.35 | 20.35 | 22.86 | 25.62 | 28.37 | 31.13 | 33.88 | 36.39 | 39.13 | 41.88 | 44.38 | 47.12 | 49.87 | 52.61 | 55.10 | 57.84 |
| 2053500 | AHOSKIE CREEK AT AHOSI | 36.28028 | -76.9994 | 63.3 | 55 | 0.890 | 20-Yr | 8.88 | 14.94 | 18.56 | 22.69 | 26.69 | 29.50 | 32.44 | 35.38 | 38.19 | 40.94 | 43.50 | 46.25 | 48.94 | 51.69 | 54.38 | 56.94 | 59.44 | 61.94 | 64.69 | 67.19 |
| | | | | | | | 30-Yr | 8.29 | 13.13 | 17.92 | 22.38 | 26.17 | 29.17 | 31.96 | 34.71 | 37.67 | 40.38 | 43.13 | 45.88 | 48.38 | 51.04 | 53.54 | 56.21 | 58.71 | 61.21 | 63.88 | 66.33 |
| | | | | | | | 40-Yr | 7.72 | 12.78 | 17.69 | 22.03 | 25.25 | 28.25 | 31.16 | 33.91 | 36.75 | 39.34 | 42.09 | 44.84 | 47.34 | 49.78 | 52.28 | 54.72 | 57.22 | 59.72 | 62.16 | 64.50 |
| | | | | | | | 50-Yr | 7.38 | 12.58 | 17.55 | 21.83 | 24.70 | 27.70 | 30.68 | 33.43 | 36.20 | 38.73 | 41.48 | 44.23 | 46.73 | 49.03 | 51.53 | 53.83 | 56.33 | 58.83 | 61.13 | 63.40 |
| 2068500 | DAN RIVER NEAR FRANCIS | 36.515 | -80.3031 | 129 | 78 | 1.427 | 20-Yr | 41.43 | 47.93 | 52.18 | 55.90 | 58.95 | 62.90 | 66.88 | 69.70 | 72.70 | 75.63 | 78.80 | 81.53 | 84.05 | 86.58 | 89.08 | 91.60 | 93.90 | 96.43 | 98.93 | 0.00 |
| | | | | | | | 30-Yr | 39.45 | 45.65 | 50.40 | 54.40 | 58.40 | 62.00 | 65.45 | 68.75 | 71.75 | 74.20 | 76.80 | 79.40 | 82.05 | 84.70 | 87.10 | 89.75 | 92.40 | 94.95 | 97.35 | 39.40 |
| | | | | | | | 40-Yr | 37.38 | 43.14 | 48.63 | 53.35 | 58.04 | 61.75 | 64.74 | 67.74 | 70.74 | 73.48 | 76.21 | 78.96 | 81.46 | 83.96 | 86.21 | 88.71 | 91.20 | 93.45 | 95.71 | 98.20 |
| | | | | | | | 50-Yr | 36.40 | 42.26 | 47.65 | 52.18 | 56.38 | 59.80 | 62.69 | 65.69 | 68.69 | 71.33 | 73.97 | 76.72 | 79.22 | 81.72 | 83.97 | 86.47 | 88.86 | 91.11 | 93.47 | 95.86 |
| 2070500 | MAYO RIVER NEAR PRICE, | 36.53389 | -79.9914 | 242 | 56 | 1.235 | 20-Yr | 36.40 | 44.90 | 50.35 | 55.60 | 60.30 | 63.75 | 66.85 | 69.40 | 72.10 | 74.65 | 77.40 | 80.10 | 82.80 | 85.45 | 87.95 | 90.40 | 92.65 | 95.10 | 97.55 | 19.80 |
| | | | | | | | 30-Yr | 35.03 | 41.63 | 46.98 | 51.37 | 55.93 | 60.22 | 63.75 | 66.63 | 69.30 | 72.15 | 74.93 | 78.30 | 81.67 | 84.78 | 87.28 | 89.53 | 91.82 | 94.07 | 96.32 | 98.57 |
| | | | | | | | 40-Yr | 31.65 | 38.60 | 44.30 | 49.15 | 53.95 | 58.35 | 62.00 | 65.35 | 68.60 | 71.80 | 74.70 | 77.60 | 80.50 | 83.15 | 85.65 | 87.90 | 90.30 | 92.55 | 94.80 | 97.05 |
| | | | | | | | 50-Yr | 29.62 | 36.78 | 42.69 | 47.82 | 52.76 | 57.23 | 60.95 | 64.58 | 68.18 | 71.59 | 74.56 | 77.18 | 79.80 | 82.17 | 84.67 | 86.92 | 89.39 | 91.64 | 93.89 | 96.14 |

**Figure 3.23 - Hydrologic Analysis Safe Yield Calculations (Moreau, 2009)**

### 3.3.2 Spatial Interpolation of Safe Yield

This hydrologic analysis provides an estimate of a safe yield characteristic for a subset of the stream flow gauges throughout the State of North Carolina. The computations provide a finely grained spatially explicit model of a safe yield characteristic for a given location. For the ***NCResSys,*** a more generalized, continuous safe yield surface is required to return the characteristic for any location throughout the State of North Carolina. To achieve this statewide coverage of the above safe yield calculations, a spatial interpolation routine has been computed. This continuous yield surface was created by utilizing various spatial interpolation approaches from deterministic inverse-distance weighting (IDW) to geo-statistical Kriging. (De Smith, Goodchild, & Longley, 2007).

