ABSTRACT

KEYWORTH, AMY JACKSON. A Quantitative Assessment of Water Inputs and Outputs to a Small Watershed in Northwestern Wake County: Evaluating the Effects of Human Water Use on Groundwater Resources. (Under the direction of Dr. John C. Fountain).

Sustained availability of safe drinking water is an increasingly important issue for Wake County planners due to the recent rapid and ongoing population growth in areas of the county that utilize groundwater for domestic water supply. Wake County planners need to know whether existing groundwater resources can be maintained in the event that the expected population increase takes place. Any anthropogenic influence can alter a natural system. The groundwater system responds to pumping with either a decrease in stored groundwater, a decrease in streamflow or both (Bredehoeft et al. 1982, Sophocleous, 2000).

Wake County is interested in developing a "risk" map as a planning tool to identify areas of Wake County which are at increased risk of groundwater overuse. There are neither adequate data on water table elevations nor stream flows in Wake County with which to assess the relation of current groundwater use to ground or surface water depletion. This case study considers whether insights into groundwater use and potential overuse could be derived from a watershed water-balance approach using existing data. This study is an exercise in identifying available data and data gaps necessary to fill in order to develop a planning tool. Data limitations (e.g., lack of stream discharge or groundwater level data) resulted in restrictions on specific conclusions regarding the study catchment, however, this aspect makes a case study on a specific, fairly typical Wake county catchment a good tool for quantitatively illustrating the significance of different types of hydrologic and water supply data in understanding the water balance and fluxes on a developed catchment with significant groundwater pumping. The study identifies available data sources, data sources that can be further developed, and existing gaps in the data necessary to increase our understanding of a Piedmont fractured bedrock aquifer system.

The results of this case study demonstrate that while the natural water balance components overwhelm the anthropogenic inputs and outputs, the impact of human water use on the catchment water balance does offer some useful insights. The quantification of the developed components of the system indicate that water is being moved within and across catchment boundaries in potentially significant ways. Community water systems (CWS) may result in interbasin transfer of water on many scales. Water is also being transferred from low elevations to higher elevations as groundwater is removed from deep wells and discharged to onsite wastewater treatment systems just below land surface. The CWS groundwater withdrawals from the study catchment increase the effective housing density in the catchment. Water recharging the aquifer from onsite wastewater treatment systems may be increasing stream flow during drought and may lead to changes in water chemistry and stream health.

A Quantitative Assessment of Water Inputs and Outputs to a Small Watershed in Northwestern Wake County: Evaluating the Effects of Human Water Use on Groundwater Resources

by
Amy Jackson Keyworth

A thesis submitted to the Graduate Faculty of
North Carolina State University
In partial fulfillment of the
Requirements for the degree of
Master of Science

Marine, Earth, and Atmospheric Sciences

Raleigh, North Carolina

2009

APPROVED BY:

Dr. David P. Genereux
Dr. April L. James

Dr. John C. Fountain
Committee Chair

DEDICATION

This work is dedicated to Dr. Harold Edward Mew, Jr., fondly known as Ted, and to my dear family. Ted was the first person to introduce me to the concept that water can flow up, if it is groundwater, and if its source is at a higher elevation. Through him I also discovered that a majority of the stream water in North Carolina was not simply rain running off the fields, but was groundwater discharging in an upward direction. The third mind-blowing concept learned from Ted is that water can be very old, and can be in the ground for tens to thousands of years before surfacing again. These concepts were so mind-boggling and so exciting, that I finally knew what I wanted to do with my life – study groundwater.

As a consequence of my newfound career path, my family life changed considerably. I am so grateful for the support of my husband, Rick, who took over all the day-to-day needs of a family of five, who read and edited papers far outside his field, and who did everything in his power to encourage and even understand everything I was undertaking. A former religion major, he's becoming quite the scientist. My three daughters, Laura, Anne and Alexis, have grown into bright, self-motivated, hard-working, confident young adults, despite, or perhaps because of my mental and physical absences over the past five years. They have all learned what powers of concentration truly are when Mom can completely miss, not merely ignore, the chaos all around. My deepest gratitude to you all.

BIOGRAPHY

A graduate of Duke University, Amy began her career as a Coastal Ecologist. Marriage; three children; moves to Oklahoma City, OK, Winchendon, MA, and Stonington, ME; and several jobs later – math teacher, recreation department secretary, proprietor of a small general store, and musician – Amy got back to her roots when the family moved to Raleigh, NC in 2000. Working for the North Carolina Department of Environment and Natural Resources, first with the North Carolina Geological Survey, and now for the Division of Water Quality, Aquifer Protection Section, Amy finally had the opportunity to work as a geologist and to discover groundwater protection.

Graduate school has been a long venture for Amy, first as a graduate student at Duke many years ago, and more recently as a full time employee of the State of North Carolina and part-time graduate student of North Carolina State University. Some of us take a while to get there, but it sure feels good to figure out the path to follow in one's life.

ACKNOWLEDGMENTS

I would like to thank many people for their assistance, encouragement, and instruction in the course of this project. In addition to those who are cited in this report, I'd like to thank the following:

Dr. John Fountain, my advisor.

Dr. David Genereux and Dr. April James, my committee members.

The NC Department of Environment and Natural Resources, Division of Water Quality, for substantial support and encouragement.

Dr. Garry Grabow, Assistant Professor, Biological and Agricultural Engineering Department, NC State University.

Carl Bailey, Alan Clark, Ted Bush and Evan Kane, my bosses at NC DENR, Division of Water Quality, who have supported and encouraged my attainment of this degree from day one.

Ray Milosh and Rick Bolich, both of whom read this in its earliest and messiest stages and listened to presentation after presentation. They helped me to clarify my thoughts and to better present them.

The Wake County Environmental Services staff, especially Mark Bailey, Greg Bright, Elliot Cornell and Wright Lowery, who have been following this project with great interest.

All those family and friends who've either had to listen to way more groundwater talk than anyone should have to, or who have simply been ignored for too long.

Several people who provided data and expertise:

- Phil Bradley, 2008, Geologist, North Carolina Geological Survey
- Melinda J. Chapman, 2008, Groundwater Specialist, US Geological Survey
- Dale Crisp, 2008, Public Utilities Director, City of Ralegh, NC
- Kurt Ness, ATC Associates
- Peter Pozo and Mickey Roberts, NC DENR staff.
- Don Rayno, 2008, NC DENR, Division of Water Resources
- Bethany Georgioulas, Environmental Engineer, NC DENR Division of Water Quality

- Mario Siqueria and Yavor Parashkevov, 2008, Free-Air CO_2 Enrichment (FACE) Experiment, Duke University
- Doug Smith, 2008, US Geological Survey
- Lorrie M. Stagner, 2008, Aqua North Carolina
- Stephanie Sudano, 2008, Town of Holly Springs

This research was supported by the Office of Science (BER), U.S. Department of Energy, Grant No. DE-FG02-95ER62083, and through its Southeast Regional Center (SERC) of the National Institute for Global Environmental Change (NIGEC) under Cooperative Agreement No. DE-FC02-03ER63613.

TABLE OF CONTENTS

LIST OF TABLES

Table **Page**

LIST OF FIGURES

1 Introduction and Problem Statement

1.1 Introduction

Sustained availability of safe drinking water is an increasingly important issue for Wake County planners, due to the recent rapid and ongoing population growth in areas of the county that utilize groundwater for domestic water supply. The population of Wake County grew by 46%, from 423,000 to 786,000, between 1990 and 2006 (US Census, 1990, 2006a). The population of the county is expected to reach one million by 2013 (Wake County, 2007a).

Wake County planners need to know whether existing groundwater resources can be maintained should the expected further development take place. In 2003, Wake County published the Comprehensive Groundwater Investigation Final Report (CGI), produced with the assistance of the CDM consulting company (CDM, 2003). The report provided a general water balance estimate for county watersheds on the order of 200 km^2 (78 mi^2) and concluded that there is currently insufficient data to provide water balance estimates at a finer scale than that. While the study found that the county has sufficient groundwater resources overall, there are areas in which stream flow and stream quality have been impacted by development, especially during a drought. Several recommendations were made, including smaller scale localized hydrogeologic studies to quantify the impact of development to both surface and ground water resources, prioritizing areas within the county where impacts to groundwater quantity and quality are most likely to occur.

The residents of Wake County obtain drinking water from either municipalities or community water systems (CWS), or by supplying their own (USGS, 2008). The City of Raleigh supplies water to 7 Wake County municipalities, and four other municipalities operate their own systems (City of Raleigh, 2007). A CWS is defined as a public water supply system that is "connected to 15 year-round residences or serves 25 persons in a residential setting on a year-round basis" (US Senate, 1996). A community water system may be either publicly or privately owned. Ultimately, all water supplied is either surface water or groundwater. In 2005, 77% of county residents received water from surface water sources, and 23% from groundwater sources (USGS, 2008). All Wake County municipalities with public water supply systems use a surface water source, but the community water systems obtain 96% of their water from groundwater sources, and the 15% of county residents who supply their own water do so via groundwater wells (US EPA, 2008).

Long-term viability of the county's groundwater resources is a matter of serious concern (Wake County, 2007b). Any anthropogenic influence will alter a natural system. Sophocleous (2000) used a water balance to describe the rate of the transition from groundwater storage depletion to surface water depletion (induced recharge to the aquifer from surface water) as a system responds to pumping. The community must determine the acceptable level of change to the natural system (Sophocleous, 2000). Wake County planners have decided that change resulting in stream degradation is unacceptable (CDM, 2003) and local residents have decided that decreased well yield is unacceptable (G. Bright, personal communication, 2007).

There is currently no regulation of the volume of water a CWS well may remove from the ground, though Wake County is considering regulations that may limit high capacity CWS wells due to the impact that such a well could have on neighboring wells. As new housing developments are built, more CWS wells will be installed to serve the homes in those developments. Large capacity wells may affect the hydraulic head in a broad geographic area and may thus reduce the yield of nearby domestic wells, affecting both the quantity and quality of the water supply. In North Carolina only one such regulation has been established. Guilford County has adopted a rule requiring the performance of a 24- hour aquifer pumping test for all high capacity wells (those with withdrawals greater than 10,000 gallons per day) to demonstrate that other wells within a 1000 ft (304.8 m) radius will not be adversely affected (Guilford County, 2007). Such a rule does not take local geology, topography, or hydrogeology into account, and thus may be too restrictive in some cases and not protective enough in others.

Wake County is interested in exploring other options to use in planning future development in order to maintain existing groundwater resources. One option is to develop a “risk” map similar in concept to that developed by Welby (1983), identifying areas of Wake County which are at increased risk of groundwater overuse. This could be approached from several directions, for example by mapping pumping rates from large capacity wells, or by mapping the locations where drops in water level (head) can be expected to be highest based on hydrogeologic data such as the screened intervals of wells, known values of hydraulic conductivity (K), transmissivity (T), storage (S) or specific storage (Ss). Unfortunately, reliable groundwater and hydrogeologic data are not easy to come by. Although there are more than 850 public water supply wells in Wake County (NC DEH, 2005), well construction records are maintained by well drillers, not hydrogeologists, and the records include inconsistent rock unit descriptions and measurements. Aquifer pumping tests are performed primarily to determine whether the yield of a well is sufficient for the expected pumping rate, rather than to determine aquifer properties (NCAC 18C, 2004).

1.2 Problem Statement and Objectives

Increasing population in Wake County may result in local groundwater use exceeding that which is sustainable. Wells going dry during recent periods of extensive drought are evidence that this may already be occurring in some areas. There are neither adequate data on water table elevations nor stream flows in Wake County with which to assess the relation of current groundwater use to ground or surface water depletion. The cost of developing a county-wide groundwater monitoring program is prohibitive. In order to optimize the available funds, future groundwater monitoring efforts should be concentrated in those areas most likely to encounter groundwater supply problems.

An obvious approach is to monitor changes in groundwater levels and flow in the areas where groundwater pumping rates are greatest. However, it is also worth considering, at least preliminarily, whether additional insights into groundwater use and potential overuse could be derived from a watershed water-balance approach (i.e., a quantitative assessment of water inputs and outputs on a watershed, and how they are affected by human use of groundwater in the watershed). This is the objective of this study. A hydrologic mass-balance approach has been useful in illustrating differences between natural and pumped hydrologic systems, and quantifying the rates at which groundwater storage and discharge to streams respond to groundwater pumping (e.g., Bredehoeft et al. 1982; Sophocleous 2000; Reilly et al. 2008). In Wake County, a watershed water balance was applied in a county-wide study (CDM, 2003).

In this case study the water balance approach was used in a small suburban catchment on the south side of Falls Lake. The catchment selected for evaluation, herein designated the Bayleaf Trail Catchment (BTC) (Figure 1), is less than 1 km^2 and includes several private residential wells that experienced stress in years with lower than average precipitation. The natural and anthropogenic or engineered aspects of water inputs and outputs were investigated, and quantified to the extent possible with existing data. A water balance calculation was employed to evaluate the water entering and leaving the catchment and assess the relative significance of the natural and anthropogenic water fluxes. Early in the study it was recognized that data limitations (e.g., lack of stream discharge or groundwater level data) would likely place limitations on specific conclusions regarding the study catchment. However, this aspect makes a case study on a specific, fairly typical Wake county catchment a good tool for quantitatively illustrating the significance of different types of hydrologic and water supply data in understanding the water balance and fluxes on a developed catchment with significant groundwater pumping. The study identifies available data sources, data sources that can be further developed, and existing gaps in the data necessary to increase our understanding of a Piedmont fractured bedrock aquifer system.

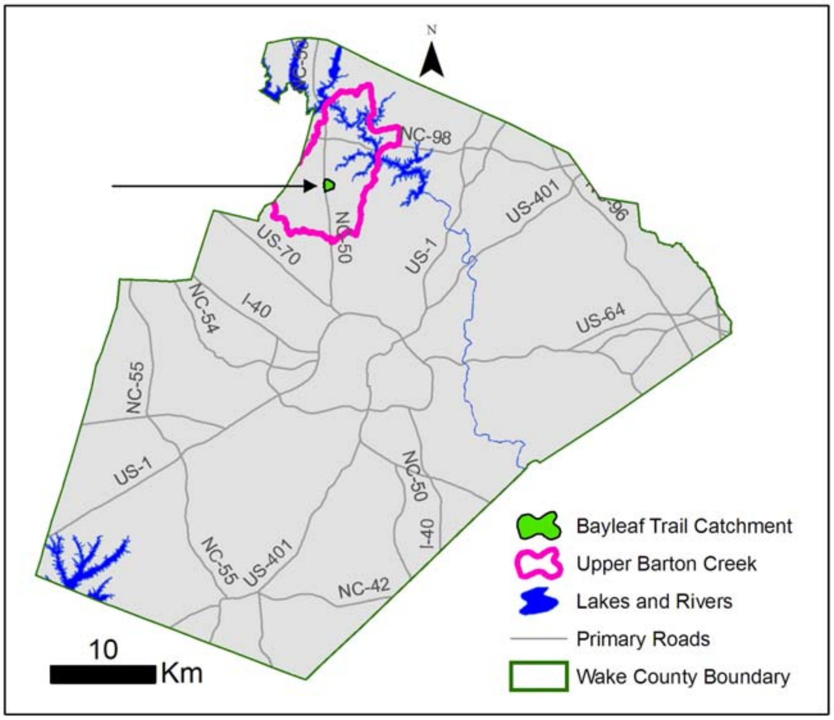


Figure 1. Study site location in Wake County, NC. The arrow is pointing to the Bayleaf Trail Catchment.

2 Background

Evaluating the sustainability of groundwater resources has been a topic of discussion and research for decades (Alley and Leake, 2004; Kalf and Woolley, 2005). When a natural system at equilibrium is developed by pumping groundwater from wells, one of three things must change: recharge to the aquifer, the volume of water in storage, or stream discharge (Bredehoeft et al, 1982). An understanding of the existing environmental and hydrologic conditions and the alterations resulting from development are required to determine sustainable use in a given aquifer system (Maimone, 2004). The water balance approach is applied throughout the world to watersheds of varying scale (Kalf and Woolley, 2005; Maimone, 2004). This section will present the general approach to a water balance as well as some background research into some of the terms. Section 4 will present the water balance terms as they relate to this case study.

2.1 Water Balance

A water balance equation is based on conservation of mass, and consists of determining the amount of water which enters a system during a given time period (inputs), the amount which leaves that system during the same time period (outputs) and the resulting change of water held in storage in that system (storage). The basic water balance equation is:

$$\text{Inputs} - \text{Outputs} = \Delta\ \text{Storage} \qquad \text{(Eqn. 1)}$$

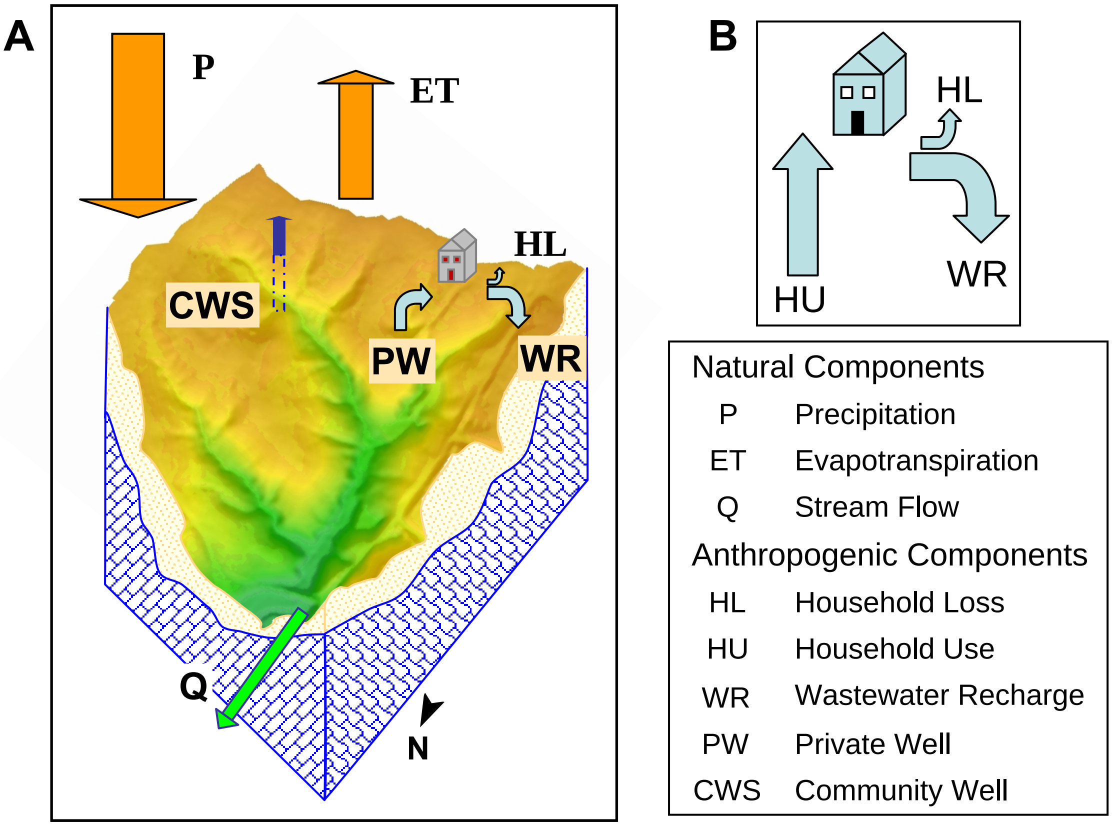
The components of a water balance equation may include both natural and anthropogenic factors. The natural components found in essentially all watersheds are precipitation (P), evapotranspiration (ET), stream flow out of the system (Q), and storage (S). Additional natural components are groundwater flow into and out of the system (G), and the proportion of stream flow made up of overland flow (O) versus groundwater discharge, or baseflow.