Deterministic spatial interpolation IDW computes a continuous surface from discrete points in which there is a distance decay of the observed values by the distance it is from the target point raised to a power coefficient. IDW generated yield surfaces were calculated based on the discrete gauge stations "safe yield" and "level of development" values, with a power coefficient of 0.75. This produces a set of safe yield IDW interpolated surfaces corresponding to failure probability and level of development, for example a surface of 20 year safe yield at 2% development (Figure 15)

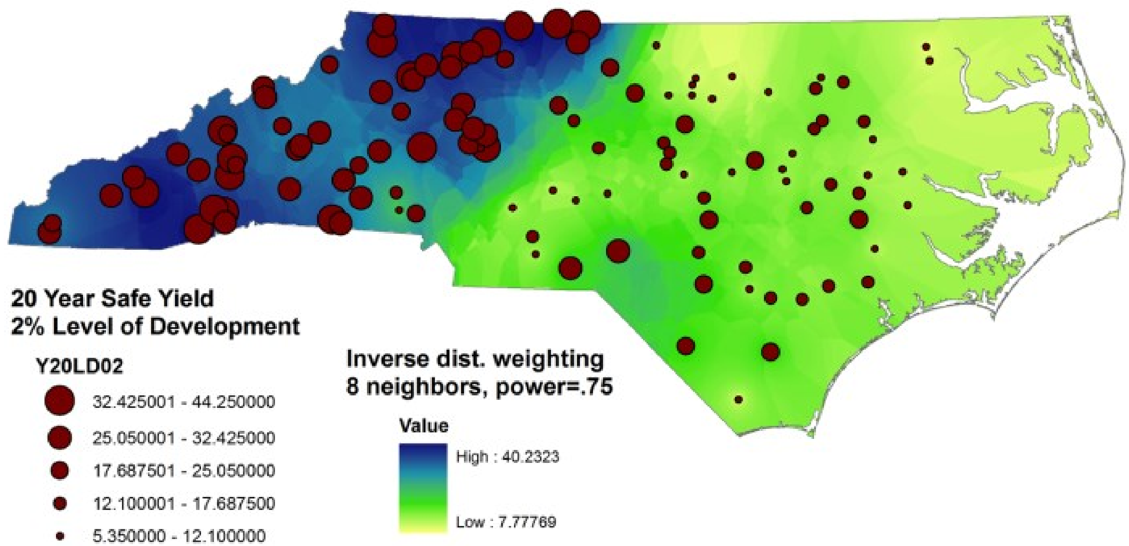



**Figure 3.24 - Safe Yield IDW Interpolated Surface - 20 year safe yield at 2% development**

For comparative purposes, a geo-statistical approach to surface interpolation of discrete safe yield calculations was computed using the Kriging approach. In this approach a statistical sample is calculated with the modeled variogram analyzed to create the statistical surface based on weights from the variogram (De Smith, Goodchild, & Longley, 2007). The same calculations based on the discrete gauge stations “safe yield” and “level of development” values were used to construct a continuous yield surface based on the Kriging approach.

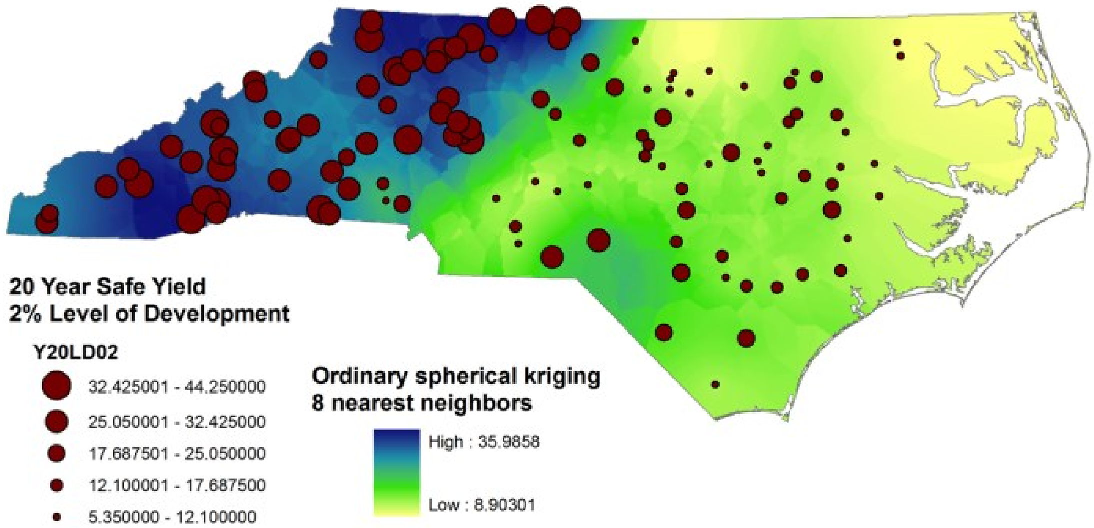



**Figure 3.25 - Safe Yield Kriging Interpolated Surface - 20 year safe yield at 2% development**

These sets of spatially interpolated surfaces allow for a measure of safe yield to be determined for any location throughout the State of North Carolina. Output from the terrain analysis component was spatially analyzed against these safe yield measures as the hydrologic characteristic for the potential reservoir location. The continuous surface of safe yield estimates can also be thematically analyzed against a range of socioeconomic conditions at coarser scales throughout the State.

### 3.4 Socioeconomic Impact Analysis

The development of the processing component for performing spatial analysis against a range of thematic socio-economic data is driven from the logical data model described in Chapter 2. The ***NCResSys*** contains a system-level component for identifying the relationship between the development of a potential reservoir location and a range of socio-economic conditions in a spatially explicit manner. A computational component for characterizing and quantifying the impact of a modeled reservoir location provides the ability to perform impact analysis against a dynamic range of socio-economic data sets, such as administrative boundaries, transportation and communication networks, urban and parklands, pollution zones, as well as population and demographics. Along with the computational processing impact analysis, broader scale analysis of the spatial relationships between the different logical data components is conducted, for example, population density by terrain-based hydrologic sub-catchments at the statewide scale. This multi-scale spatial analysis serves as an interface between the different system-level components of the ***NCResSys.***

The socioeconomic impact analysis component of the ***NCResSys*** identifies, characterizes, and quantifies the areal relationship between the modeled reservoir inundation zone location and various thematic data sets. Using mathematical computations to perform the logical Boolean operators of “Union” and “Intersection”, the area impacted by a reservoir inundation zone is calculated. These quantifications are conducted on any spatially referenced data set against modeled reservoir inundation zone. Differing spatial analysis operations are conducted on the modeled reservoir inundation zone area (polygon) to quantify point level data, such as waste water discharge sites (point in polygon), line level data, such as roads mileage (line in polygon), and areal level data, such as urban acreage (polygon in polygon) (De Smith, Goodchild, & Longley, 2007). These spatial analytical techniques provide the interface between the system and logical data components of the ***NCResSys,*** thus providing the ability to model potential reservoir development in a spatially explicit manner.

### 3.5 Conclusions

Building upon logical data model created via the OOAD methodology, system level components including processing algorithms have been designed and developed. UML diagrams representing the objects, processes, and relationships of the terrain, hydrologic, and socio-economic processing components have been developed. The ***NCResSys*** was developed in the Python programming language to provide the computational components and software to model potential reservoir locations in a spatially explicit manner. This architecture, design, and development produces a comprehensive software product for conducting multi-scale data driven analysis for modeling potential municipal water reservoir locations across the State of North Carolina.

# CHAPTER 4: RESULTS & CONSIDERATIONS

The output generated from the design and development of the ***NCResSys*** consists of physical compiled software components and the analytical capabilities for potential reservoir siting in North Carolina. To showcase these generated results this chapter highlight the physical software components that have been developed in the ***NCResSys***. A reference implementation details the capabilities of how the ***NCResSys*** is utilized for performing statewide analysis of potential municipal water supply locations. The combination of the software components explained in Chapter 3 and the logical data model described in Chapter 2 produces a powerful geospatial modeling information system for the identification of potential municipal water supply reservoir locations across the State of North Carolina. These results are described here.

## 4.1 Software Components

The design and development of the ***NCResSys*** has produced a suite of physical software components, ranging from data to compiled code. The logical data model designed per the OOAD methodology has produced a physical database model that is composed of raster, vector, and tabular data sets representing terrain, hydrology, and socio-economic components. The software components of the ***NCResSys*** consist of compiled code written in the Python language. This code is organized through a set of Python classes that correspond to the logical objects of the different components, such as Sub-Catchment, Dam, and Reservoir objects in the terrain analysis processing. Python code has been developed according to the suite of UML processing flow diagrams previously presented that implement algorithms for recursively deriving Sub-Catchments for modeling Reservoir development, described in Chapter 3. In total, the ***NCResSys*** information system results in over 5,000 lines of custom code developed in Python to perform the multi-scale spatial analysis needed to identify and model potential reservoir locations in a comprehensive, extendable, and data-driven manner.

### 4.2 Reservoir Candidate Location Analysis – Specific Implementation

To highlight the analytical capabilities of the developed software components described above, a reference implementation of the ***NCResSys*** has been conducted. This is a potential case study that showcases the power of this work for water resource management. This specific implementation performs a statewide analysis of potential reservoir locations using a set of areas deemed “off-limits” to potential reservoir development compared with population rates across North Carolina. By combining a specific thematic analysis, given a set of dynamic socio-economic conditions (off-limits & population) with the hydrologic and terrain analysis engines, the ***NCResSys*** provides coarse scale filtering with fine scale reservoir modeling capabilities. This system helps to inform water resource management.

#### 4.2.1 Statewide Thematic Analysis

This reference implementation of the ***NCResSys*** at the coarse statewide scale is composed of an analysis of potential reservoir locations against population and “off-limit” areas. In this implementation, “off-limit” areas consist of US National Parks, North Carolina State Parks, developed urban areas, and wastewater discharge pollution sites. This Parks, People, Pollution (“PPP”) criteria for this reference implementation is dynamic and can be altered to include other types of locations. Performing spatial analysis on data sets representing parklands, urban areas, and pollution locations, creates a binary spatial designation of either “off-limits” or “available.” Any area that is “PPP” is deemed “off-limits” (Figure 4.1).