A system that has undergone development will have anthropogenic components to include in the water balance. The number, type and impact of these components will vary with the developed system, but may include: 1, recharge to the aquifer from wastewater delivered to onsite septic systems or to the land surface from homes, municipal wastewater treatment systems and other facilities (wastewater recharge); 2, water withdrawn from surface water or groundwater for water supply or other uses; 3, water discharged to surface water by municipal wastewater treatment systems and other facilities; 4, water lost through evaporation from lawn watering and onsite septic systems (household loss); and 5, water leaking from the built system. These components may represent water recycling within the watershed, for example on-site septic systems, but may also represent water entering or leaving the watershed, for example municipal wastewater systems and evaporation from lawn watering. The BTC was selected because it is primarily residential, wastewater is handled exclusively through on-site septic systems, and there are no surface water withdrawals or discharges to surface water. The anthropogenic components evaluated in this study are wastewater recharge (WR), loss through evaporation from irrigation or from onsite septic systems (ETi), and groundwater withdrawals, either by private residential wells (PW) or by community water system wells (CWS).

The whole BTC hydrologic system, both natural and anthropogenic, is represented in Figure 2A, a generalized graphic representation of the inputs to and outputs from the catchment, but it must be recognized that within the catchment there is a hydrologic system for each household (Figure 2B), as well as one involving all the anthropogenic additions to the natural catchment balance. It must also be recognized that water withdrawn is not 100% consumed (Alley et al, 1999). Water entering a home (household use) leaves in two ways, either as lawn irrigation or as wastewater. The source of the water for household use may be either a private residential well or a community water service well. While a portion of the water leaving the home will be lost to evapotranspiration (household loss), the rest will recharge the aquifer (wastewater recharge). The water balance equation for one household is:

$$HU - WR = HL \qquad \text{(Eqn. 2)}$$

Where HU is household use, WR is wastewater recharge and HL is the increment of evapotranspiration from human water use for one house.



Natural Components	
P	Precipitation
ET	Evapotranspiration
Q	Stream Flow
Anthropogenic Components	
HL	Household Loss
HU	Household Use
WR	Wastewater Recharge
PW	Private Well
CWS	Community Well

Figure 2. Generalized graphic representation of the water budget showing input and output components. A. The whole BTC hydrologic system, both natural and anthropogenic. B. The hydrologic system for one household. (The arrows are relative but not to scale.)

For a system to be sustainable there must be no change in long-term storage. To derive the water balance equation used in this study, we began with the steady state water balance equation for a natural catchment system where there is no groundwater flow in and all outward groundwater flow is discharge to streams:

$$P = ETn + Q \qquad \text{(Eqn. 3)}$$

where P is precipitation, ETn is evapotranspiration due to nature, and Q is stream flow. The steady state water balance equation for the human water supply system in a developed watershed is:

$$ETi = PW + CWS - WR \qquad \text{(Eqn. 4)}$$

where ETi is the additional evapotranspiration within the catchment as a result of human water use, PW is the total groundwater withdrawal from private residential wells in BTC, CWS is groundwater withdrawal from BTC by community water service wells in the catchment, and WR is total wastewater recharge through on-site septic systems within the catchment. ETi is related to the household loss above, but reflects the sum of evaporative loss due to human uses for the entire catchment, where household loss (HL) is the loss for an individual home. The steady state water balance for the entire BTC catchment, including both natural and anthropogenic components is:

$$P = ETn + ETi + Q \qquad \text{(Eqn. 5)}$$

Or

$$P = ETn + PW + CWS - WR + Q \qquad \text{(Eqn. 6)}$$

Henceforth, ETn will be referred to as ET because ETn is much greater than ETi, and the water balance equation calculated in this study is:

$$(P + WR) = (ET + PW + CWS + Q) \qquad \text{(Eqn. 7)}$$

where P is precipitation; WR is wastewater recharge; ET is evapotranspiration; PW is private groundwater withdrawals; CWS is groundwater withdrawals via CWS wells; and Q is stream flow.

2.1.1 Wastewater Recharge

In a developed watershed, wastewater recharge (WR) is a term in the water balance (Eqn. 7) and is potentially significant in the parts of Wake County that do not have municipal or community sewer systems. There is little published research on the proportion of water entering a home that leaves the system through a septic system, or on the volumetric effects of septic system outflow on groundwater recharge, evapotranspiration and baseflow. There are studies of the contaminant effects of septic system effluent, and studies on the effectiveness of treatment in various soil types. Heisig (2000) compared the groundwater discharge (baseflow) concentration of various chemical constituents in 33 watersheds in New York State with different land use regimes: forested, agricultural, sewered, unsewered, and with or without riparian buffers. He found a direct correlation between the density of homes using onsite wastewater treatment systems and the concentration of nitrate in baseflow, indicating that septic systems do contribute to the groundwater of a watershed.

Sherlock et al (2002) monitored one septic leach field in New York State, to quantify soil water flux and direction. The soil was a product of weathered glacial till. He found that vertical flow dominated lateral movement in this case study. There is significant downward flow only during a rain event, and the flux is actually upward during dry periods, contributing to evapotranspiration.

Water added to the groundwater system through anthropogenic means, for example wastewater recharge, has been termed induced recharge in some studies. Sophocleous and

Perkins (1993) approached the concept in an agricultural setting, where the development of large-scale irrigation was the source of the induced recharge water. There were definite changes in the recharge-discharge relationship in the developed watersheds when compared to an undeveloped watershed. They found that inputs from several sources increased (saltwater from the underlying geologic formation, recharge from irrigation, and inflow from the stream); storage decreased as indicated by decreased groundwater levels; and outputs, both stream flow and evapotranspiration, decreased.

2.1.2 Discharge to Streams

There is a growing body of research on the effects of development on the hydrology of watersheds, indicating an increase of the speed of water transport through the system. Burns, et al (2005) compared three catchments with different degrees of development: undeveloped, medium density residential (1.6 houses ha^{-1} or 0.65 houses $acre^{-1}$) and high density residential (2.8 houses ha^{-1} or 0.88 houses $acre^{-1}$). They measured precipitation, stream discharge, and groundwater level; compared the water balance for each catchment; and calculated residence time using an isotope of oxygen, ^{18}O, measured in both rainfall and in stream baseflow. They found that as development increases, peak flow following a storm increases, and recession time decreases, making streams “flashier”. Aquifer storage did not seem to change with increasing anthropogenic influences, nor did groundwater residence time. In this case study discharge from septic systems seemed to increase low stream flow in dry periods. Wet season baseflow was higher in rural areas.

Stephenson (1994) compared a suburban catchment to a rural catchment and calculated a water balance for each. He measured precipitation, stream discharge and groundwater levels, and calculated evapotranspiration based on climate data. He found an increase in runoff due to impervious surfaces draining directly into storm drains and recommended installing stormwater controls to increase infiltration and decrease runoff. He also found that changes in evapotranspiration due to increases in impervious surfaces were balanced by garden irrigation and that evaporation as a percent of precipitation was the same in both catchments.

Gremillion, et al (2000) used a mass balance approach to investigate changes in flow paths due to urbanization in central Florida. This was an event-based study over a two month time period. Stream hydrographs were coupled with ^{18}O isotope tracer techniques to identify how the ratio of pre-storm groundwater (old water) to stormwater runoff (new water) changes with urbanization. The study found that the total water in the stream did not change, but the timing of peak runoff, total runoff, and the ratio of groundwater to runoff water did change due to urbanization.

Cheng and Wang (2002) evaluated the effects of urbanization on a watershed in Taiwan, and reported similar changes in runoff as those reported by Gremillion, et al (2000). As in the central Florida study, the Cheng and Wang study is event based but included analysis of 34 events occurring over several years. Chang (2007) is a truly long-term study, with daily precipitation and stream flow data for the Portland, Oregon area dating from 1951 to 2000. Reported results are mean annual runoff ratio, mean seasonal runoff ratio, and annual peak runoff ratio. Chang's study also found that development increases the annual peak runoff ratio and that runoff response time decreases.

All of these studies increase our understanding of how the relationship and timing of the stream flow components of stormwater runoff and groundwater discharge are affected by increasing development. The findings indicate that increased urbanization speeds the movement of water through the watershed, although the long-term amount of stormwater runoff may not change significantly. These studies required stream hydrograph data, which is not available for the study area and is generally available only on a somewhat limited basis.

2.2 Effect of geology

A series of studies have evaluated the relationship between geology and ground water resources in the piedmont of North Carolina (May and Thomas, 1968; Godfrey, 1978; Welby and Wilson, 1982; Welby, 1983; and Welby, 1984). The earlier studies related permeability and drainage to underlying geology through well yield analysis and sought to quantify groundwater availability based on rock type and setting (May and Thomas, 1968; Godfrey, 1978). The Welby studies (Welby and Wilson, 1982; Welby, 1983; and Welby, 1984) progress from studying those relationships in more detail to how these relationships can inform groundwater resource planning.

The findings of May and Thomas (1968) were based on 883 wells in the Raleigh area, encompassing five counties. Two hundred eighty six of these wells were in Wake County, and the wells were primarily private domestic wells. The study was a reconnaissance level overview of the geography and geology of the area and how those factors influence groundwater availability and quality. The water bearing properties of 14 geologic map units were summarized based on the study of well logs and well yields. May and Thomas concluded that permeability is related to the underlying geology. In crystalline bedrock units, permeability is primarily a function of secondary porosity due to fractures and cleavage, and well yields in such areas range from 12 to 22 gallons per minute. Triassic basin sedimentary rocks on the other hand have little primary or secondary porosity, and well yields tend to be less than 10 gallons per minute. They also established a relationship between topography and well yield, finding that well yields in valleys are more than twice the yields of wells in other locations.

Godfrey (1978) related well yield to the sedimentary rocks of the Triassic Basin in western Wake County (Figure 3). This geologic unit is to the west of the study site of interest here, but there are two items of interest to the current investigation. One is that the drainage pattern is quite different in the two areas. In the Triassic basin it is dendritic, whereas in the study area, east of the Triassic basin, there is some structural control. He also notes that the best places in the Triassic Basin to site water supply wells are near faults and diabase dikes and sills, indicating structural control over groundwater as well.

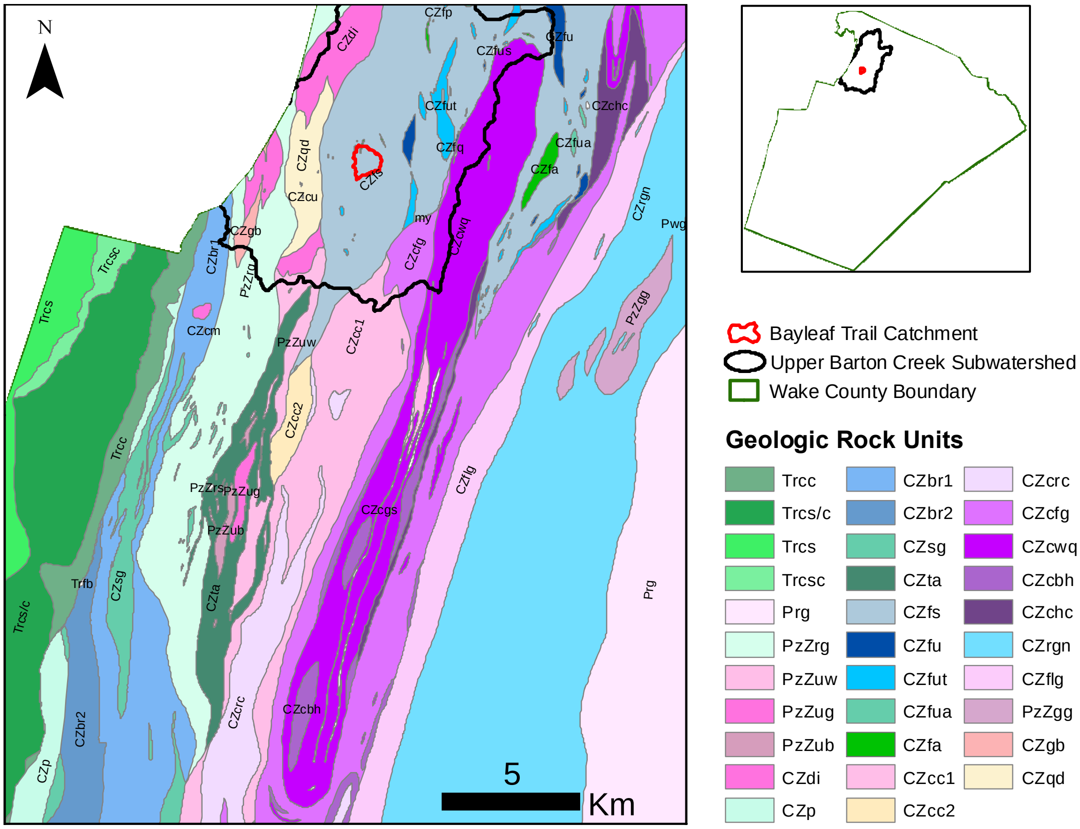


Figure 3. Geology of northwestern Wake County. The “Tr” units in green are the Triassic Basin portion of Wake County. Falls Lake Terrane units are indicate by symbols CZfs through CZfa and Raleigh Terrane units are indicated by symbols CZrgn through PzZgg. (Geologic units descriptions can be found in Clark et al, 2004.)

Welby and Wilson (1982) performed a statistical analysis of CWS wells in Wake County to determine what factors control well yield. They determined that the controlling factors, in order of influence, are (1) the size, density and connectedness of fractures in the bedrock, (2) lithology of the saprolite, (3) topographic setting, (4) saprolite thickness, (5) site elevation, and (6) distance from the well to the nearest draw. They discuss groundwater recharge at length, as a means to determine a safe withdrawal limit for a watershed. They discuss three different sources of recharge rates to use when determining this limit: recharge as a percentage of precipitation; recharge as equal to baseflow measured during the annual seven day low flow (7Q1); and recharge as equal to baseflow measured during drought, defined as the 10-year seven day low flow (7Q10). Their recommendation is to use the most conservative of these recharge rates, the 7Q10, to determine a sustainable yield to best protect the resource in drought years. Other conclusions of this study are: not all fractures are water bearing, or connected to enough other fractures to transmit water; as development increases, so will the amount of impervious surfaces in a watershed, reducing recharge in that watershed; and, recharge in crystalline bedrock settings is not regional, as it is in a Coastal Plain setting, but is concentrated in local drainage basins.

In 1983, Welby developed the first "Risk Level Area" map for Wake County as an extension of Welby and Wilson (1982) and data from additional wells was used to evaluate groundwater availability (to view the Risk Level Area map, see either Welby, 1983 or CDM, 2003). A classification system using four parameters: fracture coefficient, safe yield, annual recharge, and well yield, was developed to rate the Risk Level of a particular area of Wake County. Increased Risk Level indicates areas where recharge and groundwater storage are such that groundwater availability is limited. Recommendations regarding the density of future development are based on the Risk Level of the particular area in which the planned development lies. It was also noted that the area of influence of a well in a crystalline bedrock setting may not be circular but some other shape.

Welby (1984) developed a method for estimating the groundwater inventory and stressed the importance of using this estimate in land-use planning. He used geology (rock type and fracture density), aquifer pumping test data, and stream low flow characteristics to estimate a minimum removal amount, or “safe yield” volume, for a given aquifer. The basic assumption is that drawing groundwater levels below this minimum reserve volume would constitute groundwater mining, and lead to over-exploitation of the aquifer.

3 Site Description

3.1 Location

The objective of this research is to consider whether a quantitative assessment of both natural and anthropogenic water inputs and water outputs, i.e. a watershed water balance, can offer additional insights into groundwater use and potential overuse. The study site is located in the northwestern quadrant of Wake County (Figure 4A). A small (0.84 km^2) catchment located in the Lower Falls Lake 10-digit watershed (202 km^2) was selected. The catchment is bounded by Creedmoor Road (NC Hwy 50), Norwood Rd, Mt Vernon Church Rd and Nipper Rd (Figure 4B). The unnamed streams in this catchment flow into Upper Barton Creek (UBC) (Figure 4C). There is no official name for this catchment, so it is referred to as the Bayleaf Trail Catchment (BTC), after one of the roads within the catchment. The Bayleaf Trail Catchment was selected for several reasons. It is not in an area currently served by a municipal public water supply, nor is it likely to be. All the residents rely on groundwater sources, either private domestic wells or CWS. This catchment is far enough upstream from Falls Lake such that the lake level is not likely to affect local hydrology. There are historical stream gage data for UBC, limited water level data from one monitoring well in BTC, well construction data, well pumping data, and geological data available for this area. The land use is fairly homogenous. It is primarily residential, all the homes have septic systems, and lot sizes are generally one acre (0.004 km^2) (Wake GIS, Parcels). The Bayleaf Trail Catchment includes the headwaters of two unnamed perennial streams, as well as several intermittent streams. The catchment is in Welby's Risk Level 5 group, meaning that housing density should be no higher than 0.25 to 0.5 homes $acre^{-1}$, or lot sizes of 2 to 4 acres (0.008 km^2 to 0.016 km^2) (Welby, 1983).

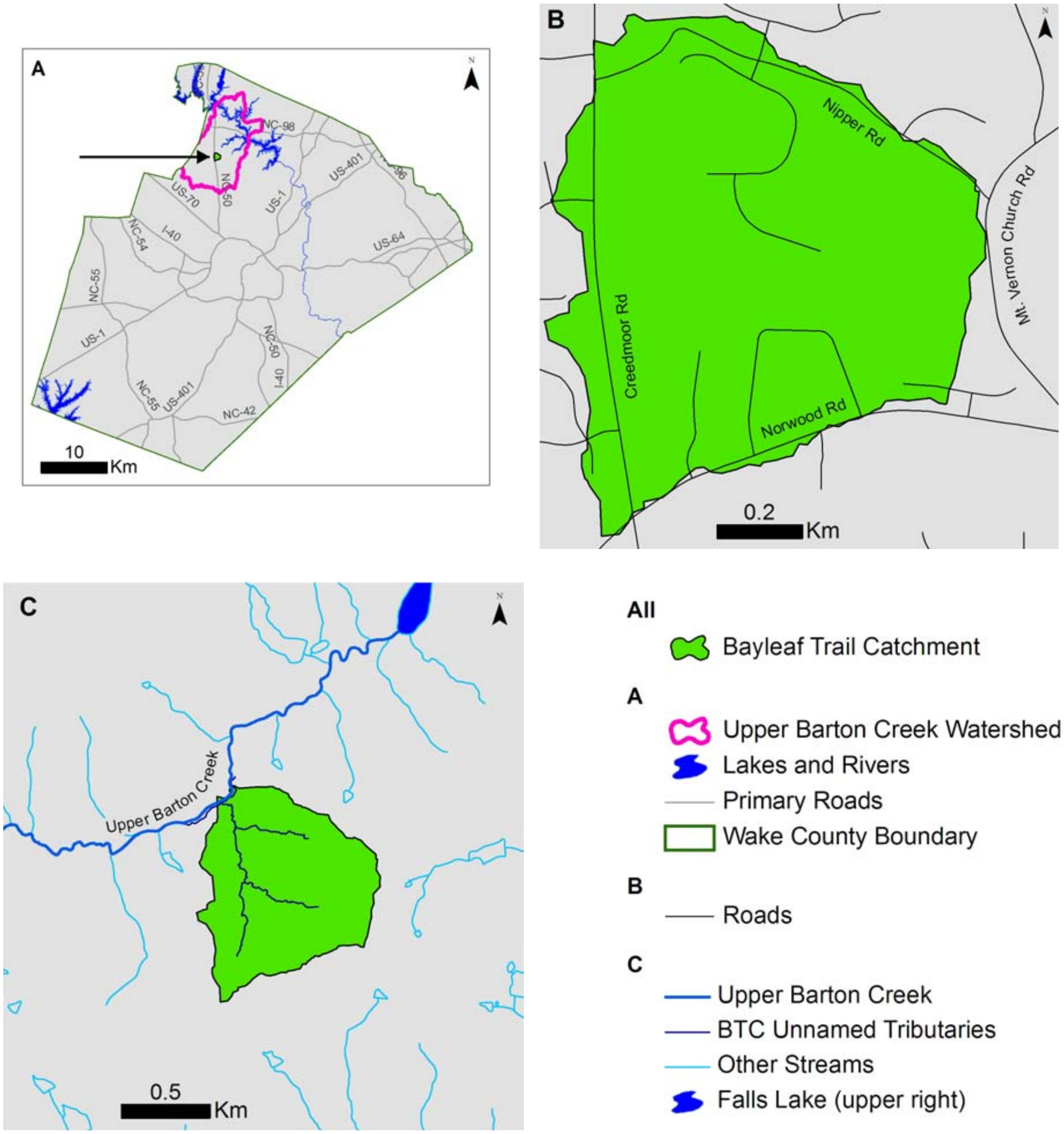


Figure 4. Study site maps. A. Map of Wake County indicating the Upper Barton Creek watershed and the Bayleaf Trail Catchment. B. Roads surrounding the Bayleaf Trail Catchment. C. Three unnamed tributaries in BTC flow into Upper Barton Creek. Upper Barton Creek flows northeast into Falls Lake.

3.2 Climate

North Carolina has a temperate, humid climate (Epperson et al, 1998). Precipitation is seasonal, in that summer rains are localized showers and thunderstorms, whereas winter sees steady rains over several days. November is the driest month. Fairly mild temperatures characterize winters. Monthly average temperatures range from a minimum of 32°F (0°C) in January to a maximum of 89°F (31.7°C) in July (Boyles et al, 2005). Long-term average precipitation for the Raleigh Agricultural Research Station located at the Lake Wheeler Road Field Laboratory (Figure 5A) ranges from a low of 3 inches (7.62 cm) in April to a high of 4.5 inches (11.4 cm) in Jan, March, and July (Figure 5B and Table 1).

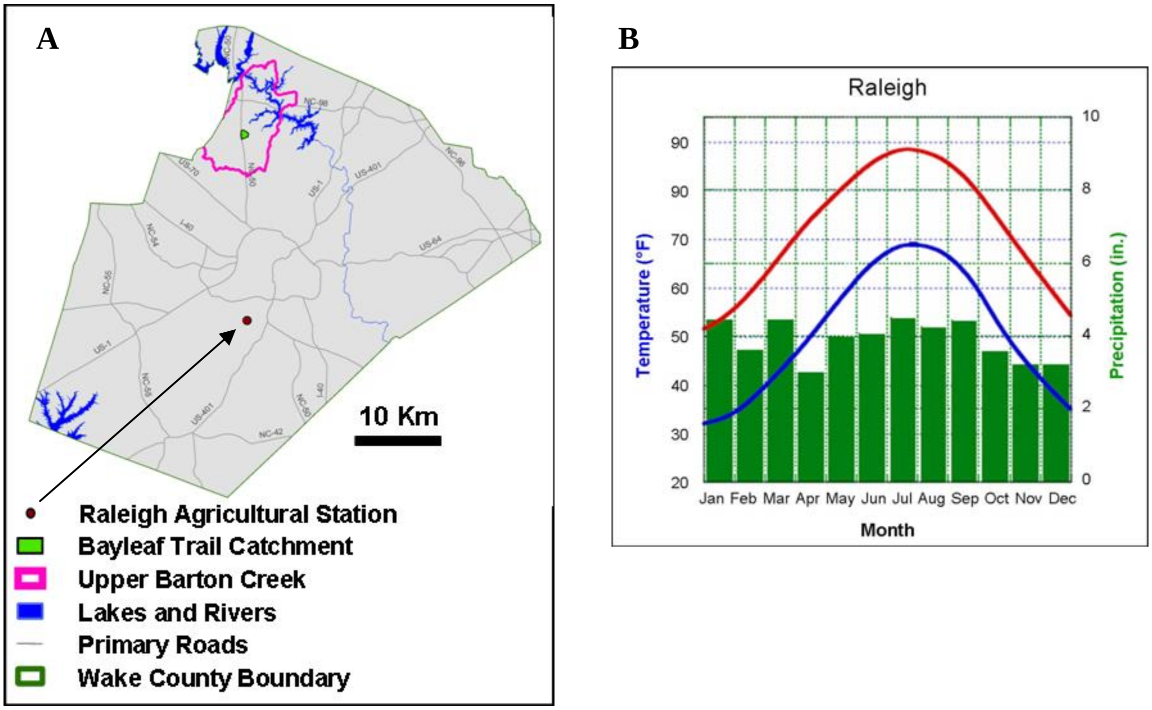


Figure 5. Long term precipitation record from the Raleigh Agricultural Station. A. The Raleigh Agricultural Research Station is located at the Lake Wheeler Road Field Laboratory. B. Normal monthly temperature and precipitation (Boyles et al, 2005).

Table 1. Means and extremes of temperature, precipitation, and degree days by month, 1971 – 2000 at the Raleigh Agricultural Research Station (Boyles et al, 2005).

Normal	Category	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Daily Temp. (°F)	Maximum	51.4	55.7	63.8	72.7	79.4	85.8	88.9	87.2	81.8	72.2	63.0	54.2	71.3
	Minimum	32.0	34.0	40.8	48.1	56.9	65.0	69.3	68.2	62.3	50.2	41.9	34.9	50.3
	Average	41.7	44.9	52.3	60.4	68.2	75.4	79.1	77.7	72.1	61.2	52.5	44.6	60.8
Monthly Precip. (in.)	Total	4.43	3.60	4.44	2.98	3.95	4.05	4.48	4.23	4.41	3.58	3.19	3.21	46.55
Monthly Degree-Days	Heating	723	564	396	162	34	0	0	0	8	166	381	635	3,069
	Cooling	0	0	0	24	131	313	437	393	219	48	0	0	1,565
Extreme Monthly Temp. (°F)	Highest	52.3	52.0	57.3	64.4	72.5	80.2	82.4	81.7	76.2	67.6	59.7	52.9	
	Year	1974	1976	1974	1981	1991	1981	1986	1980	1980	1984	1985	1971	
	Lowest	31.0	35.3	47.5	55.9	64.9	71.7	76.0	74.8	69.0	55.7	46.4	35.8	
	Year	1977	1978	1996	1983	1997	1997	2000	1992	1984	1988	1976	1989	

3.3 Terrain

The terrain is hilly, and the houses are built on or near the ridgelines, at an elevation of approximately 360 to 400 feet (109.7 to 121.9 m) above mean sea level (Figure 6). Elevation changes from valley floor to ridgetops range from 70 to 140 feet (21.2 to 42.7 m). There are wooded slopes between the backs of homes and the valley floor.

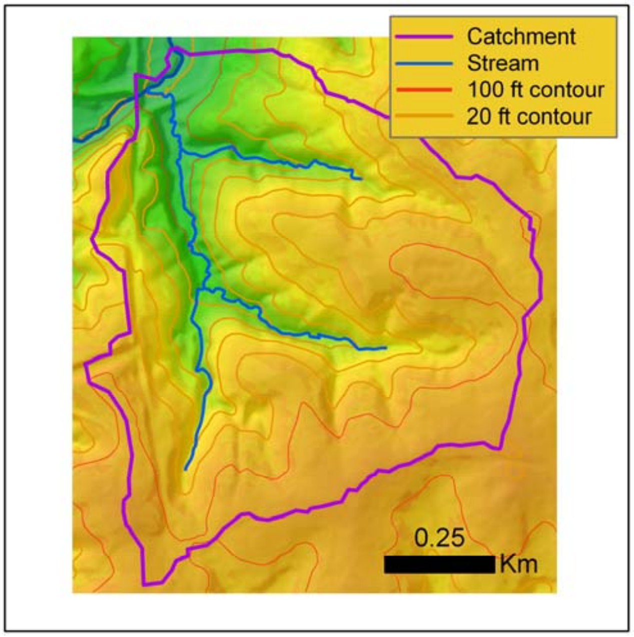


Figure 6. Topography of the Bayleaf Trail Catchment.

3.4 Geology

Much of Wake County is in the Piedmont physiographic province and is underlain by fractured bedrock. The geology of the Piedmont is fairly complex and reflects ancient subduction zones, tension zones, and the accretion of island arcs. The study area is located in the Falls Lake Terrane geologic unit (Figure 3) (Clark et al, 2004), which reflects island arc accretion as well as subduction of oceanic basalts. The Falls Lake Terrane is primarily quartzofeldspathic schist, but there are pods of mafic and ultramafic actinolites and serpentinites throughout.

While the rock unit comprising most of BTC is Falls Lake Schist, a felsic rock, the Clark et al (2004) geologic map delineates a mafic-ultramafic rock unit intersecting BTC from the north. A field visit with a geologist of the NC Geological Survey found outcrops of this mafic rock unit in the stream that parallels the western boundary of BTC (Figure 7). The strike of this rock unit is N 13° E and it dips to the west at an angle of 35° (P. Bradley, personal communication, 2008).

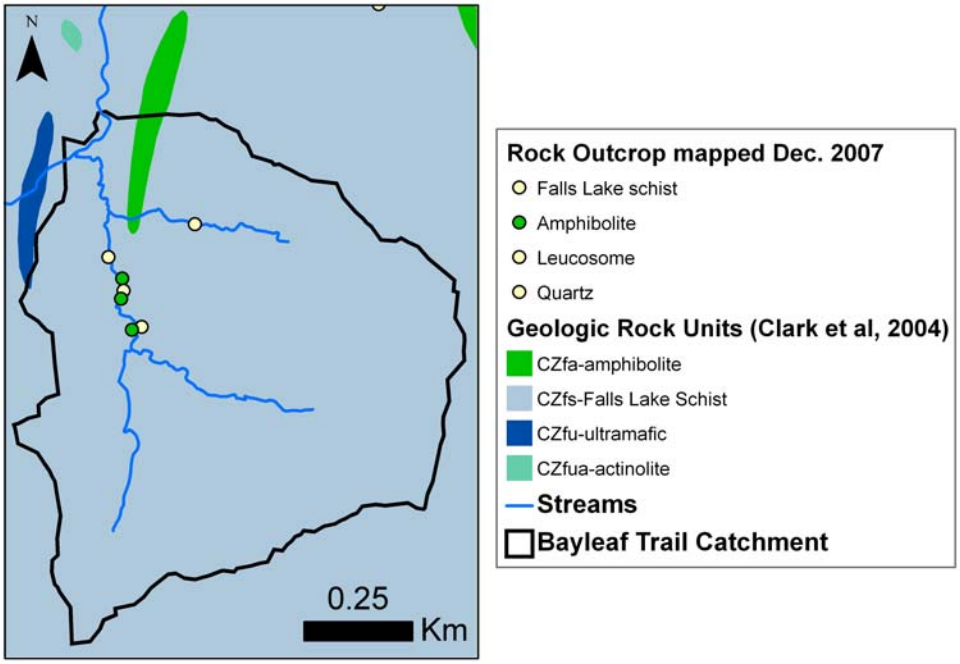


Figure 7. Geologic sketch showing approximate location of mafic rock unit (CZfa) mapped by Clark et al (2004) and outcrops mapped during a site visit (green and yellow dots). Outcrops in the stream suggest that the amphibolite rock unit is more extensive than indicated by the geologic map, continuing south and crossing the western creek.

3.5 Soils

The soil type is an important factor controlling the percent of precipitation that infiltrates and recharges the aquifer. Soils in this catchment area are primarily in the Cecil (Ce, Cg) series (Figure 8). The following description is based on Cawthorn (1970). Slopes are gentle (CeB2, 2-6 %) to very steep (CeF, 15-45 %) (Figure 9). Cecil soils are found primarily in Piedmont uplands, on inter-stream divides and side slopes, and the difference in elevation is generally 75 ft (22.9 m). These soils are well-drained and deep (5 to more than15 ft), and were formed when the land was forested, from acidic parent rock – gneisses and schists. The Ce areas are sandy loam, while Cg areas are gravelly sandy loams. There are hydric soils in the stream bottoms: Chewacla (Cm), Mantachie (Me), Wehadkee and Bibb (Wo), and Worsham (Wy) (Figure 8 - beige areas). These soils are consistent with soil, rock and drainage patterns in Wake County (Cawthorn, 1970).

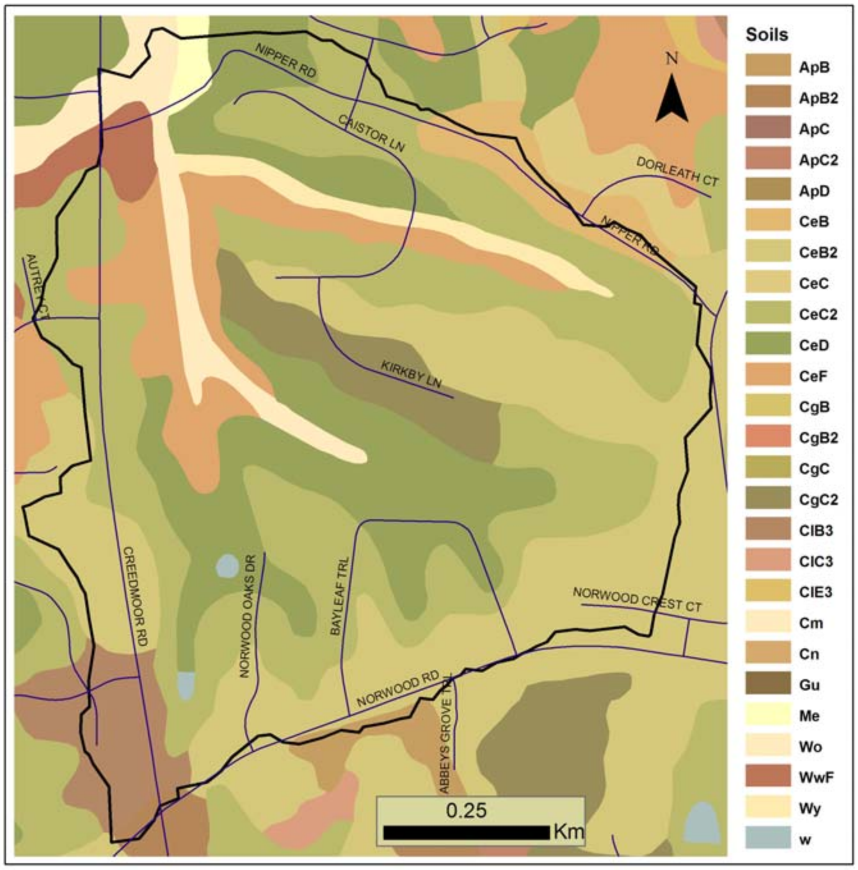


Figure 8. Soils map of the Bayleaf Trail Catchment (Cawthorn, 1970). Upland soils are generally well-drained Cecil soils, while the valley soils are hydric and poorly drained. (Soil unit terminology and descriptions can be found in Cawthorn, 1970.)

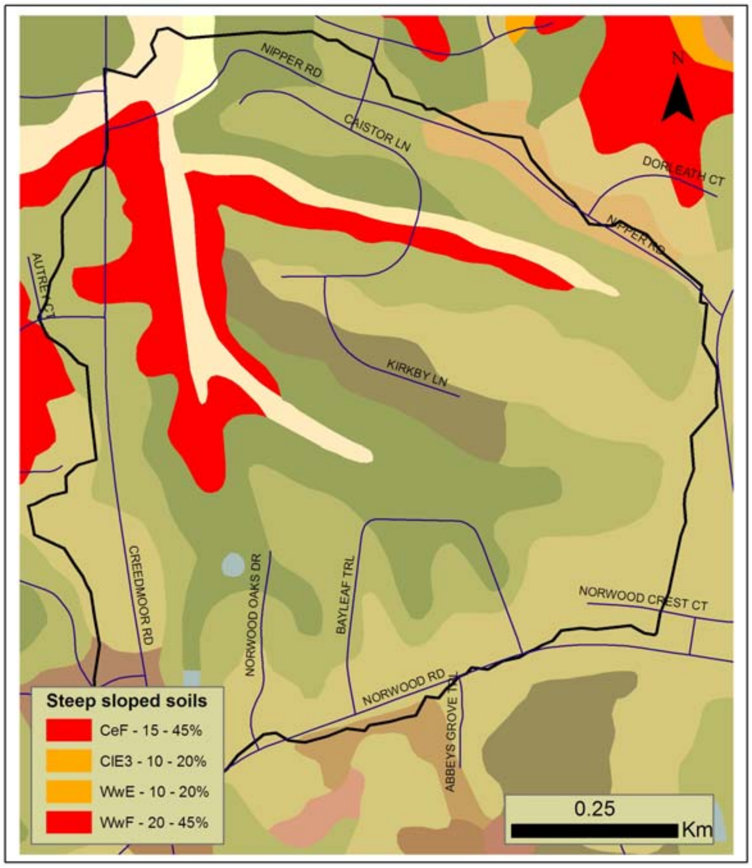


Figure 9. Soils map indicating units with steep slopes in red and orange (Cawthorn, 1970).