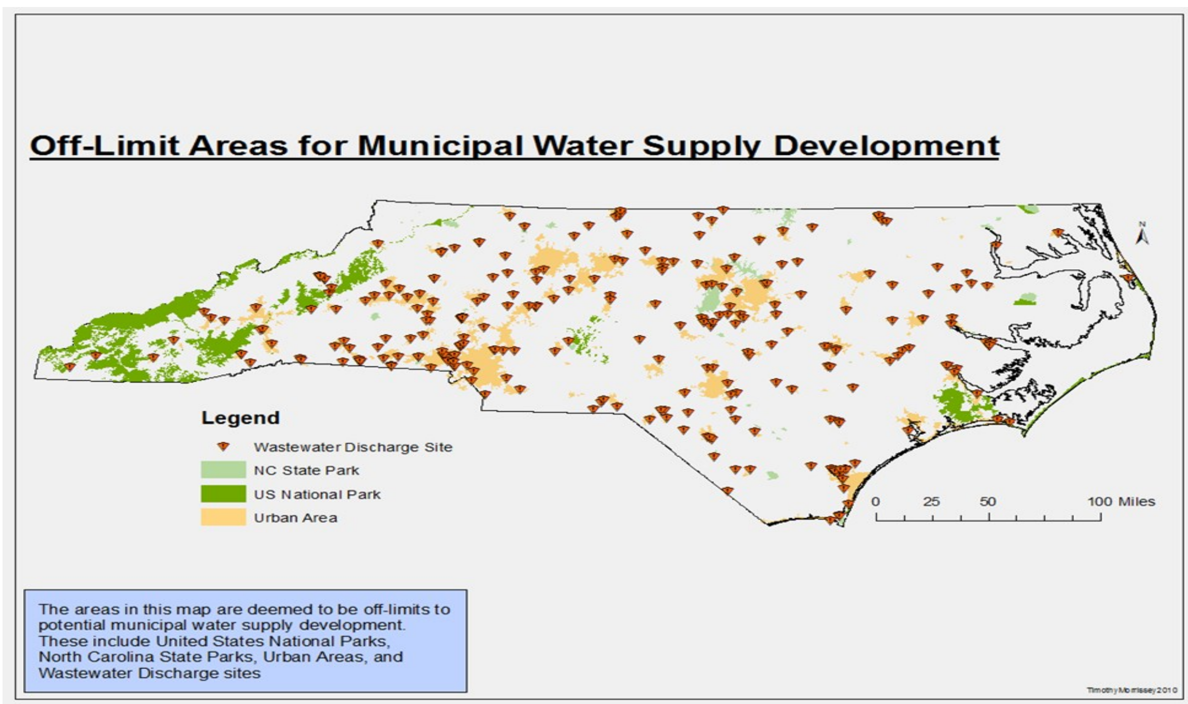



**Figure 4.26 -** ***NCResSys*** **Reference Implementation – “PPP Off-limits”**

Based on the terrain analysis process described in Chapter 3, Sub-Catchment hydrologic units for reservoir modeling have been created. Combing these Sub-Catchments with “off-limits” areas produces the available Sub-Catchments for modeling potential reservoir locations (See Figure 4.2 for Sub-

Catchments not in “off-limit” areas). This significantly reduces the available areas for subsequent analysis, given these “off-limit” criteria, for reservoir modeling. The coarse statewide scale analysis provides the first level of screening potential locations, given the dynamic socio-economic conditions under analysis.

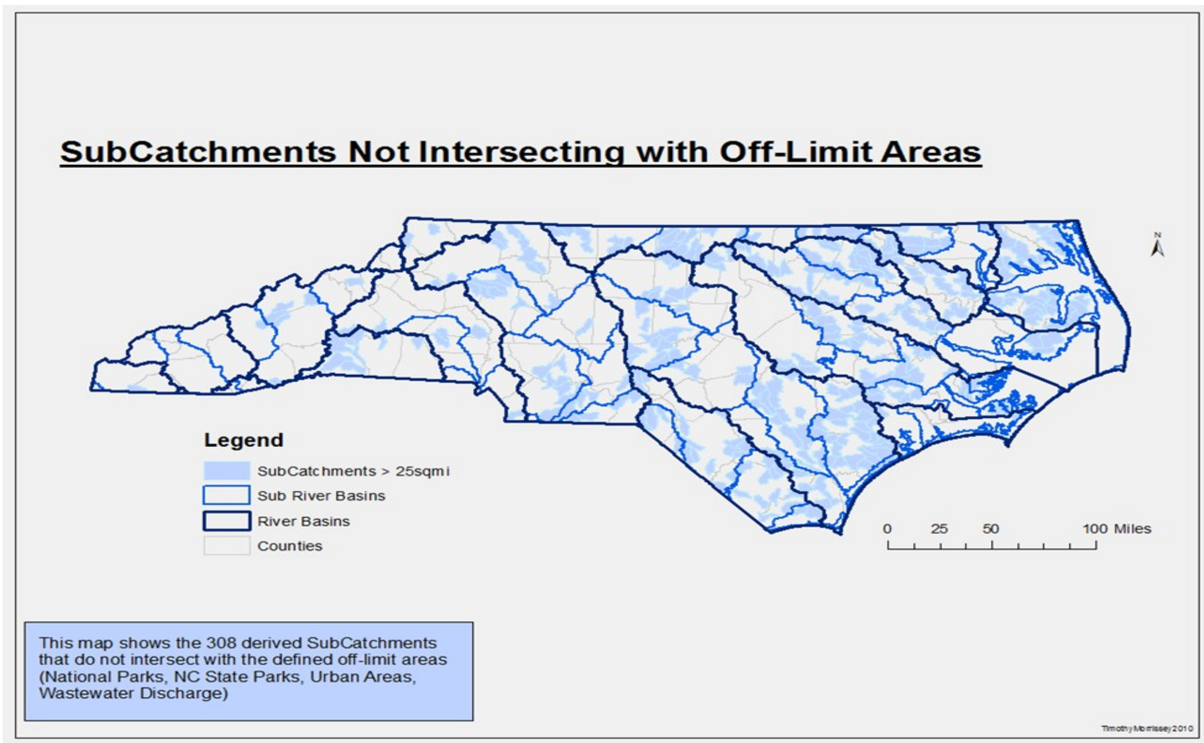



**Figure 4.27 -** ***NCResSys*** **Reference Implementation - Available Sub-Catchments**

Next, thematic socio-economic data analysis of population throughout the state is conducted to spatially quantify population density. Per this implementation, areas with higher population densities are identified as a proxy for demand on municipal water supplies. Areas with a population over 30,000 are spatially identified as the dynamic socio-economic condition to be analyzed against locations for reservoir development. Combining this population analysis with the available Sub-

Catchment areas identified above (through the terrain analysis component of ***NCResSys***) further refines the areas for potential reservoir modeling based on dynamic socio-economic conditions (See Figure 4.3). This statewide analysis combines the three logical information categories (i.e., terrain, hydrology, socio-economic) of the ***NCResSys***, thus facilitating a comprehensive water resource management information system.

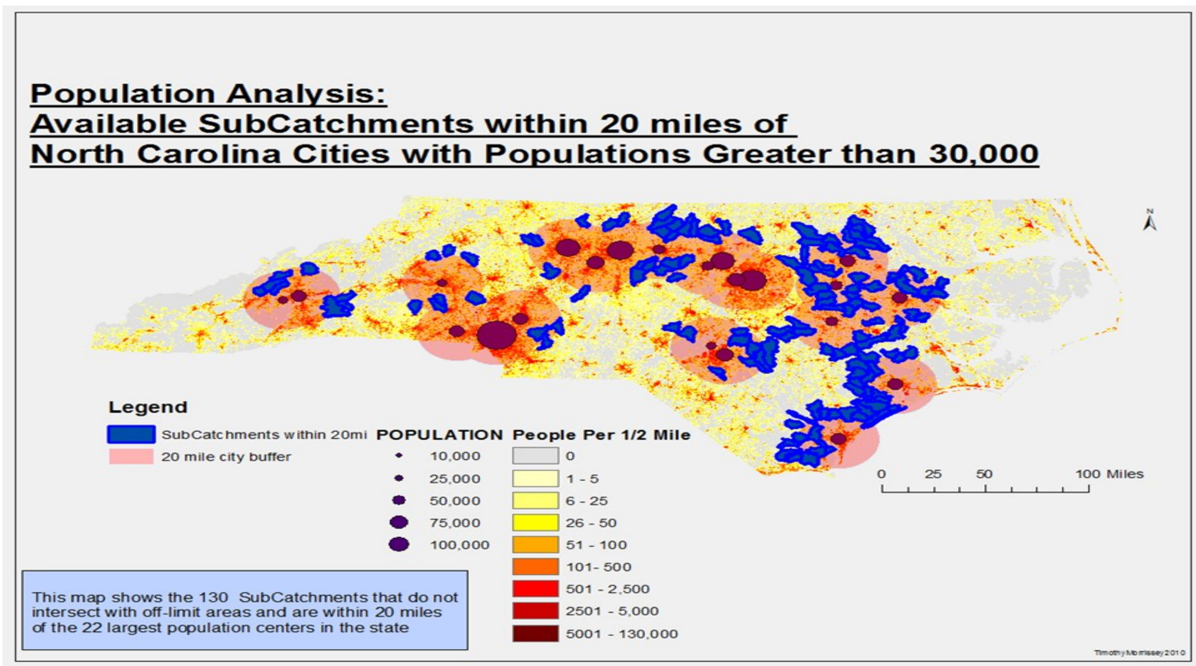



**Figure 4.28 – Dynamic Socio-Economic statewide analysis of Potential Reservoir locations**

Analysis on the land use and land cover (LULC) characteristics of the available Sub-Catchment provides a deeper analysis into the water quantity and water quality of the potential reservoir locations. The land use and land cover types of the inundated zone are important because of the impact of the physical reservoir footprint, but the LULC context of the surrounding catchment areas are extremely important to the quality of the water source for the reservoir location. The LULC of the surrounding upstream catchment areas can be identified as a layer for a specific analytic implementation. For example, Sub-Catchment areas that contain higher percentages of urban land cover types could potentially produce reservoirs with poorer water quality due to the runoff associated with impervious surface. The spatial context of the reservoir location extends to the contributing areas of the potential reservoir location. Identifying the LULC of the Sub-Catchment area assists in the decision making process for locating new reservoir locations.