3.6 Hydrogeology

Daniel (1989) published a map of North Carolina that classified the geologic rock units of the 1985 North Carolina Geologic Map (Brown et al, 1985) into 21 hydrogeologic units. The Daniel (1989) hydrogeologic units are based on three characteristics: origin, composition and texture. The hydrogeologic units relate to both primary and secondary porosity; rate and depth of weathering; and water-bearing properties of the regolith. In this classification scheme there are three origin classes (igneous, metamorphic and sedimentary) and three subclasses (metaigneous, metavolcanic, and metasedimentary). The rock composition classes are felsic, intermediate, mafic, epiclastic, undifferentiated, gneiss, marble, or quartzite. Texture refers to grain size, degree of metamorphism, and foliation. The hydrogeologic map was later digitized and is available in GIS (NC CGIA).

The Bayleaf Trail Catchment lies within a felsic gneiss and schist unit, labeled GNF on the Daniel (1989) map (Figure 10). The GNF unit is comprised of crystalline bedrock overlain by regolith. The average saturated thickness of the regolith is 38 ft (11.6 m) and the average well yield is 17.5 gpm (66.24 L min^{-1}) (Daniel and Dahlen, 2002).

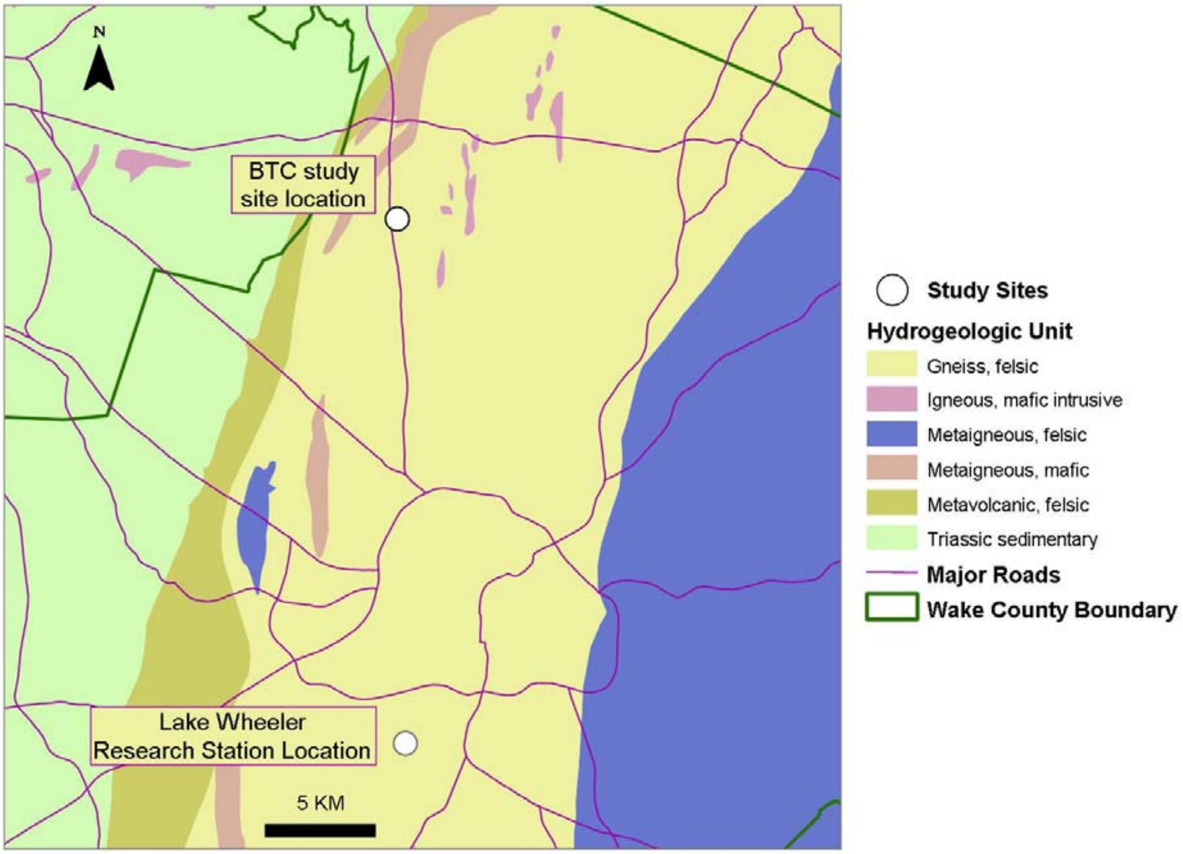


Figure 10. Hydrogeologic map of northwestern Wake County (Daniel, 1989).

3.7 Wake County Land Classification

Land use can be estimated from the Wake County parcel database maintained by the Wake County Revenue Department. The Wake County Geographic Information Services Department has developed a GIS data layer combining the digitized deeds and plats with the information in the tax parcel database. This is available for download (Wake County GIS, Parcels). The Land Class field in the database indicates the general use of a land parcel, for example, residential, commercial or industrial. There are 24 Land Classes, ten of which are represented in the Bayleaf Trail Catchment (Figure 11).

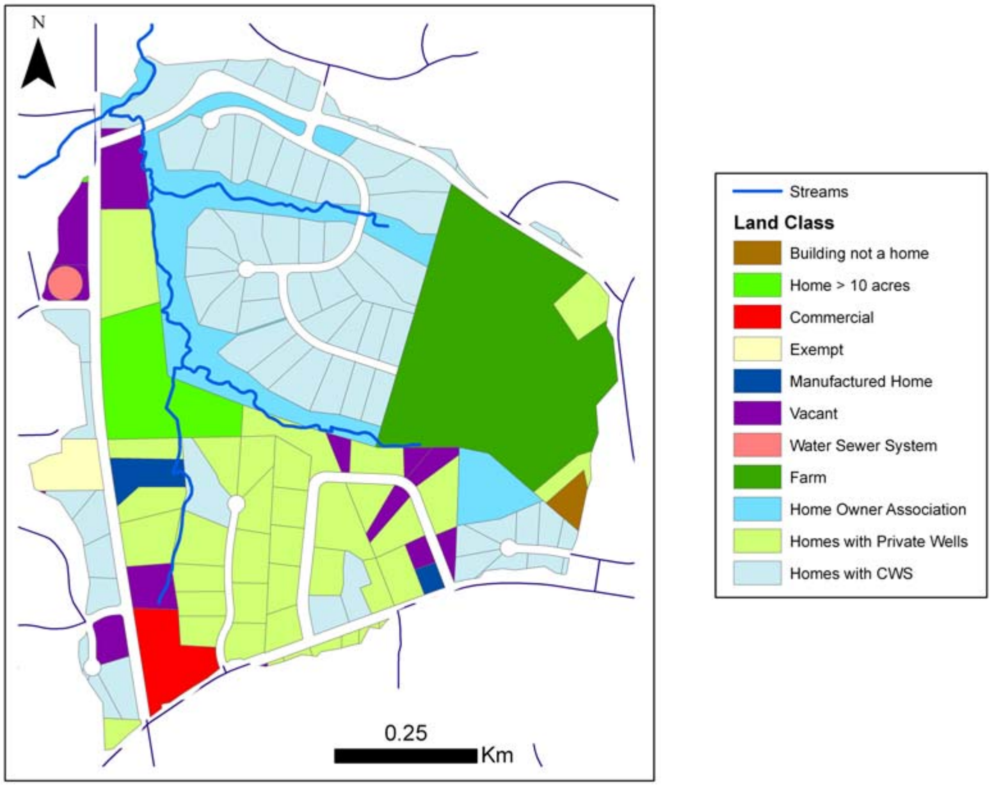


Figure 11. Wake County Land Classifications in the Bayleaf Trail Catchment (Wake County GIS, Parcels).

3.8 Well Type

There are 2 types of groundwater wells active in the Bayleaf Trail Catchment. Thirty-five homes have private domestic water supply wells (Figure 11), and a Community Water System (CWS) supplies 60 residences in the catchment (Wake County GIS, Parcels). There are a total of 67 CWS wells in northwestern Wake Co. (Figure 12) (NC DEH, 2005). Three of the 67 CWS wells are located in BTC.

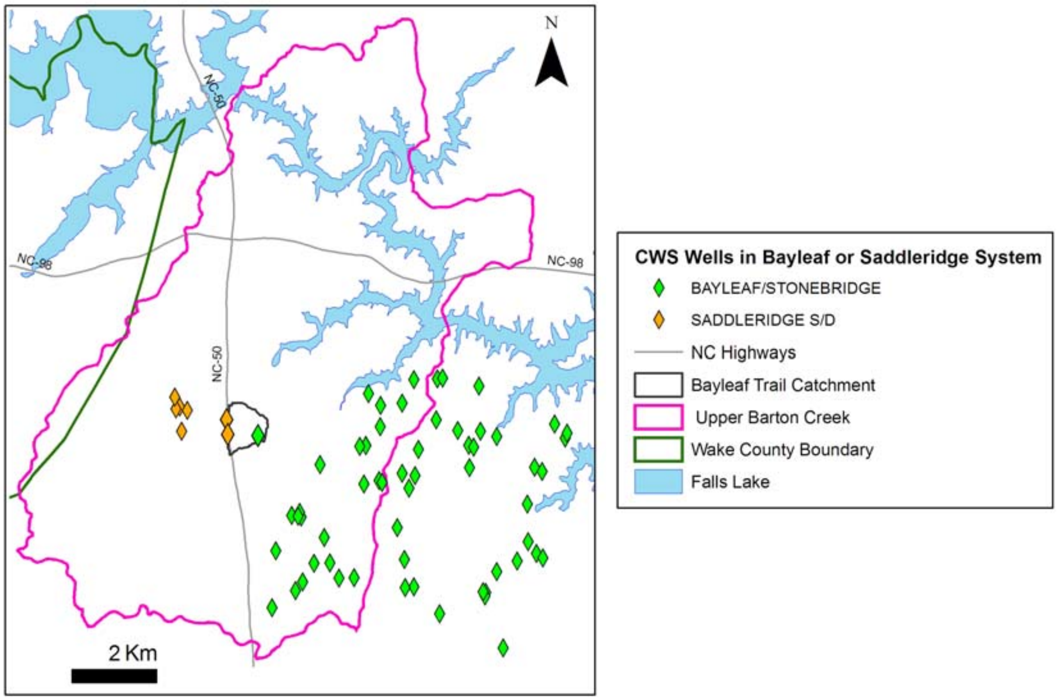


Figure 12. Map of all CWS wells in the Bayleaf/Stonebridge (60 wells) and Saddleridge (7 wells) systems in northwest Wake County (NC DEH, 2005). Three are in the Bayleaf Trail Catchment.

3.9 Stream Flow

There is no stream flow record for the Bayleaf Trail Catchment. From 1951 to 1970 the USGS operated a Low Flow Partial Record (LFPR) site in Upper Barton Creek (UBC), 4 km downstream from BTC (Figure 13) (USGS, NWIS). Data was collected only during severe droughts, and the low flow data is reported in Weaver (1998). There is an existing stream gage located below the Falls Lake Dam (Figure 13), which measures releases from Falls Lake by the U.S. Corps of Engineers, not natural stream flow. There are other recording sites in the area, another LFPR, a Crest Stage Partial Record station, and a few water quality sampling sites. There is no other Continuous-Streamflow Gaging Station in the Lower Falls Lake Watershed (D. Smith, personal communication, 2007).

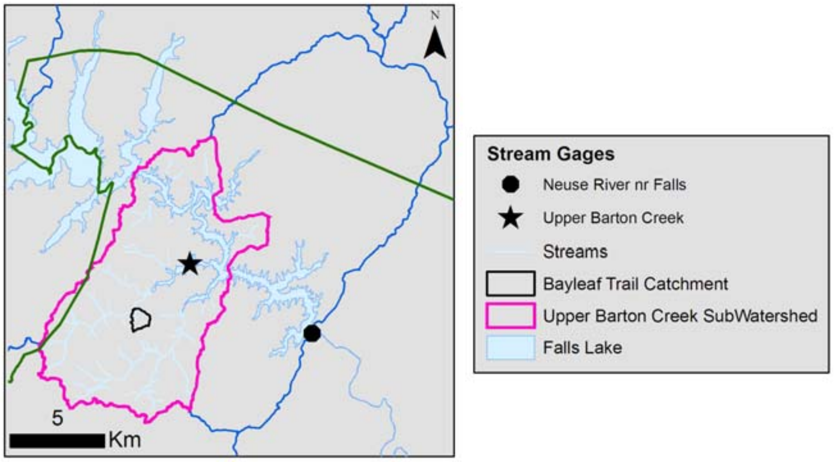


Figure 13. Stream flow data locations. The star marks a Low Flow Partial Record site on Upper Barton Creek. The circle marks the continuous stream flow gage below the Falls Lake Dam (USGS, NWIS; NC CGIA).

3.10 Previous hydrogeological work in the Bayleaf Trail Catchment

Contamination of groundwater and soil was discovered in 1991 at Gresham’s Landing, the site of a gas station/grocery located at the southwest corner of the Bayleaf Trail catchment, where Norwood and Creedmoor Roads intersect (Figure 11, red parcel). The subsequent site assessment provides information on geologic coring data, soil-boring data, and water level data from one monitoring well (Turner, 1992). There are several monitoring wells associated with this facility, and groundwater level records are available for one.

The coring and soil boring data are consistent with a geologic provenance of felsic gneiss and soil texture of silt and silty clay grading downward into silty sand. This is consistent with Falls Lake Schist bedrock and Cecil soils. Though there is reference to a bedrock core, the boring records and geologic cross-sections only indicate an encounter with weathered gneiss saprolite at 57 ft (17.4 m) (Figures 14 and 15).

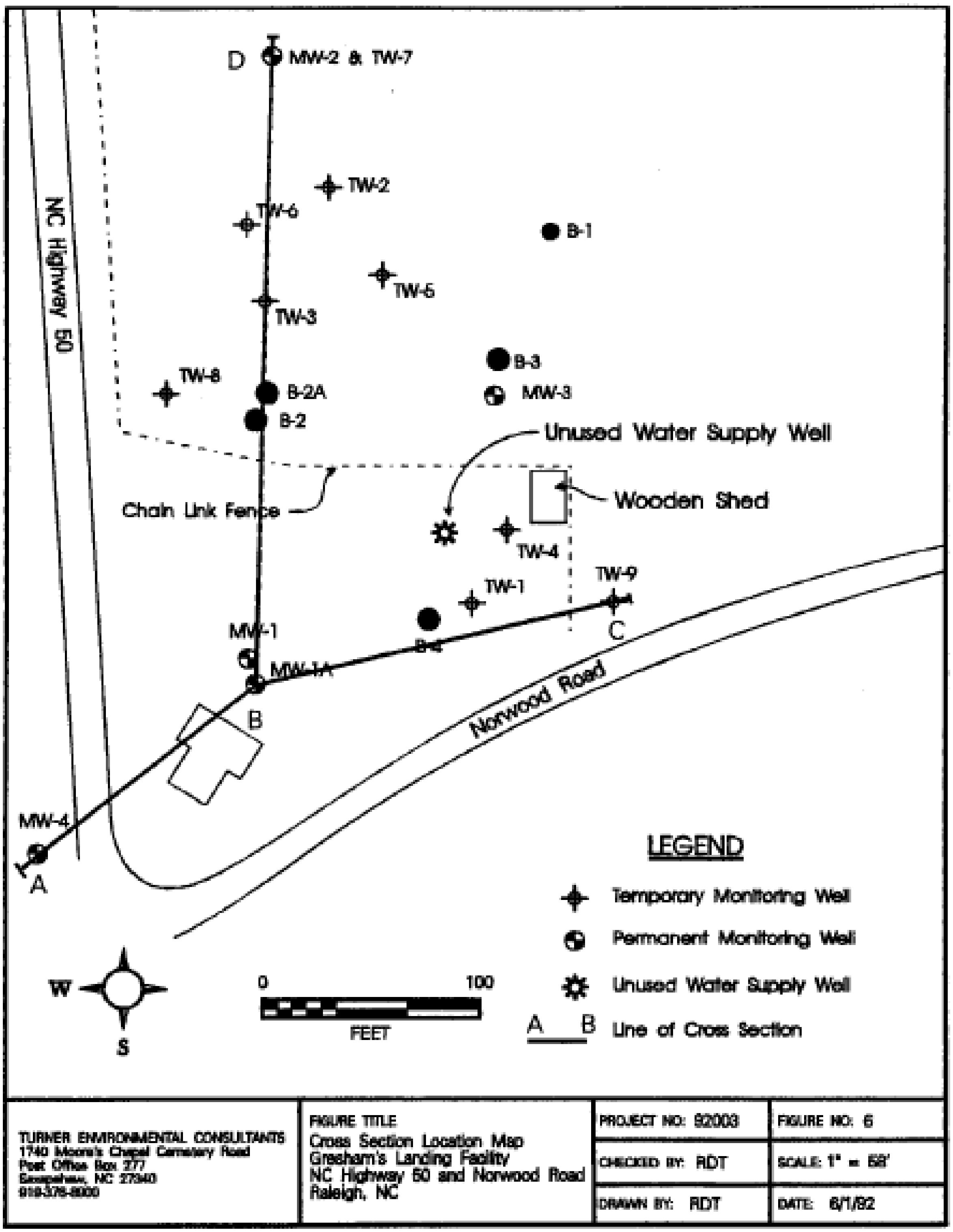


Figure 14. Cross-section location map, Gresham's Landing site (Figure 6, Turner, 1992).