The statewide analysis on dynamic socio-economic conditions, informed by hydrologic and terrain processing components, allows for deeper fine-scaled reservoir modeling and analysis on the physical characteristics of a reservoir given a specific location and dam configuration. This fine-scaled analysis component of the ***NCResSys*** extends the water resource management capabilities.

### 4.2.2 Reservoir Modeling

The Reservoir Modeling algorithm described in Chapter 3 performs the fine-scaled three-dimensional terrain analysis for a specific location and dam configurations. This algorithm performs data-driven analysis of the physical characteristics (e.g., volume and surface area) of a given dam location (x,y) and height (z). Not only are the statistics of volume and surface area calculated, but the inundated area produced from this location and dam configuration is created. The Reservoir Modeling algorithm produces a set of reservoir objects at given dam locations and dam heights (Figure 4.4).

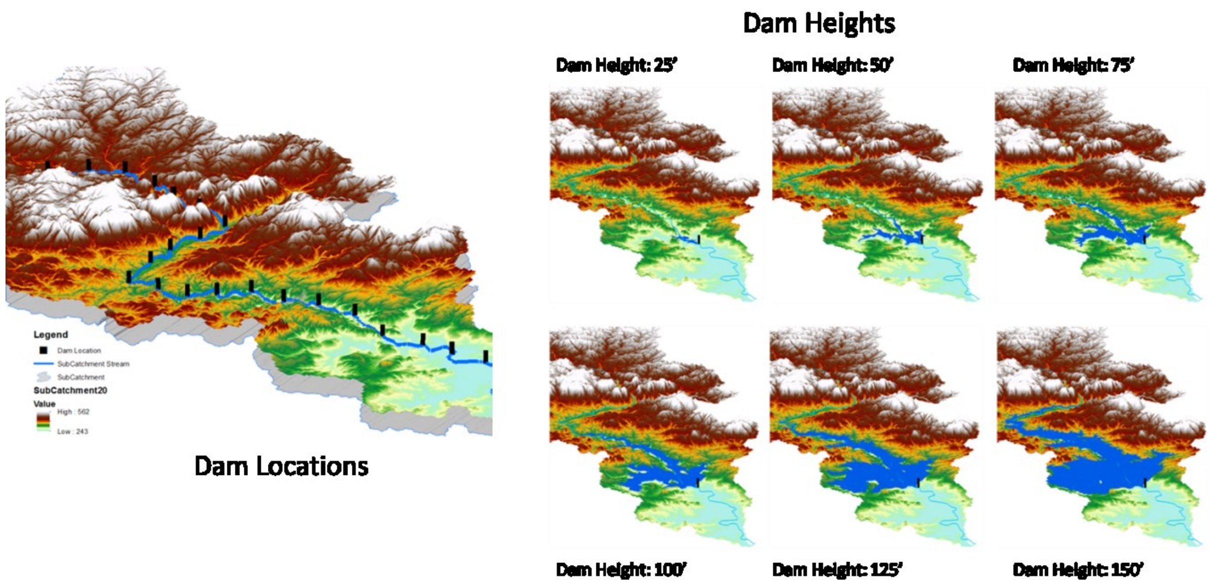
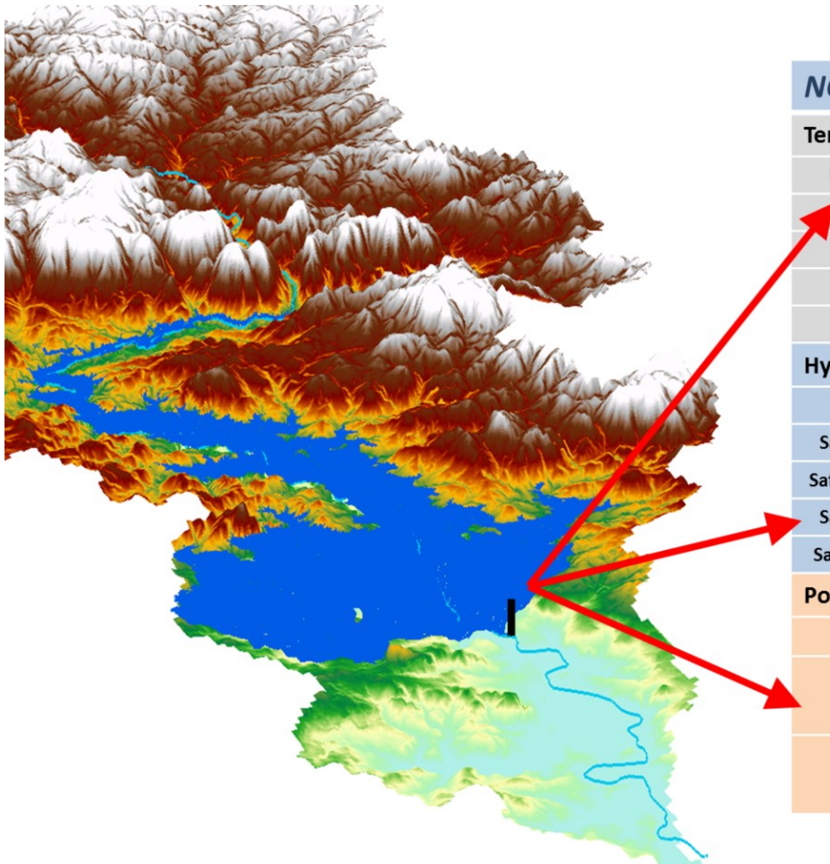