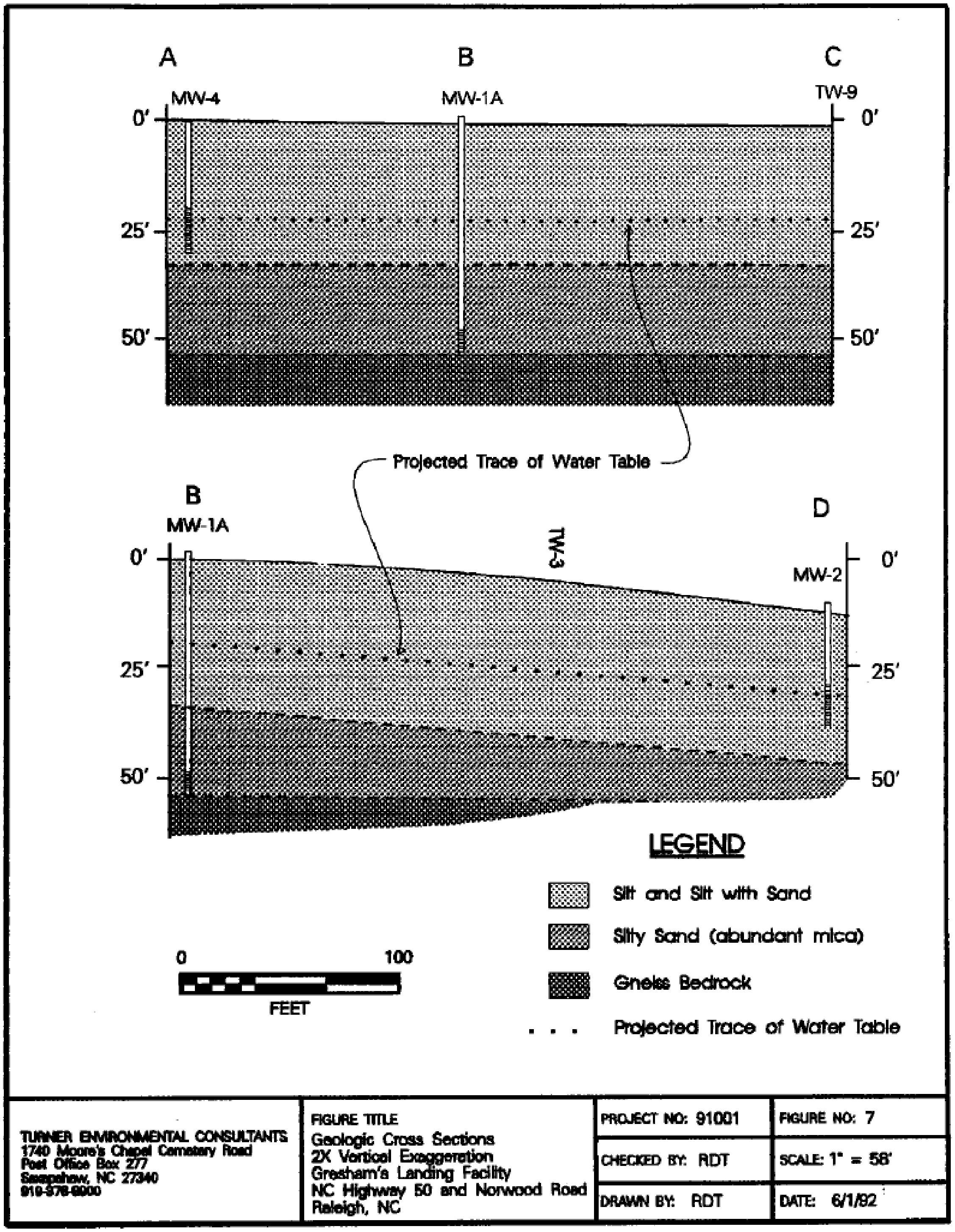


Figure 15. Geological cross section of the Gresham's Landing site (Figure 7, Turner, 1992).

Water level data from Monitoring Well 1 (MW-1) was collected with some frequency from Oct 1993 through May 1997, and only sporadically since then (Figure 16). The average water level is 26.12 feet (8 m) below ground surface. Water table lows occurred in 1995 and 2002, and there was a high water table in the winter of 2003-4. There is no record of the water table response to the 2007 drought.

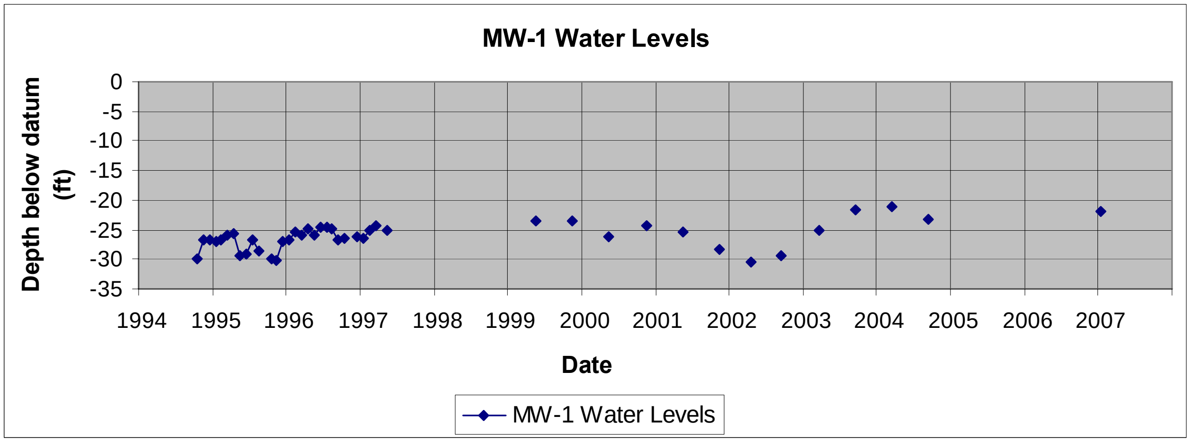


Figure 16. Groundwater level data recorded at Gresham's Landing Monitoring Well 1 (data provided by K. Ness, ATC Associates, personal communication, 2007).

The groundwater flow direction is generally north into Upper Barton Creek (Figure 17). The reported head gradient is 2.66 ft/100 ft. Based on slug tests analyzed using the Bouwer and Rice equations, the hydraulic conductivity ranges from 1.87 x 10^{-6} ft sec^{-1} to 1.0 x 10^{-4} ft sec^{-1} (5.7 x 10^{-5} cm sec^{-1} to 3.05 x 10^{-3} cm sec^{-1}) (Turner, 1992), which is consistent with silt and silty sands. Average flow velocity at the site (v_{avg}) is 8.22 x 10^{-7} ft sec^{-1} (2.51 x 10^{-5} cm sec^{-1}) or 0.07 ft day^{-1} (2.13 cm day^{-1}) (Turner, 1992).

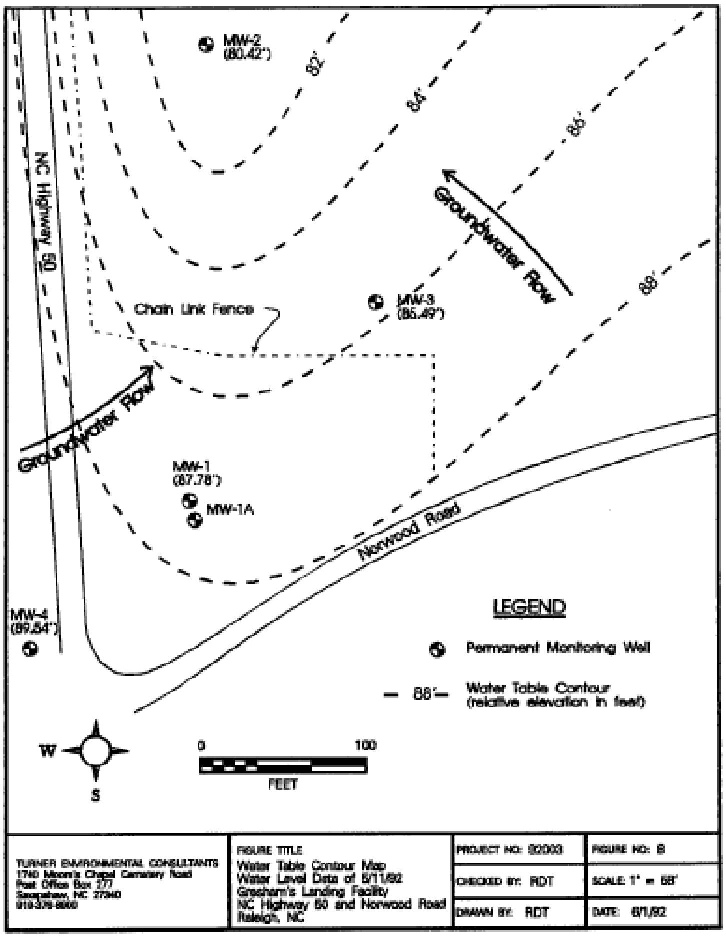


Figure 17. Groundwater flow map of the Gresham's Landing site (Figure 8, Turner, 1992)

Also in the Bayleaf Trail Catchment are three Community Water Service wells: Norwood Crest 1, Roseington 1 and Sheldon Pt. 3 (Figure 18) (NC DEH, 2005). The well sites are in close proximity to Gresham's Landing (less than 1 km) and are in the same geologic and hydrogeologic units according to published maps (Clark et al, 2004; Daniel and Dahlen, 2002). Drilling, well construction, aquifer pumping test, and pumping data for the three wells was provided by Aqua North Carolina, the company which owns and operates them (L.

Stagner, personal communication, 2008). Bedrock occurs at 77 ft (23.5 m) below land surface (bls) at Norwood Crest, and depth to saprolite is 23 ft bls (7 m). The transition zone, or the zone of weathered rock where unconsolidated saprolite grades downward to bedrock (Daniel and Dahlen, 2002), is 54 feet (16.5 m) thick. The data for Norwood Crest is from a drilling log and drilling rate cuttings, not from lithologic analysis of a geologic core. At Sheldon Pt, depth to saprolite is 40 feet bls (12.2 m), the water table was encountered at 47 feet bls (14.3 m) and bedrock at 65 feet bls (19.8 m), according to the well construction record. The well construction record for Roseington 1 is incomplete, but does indicate that the water table was encountered at 18 feet bls (5.5 m). A 24-hour aquifer test was performed at the Norwood Crest well, but there appeared to be problems with the pumping rate and the results are inconclusive. According to North Carolina Administrative Code 18C (NCAC 18C, 2004), such tests on CWS wells are not intended to determine aquifer characteristics but, rather, to determine the design capacity yield of the well which will be written into the permit (permitted yield). This is sometimes related to the capacity of the pump itself, and in some cases the permitted yield is intended to prevent interference with other public water supply wells in the area. The permitted yield of the Norwood Crest well is 15 gal min^{-1} (0.95 L sec^{-1}) (NC DEH, DWW). The two CWS wells on Creedmoor Rd, Roseington 1 and Sheldon Pt 3, have a permitted yield of 60 gal min^{-1} (3.8 L sec^{-1}) (NC DEH, DWW).

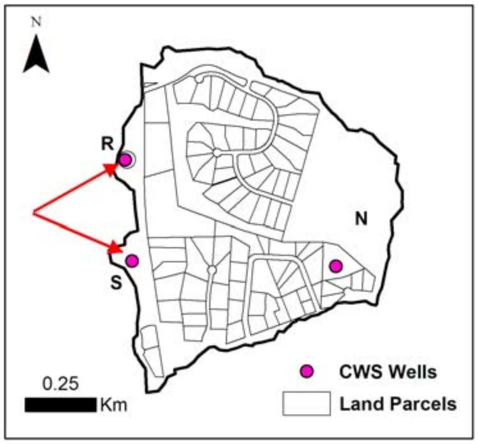


Figure 18. Community Water Service Well Locations. N – Norwood Crest 1, R – Rosington 1, S – Sheldon Pt 3 (NC DEH, 2005)

3.11 Previous related hydrogeologic work

The Lake Wheeler Road Research Station (LWRRS), 24 km south of the study area, is in the same hydrogeologic unit, GNF, and is hydrogeologically somewhat comparable to the Bayleaf Trail Catchment (Figure 10). The LWRRS is operated cooperatively by NC State University, the US Geological Survey, and NC Department of Environment and Natural Resources (NC DENR) Division of Water Quality (DWQ). The rock type at LWRRS is the Raleigh Gneiss, a metamorphic unit in the Raleigh Terrane (Figure 19) (Chapman et al, 2005; Clark et al, 2004). The LWRRS is on the eastern edge of the Raleigh belt, on the eastern flank of the Raleigh Antiform, whereas the Falls Lake schist in which BTC lies is on the western flank. Geologic coring indicates that the average bedrock depth is 77 ft (23.5 m), saprolite depth is 42 ft (12.8 m) and transition zone thickness is 35 ft (10.7 m) (Chapman et al, 2005). The hydraulic conductivity ranges from 4.6×10^{-7} ft sec^{-1} to 1.3×10^{-5} ft sec^{-1} (1.4×10^{-5} cm sec^{-1} to 3.88×10^{-4} cm sec^{-1}) at the Lake Wheeler site (Chapman et al, 2005). This is slightly lower than that at Gresham's Landing, which may indicate a higher proportion of clay at Lake Wheeler. The maximum pumpable well yield at Lake Wheeler was 40 gal min^{-1} (2.5 L sec^{-1}).

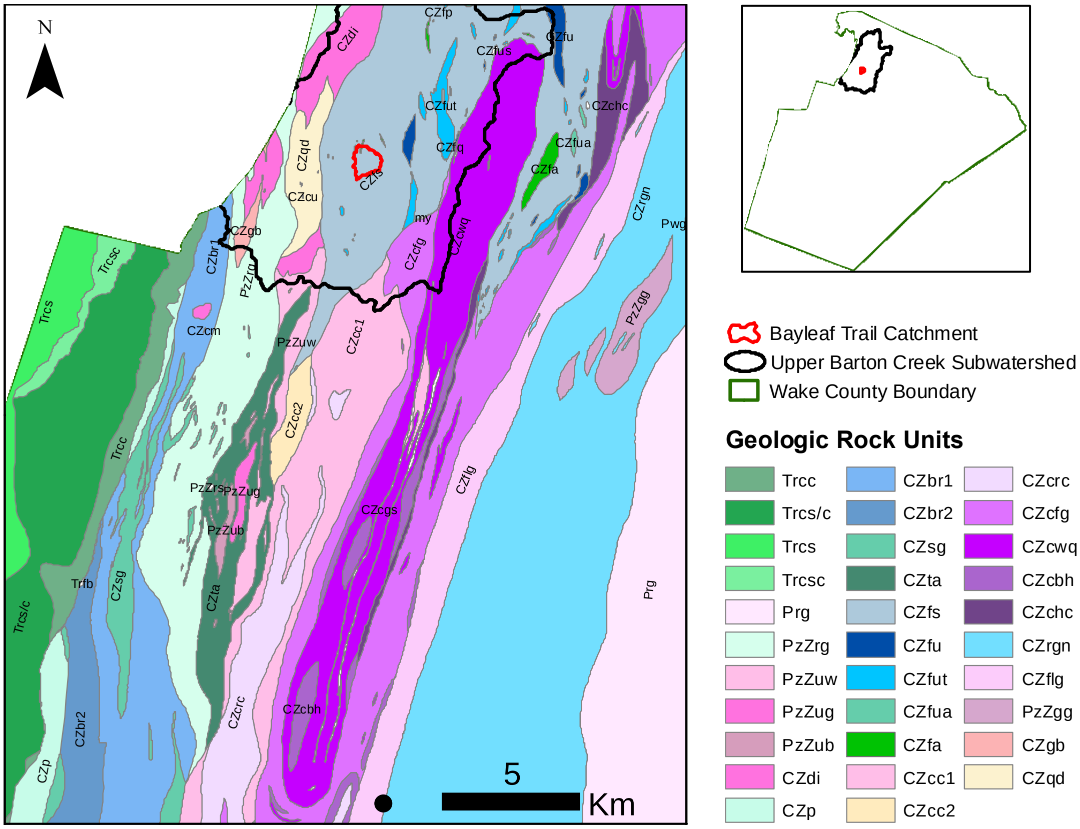


Figure 19. Geologic map of northwestern Wake County, including the Bayleaf Trail Catchment (red) and the Lake Wheeler Road Research Station (black circle) (Clark et al, 2004). (Geologic units descriptions can be found in Clark et al, 2004.)

The 2003 Wake County Comprehensive Groundwater Investigation Final Report (CGI) discussed in Section 1 provided a general understanding of the groundwater system in the county (CDM, 2003). The study was based on watersheds averaging 200 km^2 (78 mi^2) due to the availability of stream flow gages. The current study is based on a catchment area more than 2 orders of magnitude smaller than this.

3.12 Available data

Much of the data for this project is available in a GIS format. There is a table of GIS source data in the GIS references section.

4 Methods and Results

A water balance was used to evaluate the hydrology and hydrogeology of a small catchment in Wake County, NC. This application of the water balance approach defines precipitation and wastewater recharge as water inputs to the watershed. The water outputs of this watershed are defined as evapotranspiration, human water usage and stream flow. Much of the required information is available in a GIS format (GIS References), enhancing the ability to analyze data at a fine scale. Figure 2 is a generalized graphic representation of the inputs to and outputs from the Bayleaf Trail Catchment. The water balance equation is outlined in Section 2.1.

Before determining the values for the water balance components, a small scale watershed was delineated. The following paragraphs will describe that process and the methods used to estimate each component in equation 6. The water balance for BTC was estimated for four precipitation scenarios: an average climate year, two dry years, and a wet year.

4.1 Watershed Delineation

The catchment assessed in this study is two orders of magnitude smaller than the smallest watersheds mapped and indexed by the US Geological Survey (USGS) and the USDA Natural Resource Conservation Service (NRCS) (USDA, NRCS, 2004). The USGS/NRCS watershed boundaries are used throughout the United States by federal, state and local entities. The watersheds are nested and indexed according to nesting level (Figure 20). River basins are indexed with six digit numbers, subbasins with eight digit numbers, watersheds with ten digit numbers, and subwatersheds with 12 digit numbers. The mapping was based on 1:24,000 USGS digital topographic maps.

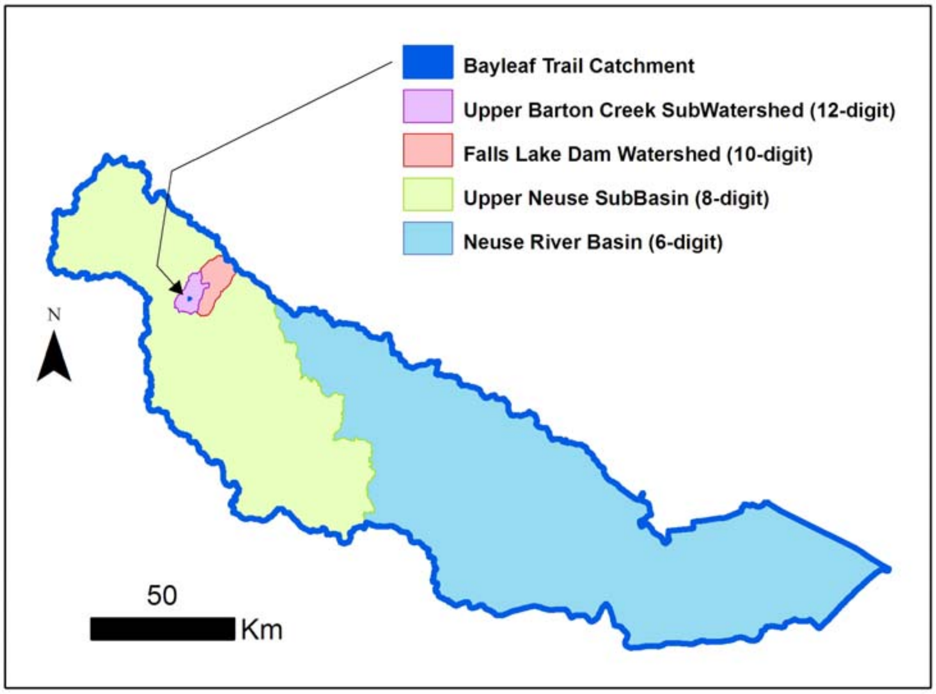


Figure 20. Watersheds are organized as nested basins. Pictured here is one example of each level in the Neuse River Basin. The blue dot is the Bayleaf Trail Catchment. The sizes are:

Neuse = 16,146 km^2, (6234 mi^2)
Upper Neuse = 1994.3 km^2, (770 mi^2)
Lower Falls Lake = 202 km^2 (77.9 mi^2)
Upper Barton Creek = 96 km^2, (37 mi^2)
Bayleaf Trail Catchment = 0.84 km^2, (0.32 mi^2)

The 12-digit watersheds are the smallest USGS/NRCS delineation that currently exist. In Wake County, the 12-digit watersheds average 79.6 km^2. However, much higher spatial resolution is possible, and Piedmont aquifers are localized, not regional. To delineate the

BTC catchment, there is a well established process (Colson, 2006) using LIDAR elevation data collected statewide in 2002. LIDAR is an acronym for Light Detection And Ranging, and is collected aerially using laser technology. LIDAR elevation data has a horizontal point spacing of approximately 3 meters (NC FMP, 2003), and a vertical accuracy of 25 cm (NC FMP, 2002). It is available from the North Carolina Floodplain Mapping Program (NC FMP).