**Figure 29.4 - NCResSys - Reservoir Modeling Output - Dam Locations & Dam Heights**

The spatial footprint of this inundated area is spatially analyzed against a suite of hydrologic and socio-economic conditions. This results in the identification, characterization, and quantification of the development impact of this specific reservoir location given the dam configuration. The combination of the spatial representation of the inundated impact area and the tabular impact analysis across terrain, hydrologic, and socio-economic conditions presents a powerful analytical output from the ***NCResSys*** (Figure 4.5).



| ***NCResSys* Output** | |
|---|---|
| **Terrain Analysis** | |
| Dam Location (x,y) | 36.0686, 78.9149 |
| Dam Height (Ft) | 150 |
| Volume (Ft³) | 10,953,108,000 |
| Surface Area (Ft²) | 154,997,900 |
| SA : V | 0.015 |
| **Hydro Analysis** | |
| River Sub-Basin | Upper Neuse |
| Safe Yield (20yr 2%) | 7.14 |
| Safe Yield (20yr 30%) | 52.01 |
| Safe Yield (50yr 2%) | 5.78 |
| Safe Yield(50yr 30%) | 44.38 |
| **Population Analysis** | |
| County | Durham/Orange |
| Population 2000 | 223,314 (Durham)<br>118,227 (Orange)<br>341,541 |
| Population 2029 | 406,895 (Durham)<br>167,679 (Orange)<br>574,574 |

**Figure 4.30 - NCResSys - Terrain, Hydro, Socio-Economic Analysis Output**

### 4.3 Conclusions

The results and outputs produced by the ***NCResSys*** demonstrate the analytical capabilities of this work for modeling potential reservoir locations at the statewide and local scales. Analytical capabilities are provided via the development of Python classes that implement the computational algorithms for performing terrain, hydrologic, and socio-economic processing routines according to the logical data object models. Performing the key analysis on each of these processing domains in a spatially explicit manner facilitates the identification and modeling of potential reservoir locations, as well as the impact of development across dynamic data conditions. The reference implementation analyzing available Sub-Catchments with regards to population at the statewide scale has been provided. Fine-scaled analysis on the physical characteristics of a reservoir location given a range of dam configurations has been conducted. The combination of these coarse and fine scaled analyses presents a spatial and impact analysis of potential reservoir development (Figure 4.6). These capabilities show this work to be a valuable asset to aid in the decision making for water resource management.