The first step in delineating watersheds is to create one digital elevation model (DEM) tile encompassing the area of interest from multiple small LIDAR tiles available from NC FMP. A tile consists of 20 foot by 20 foot "cells" arranged in a grid pattern. Each cell contains one value representing the elevation of that 20 x 20 square foot area of the earth's surface. Step 2 is to "fill pits", or use Terrain Analysis System software (TAS) (Lindsay, 2003) to find artificial low spots and "fill" them by recalculating the elevation of those spots to match the surrounding cells. The grid resulting from step 2 is then analyzed in step 3 using Terrain Analysis Using Digital Elevation Models (TAUDEM) (Tarboton, 2005) software, resulting in a stream network and watershed boundaries for the area of the input grid. One can perform this analysis at different scales by using different minimum contributing areas. BTC is a result of subdividing the Upper Barton Creek SubWatershed into 18 catchments with a minimum contributing area equal to 0.26 km^2, and watersheds averaging 5 km^2. Selection of a minimum contributing area should be based on the amount of upslope area needed in this terrain to maintain a stream. One of the three streams in BTC is intermittent, thus we have assumed that this is a reasonable minimum catchment area.

4.2 Inputs

4.2.1 Precipitation

Precipitation (P) is the largest input to the Bayleaf Trail Catchment system. Precipitation data was obtained from the North Carolina Climate Retrieval and Observations Network of the Southeast Database (NC CRONOS). Three NC CRONOS climate stations were selected for use in this study, based on length and completeness of the record (Figure 21). Annual precipitation was calculated for the years 1986 – 2007 at the Raleigh 4 SW, Raleigh Wsfo, and Raleigh State University climate stations (Figure 22). These stations were spread across the county, and the variation between them is much less than the variation from year to year. The long-term arithmetic average for precipitation at the three selected climate stations is 116.5 cm year^{-1}. An aerial average was calculated using the two-axis method (Dingman, 2002, p 121) to confirm that the arithmetic mean is acceptable to use. The result of the aerial average was 117.0 cm yr^{-1}, a difference from the arithmetic average of 0.43%. Uncertainty in precipitation measurements are due to instrument error, which, as reported for all three selected stations, was ± 1% to 5%. Uncertainty for the long-term average precipitation was calculated by applying the Student's *t*-test to the annual total precipitation measurements for 22 years at three stations (Bluman, 1992, p 299). The 95% confidence interval for the long-term average precipitation is 116.5 cm yr^{-1} ± 4.8 cm yr^{-1} (979,465 m^3 yr^{-1} ± 40,524 m^3 yr^{-1}).

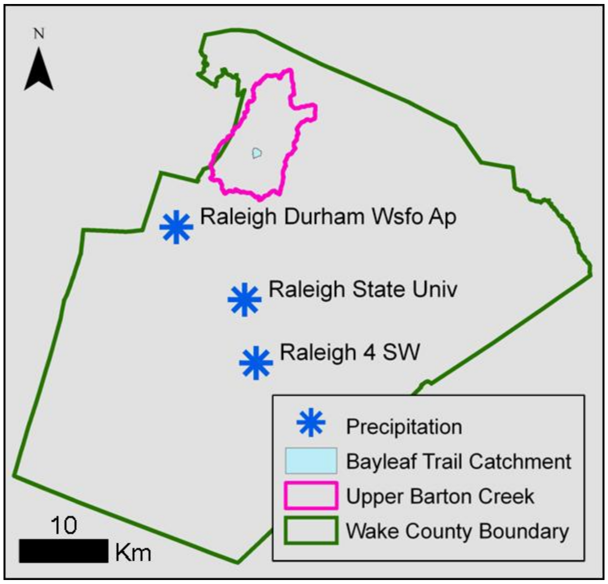


Figure 21. Data from three weather stations were used to calculate a long-term precipitation average.

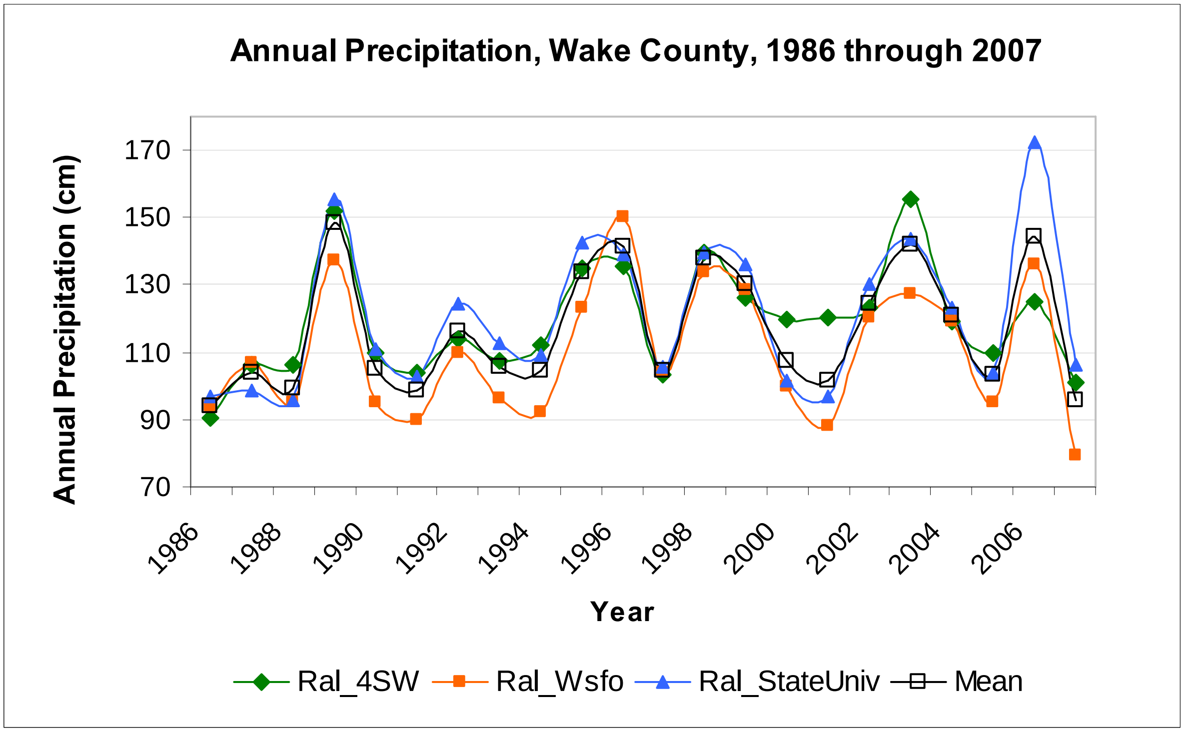


Figure 22. Time series of average annual precipitation (1986 to 2007) at the three precipitation stations in Figure 21. The average annual precipitation of the three stations during this time period is 116.5 cm yr^{-1}. The minimum was 93.9 cm in 1986 and the maximum was 148.3 cm in 1989.

4.2.2 Wastewater Recharge and ETi

Wastewater recharge (WR) returned to the catchment via septic systems was estimated by comparing water use per household with the assumed fraction discharged to the septic system. There is no established method in the literature to estimate this relationship, although a Colorado study found that, for households using septic systems, 90% of water entering a household becomes groundwater recharge (Dano, 2002). Estimated water use per household was obtained from the USGS Estimated Use of Water in the United States in 2000, USGS Circular 1268 (Hutson et al, 2004). The Estimated Use of Water in the United States County-Level Data supports the report (USGS, 2008). The water use report is a collection of data on all types of water use and has been produced by the USGS every five years since 1950. A draft of the North Carolina county-level data for 2005 is currently under review (D. Rayno, personal communication, 2007).

In 2005, private domestic well use in Wake County was estimated at 55 gallons per person per day (0.21 m^3 $person^{-1}$ day^{-1}) (Terziotti et al, 1994; D. Rayno, personal communication, 2008). The USGS did not report error in their estimate of per person water use, so error was assumed to be 10%, or 55 gal day^{-1} ± 5.5 gal day^{-1}. The US Census Bureau estimates that there are 2.58 ± 0.03 people per household in Wake County (US Census, 2006b). According to data supplied by the City of Raleigh (D. Crisp, personal communication, 2008) and the Town of Holly Springs (S. Sudano, personal communication, 2008), 80% to 90% of the water entering homes in their systems is returned to the public sewage system. Assuming residents using private on-site septic systems have a similar ratio of water use to wastewater, the value of 85% ± 5% of water use was applied to determine wastewater recharge. The number of homes was estimated from Land Parcel GIS data for Wake County (Wake County GIS). An error of 5% is assumed, since the actual number of active septic systems at any point in time may vary somewhat. The number of houses is estimated to be 95 ± 5 houses. All of the wastewater in BTC is treated by on-site septic systems. Average annual wastewater recharge to the catchment aquifer from septic systems is estimated to be 4.18 Mgal yr^{-1} (15,831.8 m^3 yr^{-1} or 1.9 cm yr^{-1}), equal to (2.58 people/household) (95 houses) (55 gallons person^{-1} day^{-1}) (0.85).

Uncertainty in this component involves four factors: per person water use, people per household, the number of septic systems in BTC, and whether 85% is the correct estimate of household water returned to the catchment. Because each of these factors uses different units a fractional uncertainty was calculated for each and because these are independent factors the Provisional Rule of Uncertainty in Products and Quotients and addition in quadrature can be used to determine the uncertainty of the average annual wastewater recharge calculation (Taylor, 1997, p 53 and p 61). A rough estimate of uncertainty not tied to a specific confidence interval is 12.7%, and the results are thus 15,831.8 m^3 yr^{-1} ± 2008.5 m^3 yr^{-1} (1.9 cm yr^{-1} ± 0.2 cm yr^{-1}).

Water is lost from the watershed by human activities, through evaporation from irrigation, from septic systems, and by other means (ETi for the entire catchment, HL for an individual home). These losses are outputs from the catchment water balance and since 85% of water use is assumed to returned via wastewater recharge, ETi is assumed to be 15% of water use. There is currently no accepted method to account for these losses. Since homeowners primarily irrigate lawns during hot dry weather it can be assumed that 100% of irrigation water is either evaporated or transpired (CDM, 2003; Dano, 2002), removing irrigation from consideration in the water balance for BTC. If evaporation of irrigation is less than 100%, the difference would be a return to the system similar to wastewater recharge.

4.3 Outputs

The final component of the water balance equation is outputs. The water output components in the BTC are evapotranspiration (ET), groundwater withdrawals (PW and CWS), and stream flow (Q) (Eqn. 7).

4.3.1 Evapotranspiration

Evapotranspiration (ET) can be measured or Potential Evapotranspiration (PET) calculated using a variety of instruments and methods. There is no single method generally considered to be the best in all circumstances. Each method requires different parameters and the method chosen is dependent on the available data in a given situation. In previous studies, the range of annual ET reported for the region is 30.5 in yr^{-1} (77.5 cm yr^{-1}) (Welby and Wilson, 1982) to 34.1 in yr^{-1} (86.6 cm yr^{-1}) (Daniel, 1996). According to Epperson et al (1988), average annual ET for Raleigh is 32.8 in yr^{-1} (83.3 cm yr^{-1}), but there is no indication whether this is a measured value or calculated, nor of the methods used. For this study evapotranspiration for Wake County was determined using eddy covariance data obtained from the Duke University Free-Air CO_2 Enrichment (FACE) Experiment located approximately 36 km west of BTC (Figure 23) (FACE, 2008).

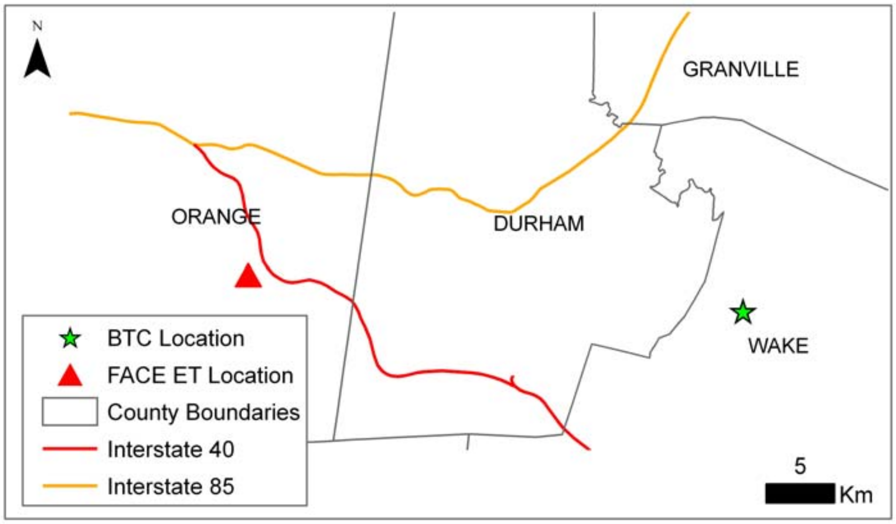


Figure 23. Location of the Duke University FACE site in relation to BTC.

Eddy covariance or eddy correlation is the measurement of vertical heat transfer at a surface. The difference between upward and downward fluxes is a measure of either evaporation, when upward movement is greater than downward, or condensation in the opposite case. The eddy covariance method measures true evapotranspiration, but is primarily used as a research tool and is not widely available. The data provided for this study is from the planted pine forest FACE experimental site in the Duke Forest. The FACE site has homogeneous loblolly pine vegetation, and data is available for 2003 through 2007 (Figure 24) (FACE, 2008; Y. Parashkevov, personal communication).

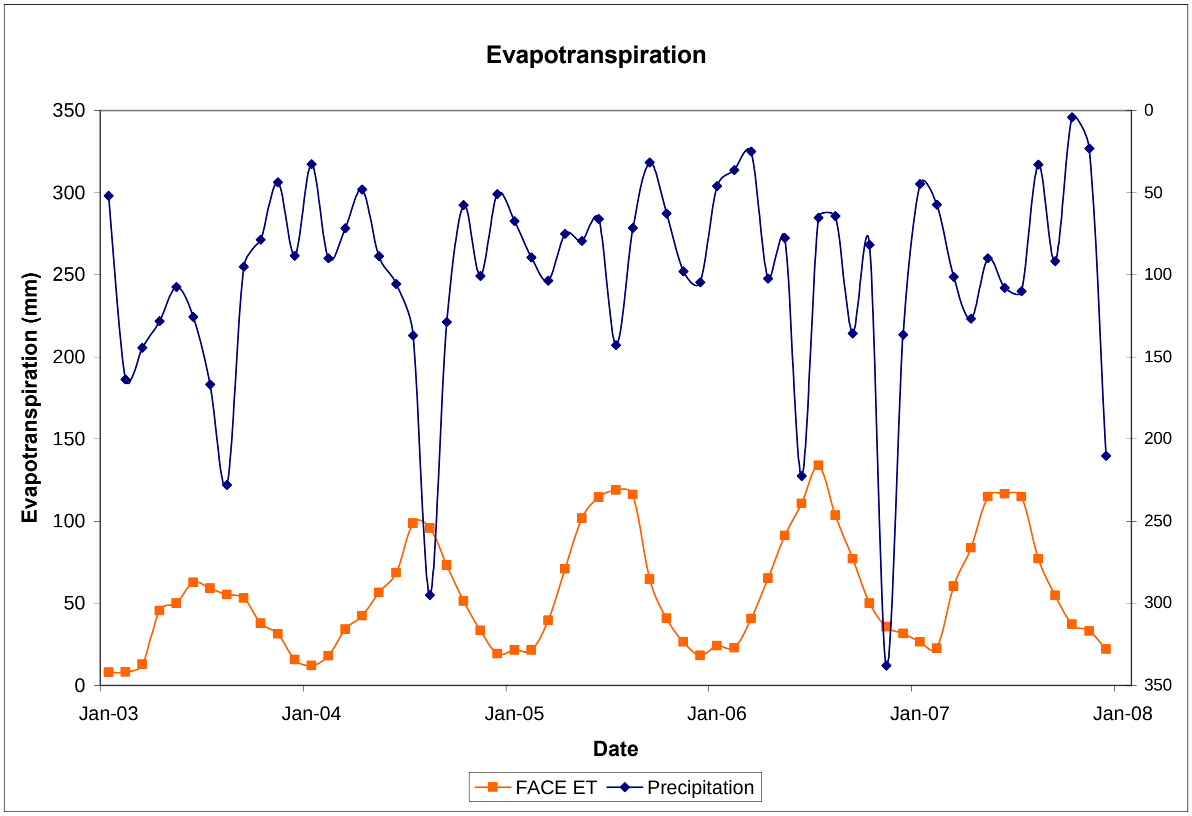


Figure 24. Monthly total evapotranspiration and precipitation for the years 2003 – 2007. Evapotranspiration is from eddy covariance data collected at the FACE site in the Duke Forest, and precipitation is a county-wide average.

The type of trees at a site of interest is important because different tree canopies do lead to differences in evapotranspiration. While the FACE program provided data for the planted pine forest, the BTC tree canopy is mixed hardwoods and conifers (personal observation, December, 2007). Stoy et al (2006) compared ET from 2001 to 2004 at three FACE sites in the Duke Forest, an old agricultural field, a planted pine forest and a late-successional hardwood forest. They found that ET at the FACE pine plantation is generally higher than that at the FACE hardwood forest site as well as being more sensitive to differences in climate, for example drought and ice damage (Stoy et al, 2006). Komatsu (2005) found a difference in evapotranspiration rates between broad-leafed and coniferous forests, as well as variations related to the height of the coniferous canopy. Stoy et al (2006) reported that ET at the FACE hardwood site varies from 87% to 104% of that at the planted pine forest for the years 2001 through 2004. The forest at BTC seems to be midway between the two FACE forest types, and thus data from the planted pine forest provides a reasonable estimate of ET at BTC. The FACE data for 2003 and 2004 are suspiciously low, and are probably due to damage to the tree canopy as a result of an ice storm late in 2002 (Stoy, 2006). It is likely that the tree canopy in BTC would have suffered similar damage, since the ice storm was regional in scope.