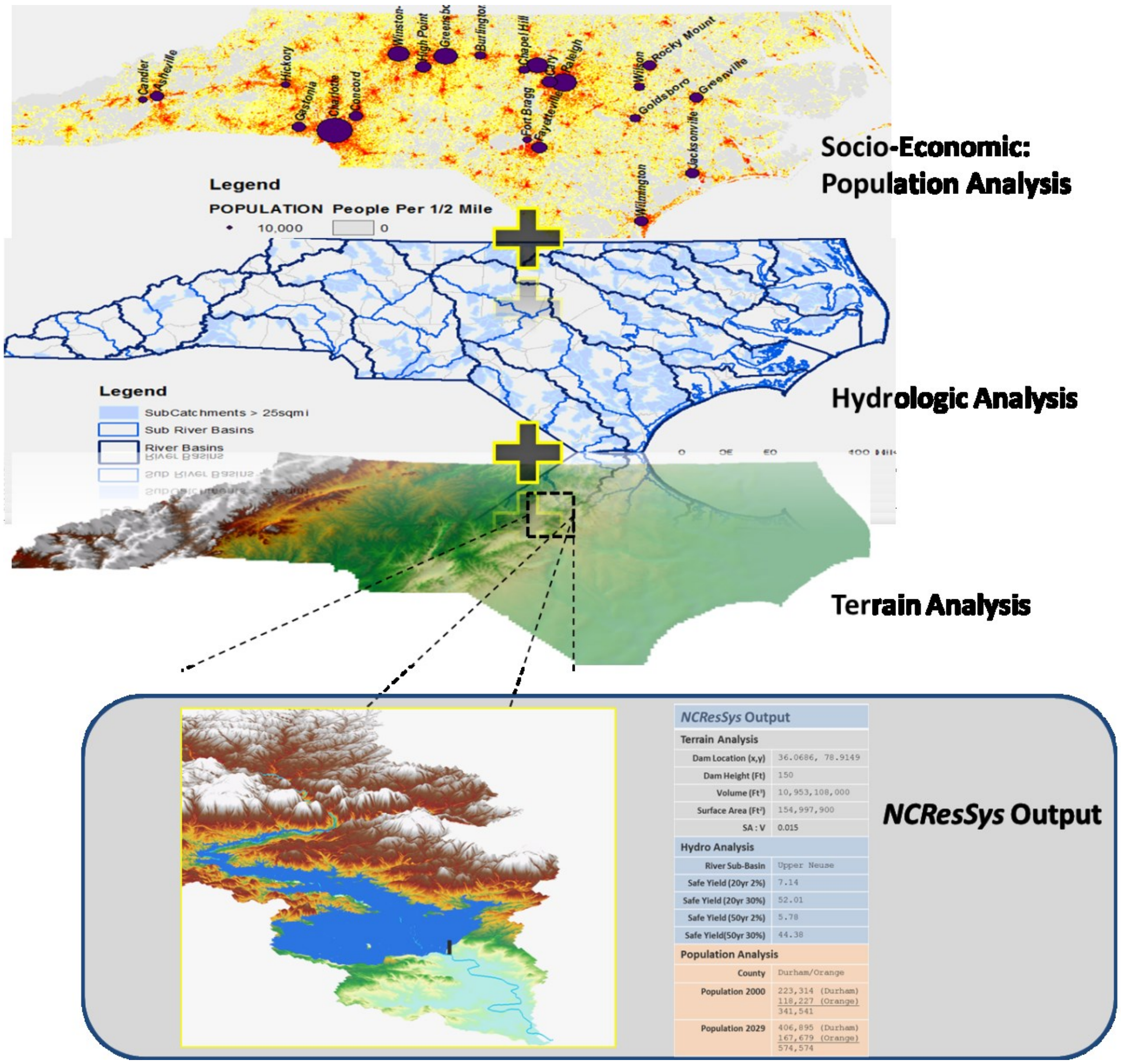



**Figure 4.31 - NCResSys Output**

# CHAPTER 5: FUTURE DIRECTION & CONCLUSION

The primary objective of this research is the development of a comprehensive, geospatial information system utilizing digital spatial datasets and technologies for the purpose of modeling potential municipal water supply reservoir sites across the State of North Carolina. To achieve this primary goal, a computational information system, ***NCResSys,*** has been designed by applying principles of software engineering, hydrology, and computational geography to conduct hydrologic and terrain analysis across the State in a spatially-explicit, Geographic Information System (GIS) environment. Software engineering principles provide the framework for designing and developing the ***NCResSys*** as an extensible, object-oriented, component-based, data-driven computational solution for modeling potential water supply reservoirs at multiple spatial and thematic scales. This type of comprehensive software solution can provide rich data analysis for water resource management and planning.

## 5.1 Review

This document has served to detail the components of work that have been conducted on the ***NCResSys*** for identifying and modeling potential municipal water supply reservoir locations across the State of North Carolina. Chapter 1 introduces the background and need for a comprehensive approach to municipal water supply management in North Carolina. The analytical problem solving framework and data components are also introduced in this Chapter. Chapter 2 discusses in detail the logical data model that drives the system-level design of the ***NCResSys*** solution. In this Chapter the physical data sets are described in terms of their data source, attributes, logical domain, and other metadata characteristics. Chapter 3 provides extensive description on the System Architecture and Technical Design of this application. The design and implementation of the computational algorithms for performing the multi-scale Terrain Analysis capabilities of the ***NCResSys*** are discussed. A reference implementation of the ***NCResSys*** dealing with parks, pollution, and people showcases the analytical capacity and outputs of this work in Chapter 4. Here, in Chapter 5 the document is reviewed, future directions are mentioned, and the project is concluded.

### 5.2 Future Direction

***NCResSys*** in its current implementation is a comprehensive geospatial information system for modeling potential reservoir locations at multiple levels of analysis throughout North Carolina. The reference implementation described in Chapter 4 is an example of how the software components of ***NCResSys*** can be utilized as part of a thematic research endeavor. Future directions of this work include the design and development of a web mapping application that can serve as the end-user interface with the multiple-scale terrain, hydrologic, and socio-economic processing of ***NCResSys***. Additional software components can be designed and developed to interface with the ***NCResSys*** for maximizing the utility in water resource management decision making.

Specifically the selection of criteria for constructing ‘off-limit’ areas for reservoir development could be designed as an additional component and extension of the system components described in this thesis. This would provide a level of customization, according to the stakeholder interests, for the statewide and local scale analysis of potential reservoir development locations. For example, an environmental group such as Trout Unlimited may want to consider specific areas as “off-limits” or identify the impact of reservoir development on specific stream reaches. Providing a web-based tool for interactively selecting a dam location and configuration will help to maximize the utility of the computational modeling engine developed in this research work. Empowering end-users to dynamically model reservoir locations through clicking a web mapping application to configure dam properties would provide an effective tool for identifying and quantifying the impact of reservoir development across a range of planning scenarios. The modular architecture and technical design of the ***NCResSys*** allows for interfaces to be developed for a range of interactive mapping applications. Analysis and research across a range of thematic conditions can utilize the processing power and capabilities of the ***NCResSys*** for identifying potential reservoir impact across the state.

### 5.3 Conclusion

This research has shown how components of multiple disciplines can be synthesized and applied together to produce a comprehensive software solution for water resource management and planning. Software engineering principles and methodologies have been applied to define the logical data components and relationships that drive the computational problem solving throughout the solution. The Computational Geography approaches of GIS and Remote Sensing have been extensively utilized to perform spatial, terrain, and hydrologic analysis. These analytical capabilities have been informed by the principles of Physical Geography and Hydrology. This research has produced the ***NCResSys*** which synthesizes these various disciplines and methodologies into a comprehensive analytical approach to solving the problem concerning municipal water supply reservoirs and potential future development. This cross-disciplinary approach to problem solving can benefit decision making for not only water resource management but for a wide range of subject areas. This research has served as an example of the analytical power that occurs at the intersection of people, place, and technology.

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