Uncertainty in eddy covariance data is due to instrument error, climate conditions, and measurement gaps and has been covered extensively in the literature on eddy covariance. Goulden et al (1996) worked to establish a reliable method to determine uncertainty, and later researchers continue to apply his methods (Oren, et al, 2006; Stoy et al, 2006; Stoy et al 2008). Oren et al (2006) reported a latent heat error of 6% (latent heat is converted to ET through a unit conversion). Stoy et al (2006) reported error of 6.7% to 9.3% for the planted pine forest, and 9.1% to 10.5% for the hardwood forest. Goulden et al (1996) reported a long-term precision of eddy covariance data of ± 5%. Given the difference in forest type and the presence of human influences in BTC, this study assumed an uncertainty in ET of 10%, and the estimate for average annual ET for the years 2003 through 2007 is 563,250.1 m^3 yr^{-1} ± 56,325.0 m^3 yr^{-1} (67.0 cm yr^{-1} ± 6.7 cm yr^{-1}).

4.3.2 Groundwater Withdrawal from Private Wells

Groundwater water withdrawal from private domestic wells was calculated as (2.58 people/household) (35 houses) (55 gallons person^{-1} day^{-1}) = 1.8 million gallons per year (6862.1 m^{3} yr^{-1}). The quantities used for per person water use and the average number of people per household in Wake County are described in Section 4.2.2 of this paper. The Wake County GIS Parcel data Land Class designation was used to determine that 35 homes in BTC are not included in a CWS, and it was assumed that these homes use private domestic wells to satisfy their water needs. As in Section 4.2.2, an error of 5% is assumed, since the actual number of active private wells may vary somewhat at any point in time.

Uncertainty in this component involves similar factors to those for wastewater recharge, two of which are the same, per person water use and people per household. The number of private domestic wells in BTC is different from the number of septic systems used in Section 4.2.2 because, while all residents use onsite septic systems, there are two drinking water source systems – private wells and community water service systems. Because these three factors use different units, a fractional uncertainty was calculated for each and because these are independent factors the Provisional Rule of Uncertainty in Products and Quotients and addition in quadrature can be used to determine the uncertainty of the long-term private well use calculation (Taylor, 1997, p 53 and p 61). A rough estimate of uncertainty not tied to a specific confidence interval is 11.2%, and the results are thus 6862.1 m^{3} yr^{-1} ± 771.3 m^{3} yr^{-1} (0.8 cm yr^{-1} ± 0.09 cm yr^{-1}).

4.3.3 Groundwater Withdrawal from CWS Wells

Calculating CWS groundwater withdrawal required a different approach than private groundwater withdrawals. There are 67 wells in the Bayleaf/Stonebridge and Saddleridge CWS systems, located throughout northwestern Wake (Figure 12). Water is pumped from all of these wells, mixed, and distributed according to demand. Thus knowing the use in any one household or neighborhood does not reveal how much water is being withdrawn from a particular catchment. Rather, the amount pumped by any CWS wells in a given catchment is the information required. There is groundwater withdrawal from three CWS wells located in BTC . Two of these wells, Roseington 1 and Sheldon Pt 3, are located just inside the boundary of the catchment and one, Norwood Crest 1, is well within the catchment (Figure 18).

Total gallons pumped per given time period data were obtained for each well from Aqua North Carolina, the owner of the three CWS wells in the BTC (L. Stagner, personal communication, 2008). The average annual total withdrawal for each well is listed in Table 2. The complete monthly pumping records for 2000 to 2007 are graphed in Figure 25. Note that while Sheldon Pt. 3 and Norwood Crest 1 both reached their peak annual volume pumped in 2005 and have declined since then, the annual volume pumped from Roseington 1 has increased during the same time period (Figure 26). The combined annual withdrawal of these three wells has increased yearly since 2001 (Figure 27).

Table 2. CWS well yields, depth and average annual withdrawals.

CWS Well	Yield	Average Annual Withdrawal	Average pumped daily	CWS area of influence within BTC	Pumped from BTC	Pumped from BTC
	(gal min^{-1})	(Mgal yr^{-1})	(gal day^{-1})	%	(m^3 yr^{-1})	(cm yr^{-1})
Rosington 1	60	5.494	15052.05	46.9	9,760.1	1.2
Sheldon Pt 3	60	5.958	16323.29	51.1	11,529.4	1.4
Norwood Crest 1	15	1.928	5282.19	100	7,298.3	0.9
Total pumped from BTC					28,587.7	3.4

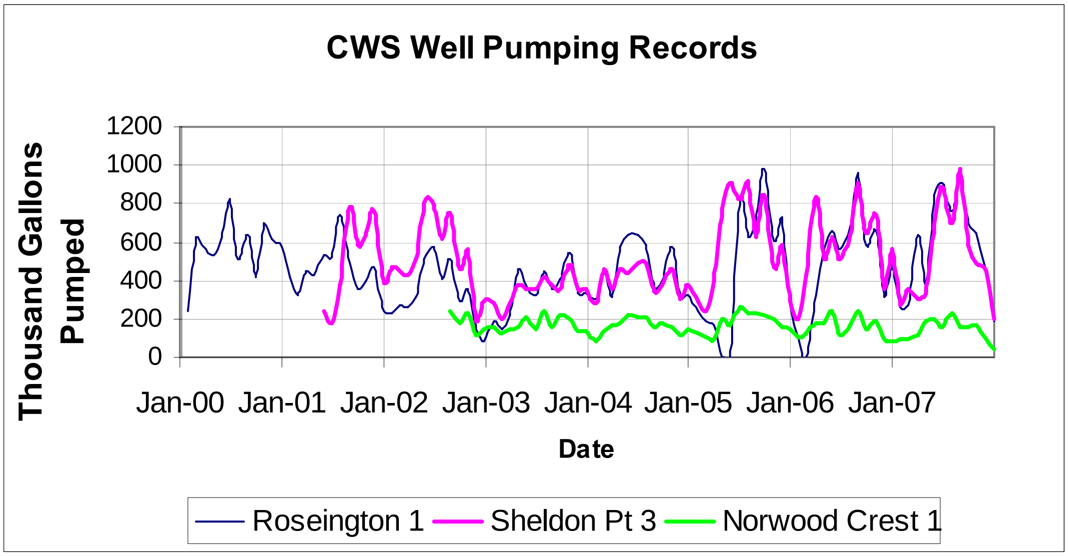


Figure 25. Monthly pumping records for the community water service wells located in the Bayleaf Trail Catchment.

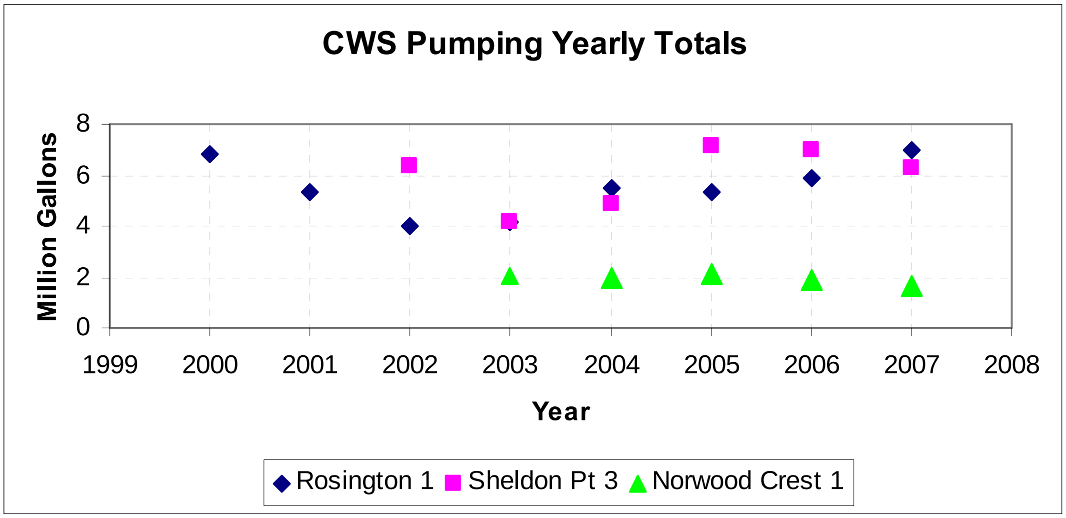


Figure 26. Total gallons pumped per year from each of the community water service wells located in the Bayleaf Trail Catchment.

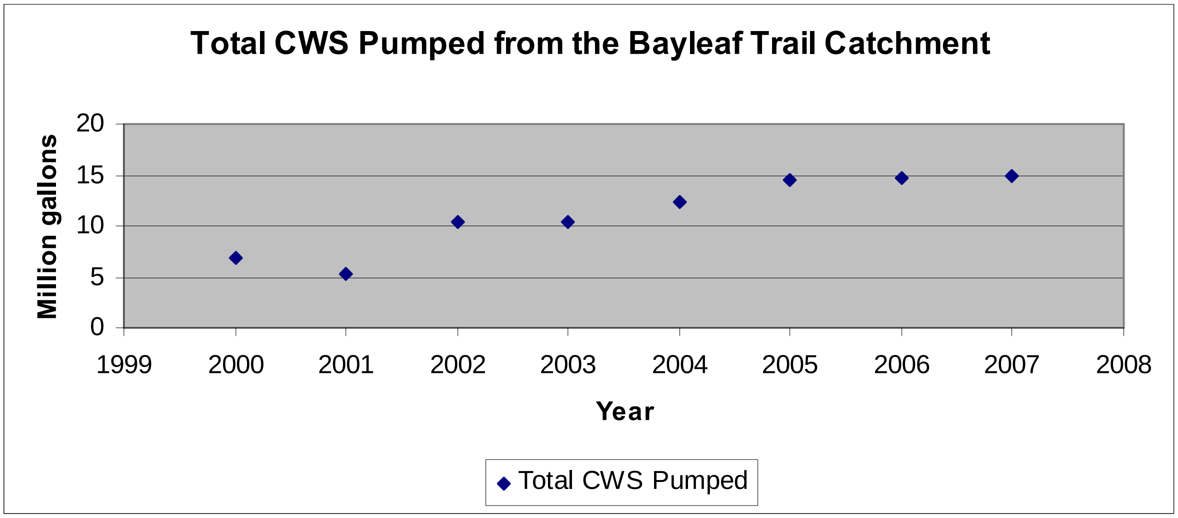


Figure 27. Total Community Water System withdrawals from the Bayleaf Trail Catchment. Note that total withdrawals have steadily increased since 2001. The growth in use has slowed somewhat since 2005, but continues to increase by 0.2 Mgal yr^{-1}.

Due to their proximity to the catchment boundary, it is likely that the Roseington 1 and Sheldon Pt 3 wells draw water from two different catchments, BTC and the catchment to the west. For the purposes of this study, a radial area of influence was drawn around each well, according to its yield following the guidance of the Guilford County rule mentioned in the Introduction (Guilford County, 2007). The rule requires the performance of a 24-hour aquifer pumping test for wells with withdrawals greater than 10,000 gallons per day. The radial area of influence of a large capacity well is assumed to be 1000 ft (304.8 m). Wells withdrawing less than 10,000 gallons per day do not fall under the rule, and there is no guidance to establish the radius of the area of influence. Roseington 1 and Sheldon Pt 3 are large wells, pumping 15,000 gal day^{-1} (56.8 m^3 day^{-1}) so the Guilford County rule was applied, and a 1000 ft (304.8 m) radial area of influence, or buffer, was drawn around those two wells in a GIS (Figure 28). The percent of the buffer area within BTC was calculated and that percentage was then applied to the total pumpage of those two wells. Using this method it is estimated that the Roseington 1 well draws 47% of its water from BTC, and Sheldon Pt 3 draws 51% of its water from BTC (Figure 28). The Norwood Crest 1 well, lying well within the catchment boundary and pumping 5000 gal day^{-1} (18.9 m^3 day^{-1}), does not have a high enough pumping rate to fall under the Guilford County rule. For the purposes of this study, it is assumed that 100% of the water pumped by the Norwood Crest 1 well is withdrawn from BTC. It is located 130 m (426.5 ft) from the nearest boundary, and the assumption was made that the area of influence extends to the catchment boundary, thus a 130 m radius was assumed. The CWS value used in Eqn. 7 is thus the sum of the values in the “Pumped from BTC” columns in Table 2.

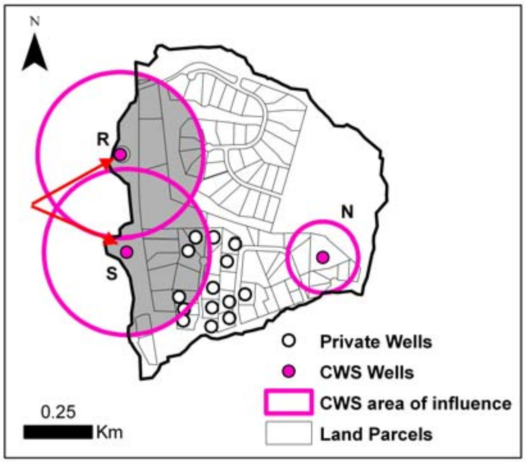


Figure 28. Potential areas of influence of CWS wells within the Bayleaf Trail Catchment. A 304.8 m (1000 ft) radius was applied to Roseington 1 (R) and Sheldon Pt 3 (S), and a 130 m (426.5 ft) radius was applied to Norwood Crest 1 (N). The shaded areas around Rosington 1 and Sheldon Pt 3 are the portion of the area of influence that lies within the BTC.

The uncertainty calculated for the CWS component is that due to the area of influence calculation. There may be error in the reported pumping volumes, but the CWS owner did not report any. The magnitude of the estimated CWS withdrawals from BTC is dependent on the shape and size of the area of influence, the percent of that area that is within BTC and whether the percent of area truly represents the percent of total CWS withdrawals that is water drawn from BTC. To account for uncertainty in the radius of influence of each CWS and therefore the amount of water pumped from BTC in an average year, an uncertainty of ± 5% was applied to the radius of influence calculated for each well. For example in the case of Roseington 1, the estimated withdrawal from BTC is 47% of the total water pumped from that well, with a potential range of 42% to 52%. Because withdrawals from each well are independent of each other the Provisional Rule of Uncertainty in Products and Quotients and addition in quadrature can be used to determine the uncertainty of the average annual total

CWS withdrawal from BTC (Taylor, 1997, p 53 and p 61). The total output via CWS withdrawals from BTC is estimated as 28,587.7 m^3 yr^{-1} ± 838.8 m^3 yr^{-1} (3.4 cm yr^{-1} ± 0.1 cm yr^{-1}).

4.3.4 Stream Flow

All of the available stream data collection sites reasonably near the Bayleaf Trail Catchment were presented in Section 3.9 of this paper. The data recorded from 1950 to 1970 at the Low Flow Partial Record (LFPR) station in Upper Barton Creek (UBC) were used by the USGS to estimate the lowest 7-day stream flow in a ten year time period, and is referred to as Q7,10 low flow data (Weaver, 1998). This historic low flow data can be used as a guide to predevelopment drought conditions. Stream flow in a drought is baseflow, the source of which is entirely groundwater. There are no other stream flow data available at this time.

The Q7,10 for the Upper Barton Creek LFPR for the time period above is 0.062 ft^3 sec^{-1} mi^{-2} (2.14 cm yr^{-1}) (Welby and Wilson, 1982). Assuming the value for UBC applies to BTC, the smaller catchment nested within UBC, the estimated Q7,10 for BTC is 2.14 cm yr^{-1}. No uncertainty was reported in the source publication for this estimate.

4.4 Water Balance Equation Results

The water balance for BTC was solved for stream flow, assuming long-term constant storage conditions, our working assumption. As stream flow data becomes available, it can be used to validate this assumption. A long term decrease in stream flow is likely to indicate a decrease in storage. The stream flow equation for BTC is a restated version of equation 7:

$$(P + WR) - (ET + PW + CWS) = Q \qquad \text{(Eqn. 8)}$$

where P is precipitation, WR is wastewater recharge, ET is evapotranspiration, PW is groundwater withdrawals by private residential wells, CWS is groundwater withdrawals by community water service wells, and Q is stream flow.

The water fluxes associated with the BTC water supply system are summarized in Table 3. In BTC, the water withdrawn by CWS wells is far in excess of that which can be used by the 60 homes in BTC which receive water from a CWS system. Sixty percent of the CWS withdrawal is exported to other catchments for water supply, resulting in a loss from the catchment water balance. Thus, while the water balance equation for the human water supply system in a developed watershed as described in Section 2.1 is

$$ETi = PW + CWS - WR \qquad \text{(Eqn. 4),}$$

the water balance for human water use in BTC is:

$$\text{Total Loss (BTC)} = CWS_{out} + ETi = (PW + CWS_{in}) - WR \quad \text{(Eqn. 9)}$$

where ETi is the increment of evapotranspiration caused by human use, PW is groundwater withdrawal from private residential wells, CWS is total groundwater withdrawal from community water service wells, WR is wastewater recharge through on-site septic systems, CWS_{in} is water pumped from BTC by CWS wells and returned to BTC through homes served by a CWS, and CWS_{out} is water pumped from BTC by CWS wells and served to homes outside BTC. In the case of BTC the water loss from the catchment due to human uses is 2.33 cm yr^{-1} (19618.0 m^{3} yr^{-1}), largely due to the withdrawals by the CWS wells (Table 3).

Table 3. Components of the water budget for the current water supply system in BTC based on annual water use.

Component	**Symbol**	**Number of Households or Wells**	**m^{3} yr^{-1}**	**cm yr^{-1}**
Single Household				
Private Well Withdrawals [1]	PW	1	196.1	0.023
Wastewater Recharge [2]	WR	1	166.7	0.02 [3]
HL [4]	HL	1	29.4	0.0035
Bayleaf Trail Catchment				
Private Well Withdrawals [5]	PW	35	6,862.1	0.8
CWS Withdrawals used by BTC homeowners [6]	CWS_{in}	60	11,763.6	1.4
CWS Withdrawals pumped outside BTC [7]	CWS_{out}	86 [8]	-16,824.1	-2.0
Wastewater Recharge [9]	WR	95	15,831.8	1.88
Evapotranspiration due to human use [10]	ETi	95	-2,793.9	-0.33
Total loss from BTC			**19,618.0**	**2.33**

Assumptions outlined in Section 4.2.2 unless otherwise noted.

[1] Based on water use assumptions applied to each household
[2] Based on assumption that WR = 85% of PW
[3] 0.02 rounded up from 0.0195
[4] Based on assumption that HL = 15% of PW
[5] Based on water use assumptions applied to 35 households
[6] Based on water use assumptions applied to 60 households
[7] Total CWS withdrawals from BTC (Section 4.3.3) minus water use for 60 households
[8] Number of homes that could be served
[9] Based on application of the assumption that WR = 85% of water use applied to 95 households
[10] Based on assumption that ETi = 15% of water use in 95 households

The overall water balance for BTC was calculated for four given precipitation inputs: a long-term average climate year, two dry years, and a wet year. The years 2005 and 2007 (dry years), and 2006 (wet year) were selected due to the availability of a complete climate dataset. For the dry years, we assume a 30% reduction in household water use, based on reductions in use experienced by the City of Raleigh Public Water System in 2007 (D. Crisp, personal communication, 2008). The water balance for the Bayleaf Trail Catchment is listed in Table 4, and graphically displayed in Figure 29.

While the water balance equation was solved using the assumption that change in storage (ΔS) is equal to zero, this is actually true only for the long-term average in a natural system. Thus, Q in equation 8 is actually Q plus ΔS, where $\Delta S = 0$ in an average year. In an individual year, ΔS will be positive or negative when compared to the long-term average. For example, if there was a 1 m drop in the water table in 2007, and the porosity of the aquifer is 0.2 cm^3/cm^3, (20% of the volume is voids which can store water), the resulting ΔS is -20 cm. For a porosity of 0.05 cm^3/cm^3, ΔS is -5 cm. Thus for 2007, $Q + \Delta S = 16.3$ cm is probably a gross underestimate of stream discharge. There is anecdotal evidence that the water table dropped that year by 15 m (M. Chapman, USGS, personal communication), which, at porosity of 0.05 cm^3/cm^3, would be a ΔS of -75 cm. The change in storage cannot be quantified without actual stream flow (Q) or water level data.

Stream Flow uncertainty for the long-term average year was calculated for Q only, assuming a long term $\Delta S = 0$. Uncertainty was calculated as a sum in quadrature of the component uncertainties (Table 5). In Figure 30 it is quite apparent that for the average year the uncertainties in the natural components are larger than the magnitudes of the anthropogenic components.

Table 4. Water balance for the Bayleaf Trail Catchment. This is a whole catchment water balance including both natural and anthropogenic components. Comparisons can be made between an average year, a wet year and two distinct dry years. Source data units are in white rows, common units are in gray rows.

Component	Units	Average Year	Dry year (2005)	Dry year (2007)	Wet year (2006)
Precipitation (P)[1]	$m^3\ yr^{-1}$	979,465.1	867,646.4	803,749.9	1,215,125.3
	$cm\ yr^{-1}$	116.5	103.2	95.6	144.5
WW Recharge (for 95 homes) (WR)[2]	$gal\ person^{-1}\ day^{-1}$	46.8	32.7	32.7	46.8
	$m^3\ yr^{-1}$	15,831.8	11,082.3	11,082.3	15,831.8
	$cm\ yr^{-1}$	1.9	1.3	1.3	1.9
Evapotrans-piration (ET)[3]	$m^3\ yr^{-1}$	563,250.1	635,022.9	642,472.0	661,583.9
	$cm\ yr^{-1}$	67.0	75.5	76.4	78.7
Wells Private (for 35 homes) (PW)[4]	$gal\ person^{-1}\ day^{-1}$	55.0	38.5	38.5	55.0
	$m^3\ yr^{-1}$	6,862.1	4,803.5	4,803.5	6,862.1
	$cm\ yr^{-1}$	0.8	0.6	0.6	0.8
Wells CWS (CWS)[5]	$Mgal\ yr^{-1}$	7.6	8	8.2	8.2
	$m^3\ yr^{-1}$	28,587.7	30,293.9	30,858.9	30,938.1
	$cm\ yr^{-1}$	3.4	3.6	3.7	3.7
Stream Flow ($Q + \Delta S$)[6]	$m^3\ yr^{-1}$	396,597.1	208,606.4	136,697.8	531,573.0
	$cm\ yr^{-1}$	47.2[6]	24.8	16.3	63.2

[1] P based on climate data described in Section 4.2.1
[2] WR based on assumption in Section 4.2.2 that WR = 85% of household water use
[3] ET based on eddy covariance data described in Section 4.3.1
[4] PW based on water use assumptions in Section 4.2.2 applied to 35 households
[5] CWS based on CWS pumping measurements and area of influence assumptions made in Section 4.3.3
[6] The assumption is that in the average year $\Delta S = 0$

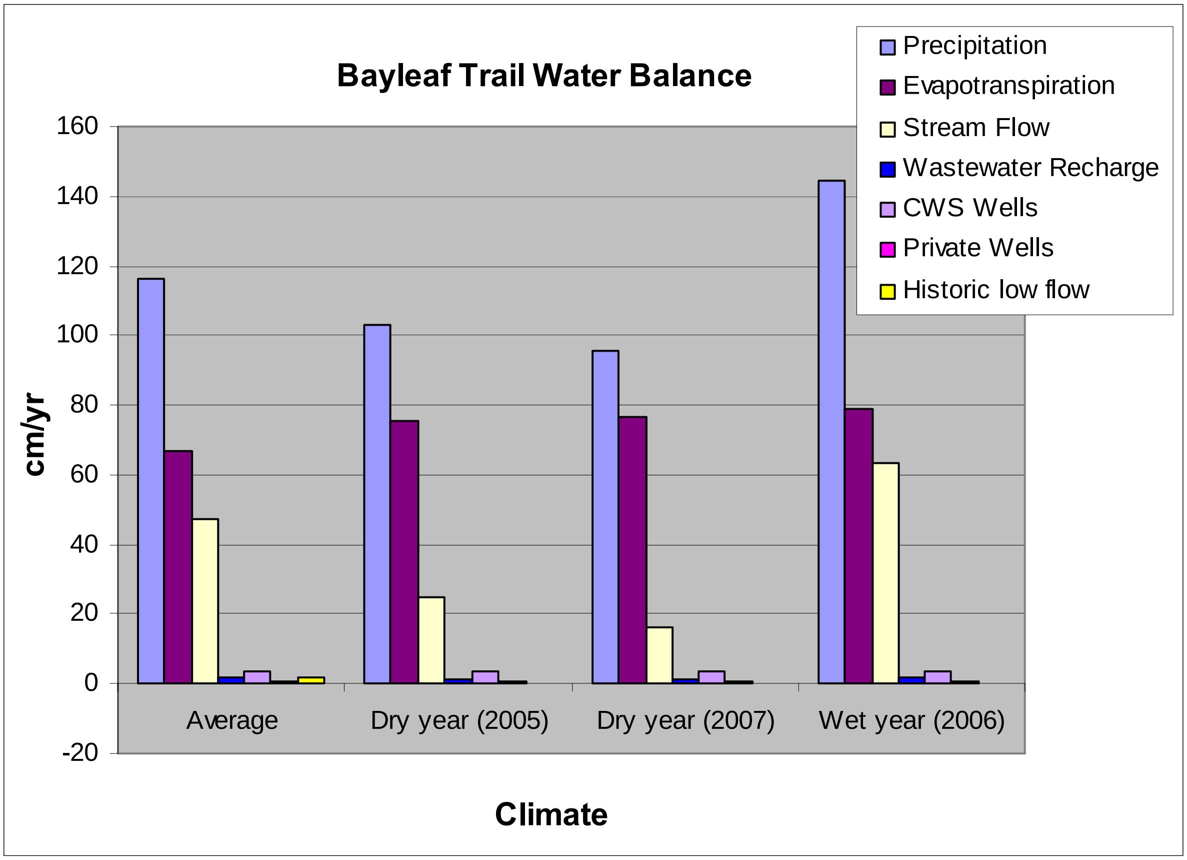
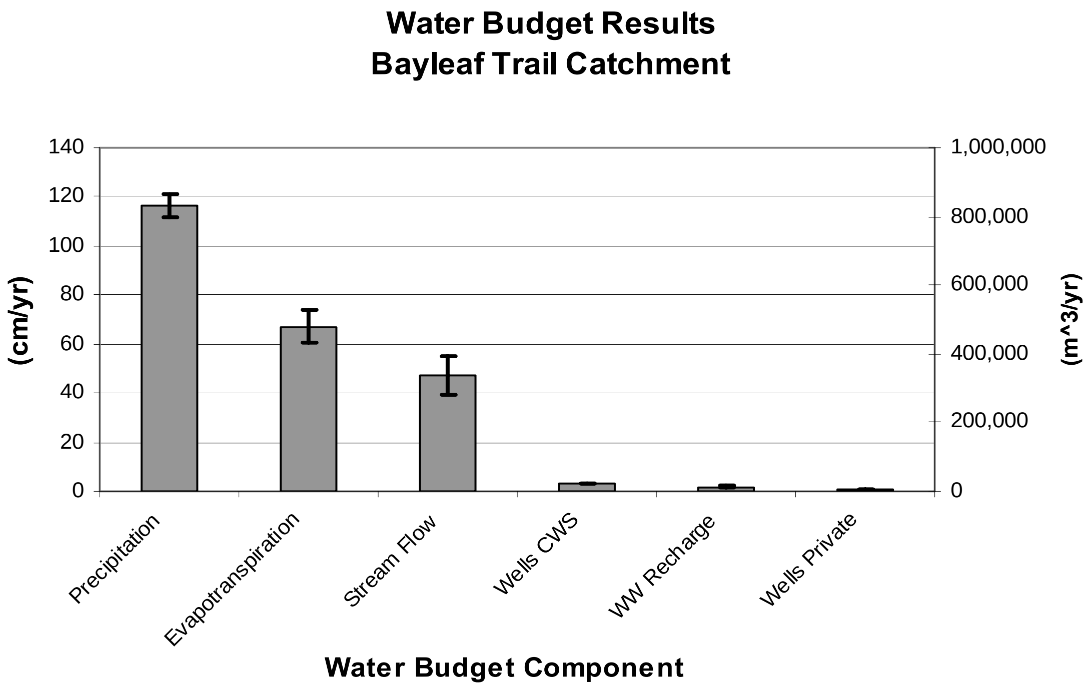


Figure 29. Graph of the magnitudes of the components of the whole catchment water balance for BTC for an average year, two dry years, 2005 and 2007, and for a wet year, 2006.

Table 5. Uncertainty of average year values in Table 4.

Component	Units	Average Year	Uncertainty
Precipitation	**m^3 yr^{-1}**	979,465.1	± 40,524
	cm yr^{-1}	116.5	± 4.8
WW Recharge	**m^3 yr^{-1}**	15,831.8	± 2008.5
	cm yr^{-1}	1.9	± 0.2
Evapotranspiration	**m^3 yr^{-1}**	563,250.1	± 56,325.0
	cm yr^{-1}	67.0	± 6.7
Wells Private	**m^3 yr^{-1}**	6,862.1	± 771.3
	cm yr^{-1}	0.8	± 0.09
Wells CWS	**m^3 yr^{-1}**	28,587.7	± 848.8
	cm yr^{-1}	3.4	± 0.1
Stream Flow	**m^3 yr^{-1}**	396,597.1	± 69,426.5
	cm yr^{-1}	47.2	± 8.3



(P + WR) - (ET + CWS + PW) = Q

cm/yr [116 (±4.8) + 1.9 (±0.24)] + [67 (± 6.7) + 3.4 (± 0.1) + 0.8 (± 0.1)] = 47.2 (± 8.3)

m^3/yr [979.5 (± 40.5) + 15.8 (±2.0)] + [563.3 (± 56.3) + 28.6 (± 0.8) + 6.9 (± 0.8)] = 396.6 (± 69.4)

Figure 30. Graph of the long-term average annual whole catchment water balance for BTC, including uncertainty analysis.

5 Discussion

The stream flow results of the water balance equation as applied in this study show that flow in all years exceeds the historic low flow (Q7,10) levels estimated for BTC in Section 4.3.4 (2.14 cm yr). The water balance results also show that the magnitudes of the anthropogenic components are dwarfed by that of the natural components (Table 4). The historical range of precipitation received by and of evapotranspiration lost from the catchment is far greater than the annual groundwater use in the catchment (Figure 29), indicating that climatic variability has a far larger effect on groundwater resources in BTC than withdrawals from wells and induced recharge from septic systems. While this result argues against the effectiveness of using a whole catchment water balance that includes both natural and anthropogenic water inputs and outputs, there are some insights to be gained from the anthropogenic water balance.

The anthropogenic water balance estimated for BTC demonstrates the extent of artificial movement of water around the landscape. Water is moved by community water systems from catchment to catchment. The Bayleaf/Stonebridge system shown in Figure 12 consists of 60 CWS wells connected in a single system that crosses watershed boundaries. In the case of BTC, 60% of the water pumped from CWS wells is removed from the catchment and CWS pumping rates have increased every year from 2001 to 2007 (Figure 27). The water removed is equivalent to that used by 85.5 households, increasing the CWS water use for this catchment from 60 households to the equivalent of 145.7 households. The effect of CWS withdrawals and transfer out of the catchment is to nearly double the effective housing density of BTC, well beyond density estimates used by planners. The Welby (1983) housing density recommendations for this "risk level" area are 2 to 4 acres per household (Table 6). The effective housing density resulting from current CWS withdrawals is 1 acre per household. The real water use effect is actually greater than this. An estimated 85% of the water supplied to the 60 homes located within the catchment is returned to BTC through wastewater recharge, but the water supplied to the 85.5 homes located outside the catchment recharges other catchments and is 100% lost to BTC.

Table 6. Housing density. A comparison of actual housing density to the housing density effect of the CWS withdrawals and to Welby's (1983) recommendations.

	Households per km^2	**Households per acre**	**Lot size (km^2)**	**Lot size (acres)**
Actual housing density in BTC	113	0.46	0.009	2.2
Virtual housing density accommodated by CWS withdrawal	215.3	0.87	0.005	1.15
Welby (1983) recommendations	62 to 124	0.25 to 0.5	0.008 to 0.016	2 - 4

Another alteration in natural water movement due to anthropogenic water use is the elevation of discharge of deep groundwater. Under natural conditions, much of the deep groundwater flows down gradient through fractures and eventually discharges at some lower elevation, some within the same 12-digit watershed, and some farther away. Both private and CWS wells withdraw groundwater from depths of approximately 60 to 250 m below land surface (200 to 800 feet) (NC DEH, DWW; Wake County iMaps). Once this water is used by a household it either evaporates or is discharged to onsite septic systems just below land surface. This is not an easily measurable phenomenon, but potential consequences within the catchment itself are an increase in stream flow and/or a decrease in storage. There are no stream flow gages in the catchment, but an attempt was made to use water level data from a monitoring well at Gresham’s Landing in BTC to evaluate changes in groundwater storage (ΔS) over time. As seen in Figure 16, there have been considerable time gaps in the water level record, and the data is insufficient to estimate ΔS.

An interesting finding of this study is that during a site visit on Dec. 21, 2007, after several months of drought, there was water flowing in the streams mapped as intermittent streams by the USGS. It is possible that wastewater recharge around an intermittent stream could make that stream more of a perennial stream. From 2001 to 2007 there was no change in the number of households in BTC, so wastewater recharge was an almost constant input more dependant on human behavior than on climate. If wastewater recharge does help to maintain stream flow there may be water quality effects due to the chemistry of the water from this source (Burns et al, 2005; Heisig, 2000). Biological, ecological and water quality assessments of these streams may indicate the extent of wastewater recharge influence on stream flow. Stream degradation may result from either a decrease in natural flow or an increase in nutrients and other pollutants from septic systems.

The other two water balance components which are influenced by human water use are evapotranspiration due to human water use (ETi) and groundwater withdrawals by private residential wells. ETi (0.33 cm/yr) amounts to 0.5% or less of natural evapotranspiration (ETn, 67.0 cm/yr). Thus, while it does increase total evapotranspiration it is by such a small increment that the total water balance results in Table 4 do not take ETi into account. In order for ETi to be measurable in a whole catchment water balance, it would need to be greater than 5% of ETn, or ETi resulting from 950 homes. Groundwater withdrawals by private wells equal approximately 24% of that withdrawn by CWS wells. In the case of private wells, it is assumed that 85% recharges the BTC aquifer and the ETi loss from BTC due to houses with private wells is 0.078 cm/yr.

6 Conclusions

The objective of this research was to consider whether a watershed water balance can offer additional insights into groundwater use and potential overuse. The results demonstrate that while the natural water balance components overwhelm the anthropogenic inputs and outputs, the water balance of human water use does offer some useful insights. The quantification of the developed components of the system indicate that water is being moved around the landscape in unnatural ways. Through community water system engineering there is interbasin transfer of water at very local and possibly at much larger scales. Water is being transferred from low elevations to higher elevations as groundwater is removed from deep wells and discharged to onsite wastewater treatment systems just below land surface. The effect of CWS groundwater withdrawals is much greater than that of private residential wells in BTC, and the removal of water from BTC by community water systems increases the effective housing density in the catchment. Water recharging the aquifer from onsite wastewater treatment systems may be increasing stream flow during drought and may lead to changes in water chemistry and stream health.

This research was undertaken because of the interest of Wake County planners to develop a "risk" map identifying areas in the county at increased risk of groundwater overuse. Mapping relative water use may provide the methodology needed to do this. This would involve estimating the anthropogenic water balances of neighboring catchments and mapping their gains and losses due to CWS withdrawals. An important question remaining is the spatial scale at which the gains and losses are detectable. The scale used in this study was based on the locations of several private residential wells with a history of going dry during droughts, but this scale may be too fine to be practical. If too large a scale is used the effects would be blended and lost as was the case in the CDM (2003) study. Another consideration in developing a risk map is the manner in which community water systems withdraw, mix and distribute groundwater. As seen in Figure 12, a single system is not organized by watershed, thus groundwater is piped from and to distinct natural watersheds. The effect of this redistribution should be measurable by changes in groundwater storage and/or stream flow.

This study attempted to use a data source not previously considered for use in groundwater studies in Wake County. Monitoring wells at permitted facilities such as Gresham's Landing can be used to obtain water level data. In addition, every year private wells are abandoned for one reason or another, and those wells are filled in and made unusable. Both monitoring wells and abandoned wells could be fitted with automatic water level recorders, allowing for more consistent data records and broadening the water level monitoring network at relatively little expense. This data would be used to determine the change in groundwater storage (ΔS) with time. A better understanding of ΔS would improve prediction of ideal housing densities and the likelihood that a particular catchment is in danger of excessive groundwater use. This can be achieved either by increased water level monitoring or monitoring stream flow in smaller streams. A combination of automating the recording of water levels where suitable wells are available, and automated stream flow monitoring where they are not, would fill critical data gaps.

Recommendations

- Determine the ideal scale to use for mapping the relative water use between catchments.
- Planners should take into account effective housing density not physical housing density when permitting new housing and commercial development.
- Studies should be undertaken to determine the effect of onsite wastewater systems on stream flow, water chemistry and stream health in Piedmont catchments where mapped intermittent streams are becoming more perennial.
- Automate water level data recording in monitoring and abandoned wells to increase the density of the network of water level monitoring stations.
- Measure stream flow at more locations, especially in areas that have wells under stress and areas where effective housing density is greater than that recommended by county zoning rules and the Welby risk map (Welby, 1983).

References

Alley, W.M. and Leake, S.A., 2004. The Journey from Safe Yield to Sustainability. Ground Water. 42 (1): 12-16.

Alley, W.M., Reilly, T.E. and Franke, O.L., 1999. Sustainability of Ground-Water Resources, U.S. Geological Survey Circular 1186. 79 pages.

Bluman, A.G., 1992. Elementary Statistics: A step by step approach. Wm. C. Brown Publishers. 598 pages.

Boyles, S., Holder, C., and Raman, S., 2005. North Carolina Climate: A Summary of Climate Normals and Averages at 18 Agricultural Research Stations. NC Agricultural Research Service, College of Agriculture and Life Sciences, Technical Bulletin 322. 94 pages.

Bredehoeft, J.D., Papadopulos, S.S. and Cooper, H.H., Jr., 1982. Groundwater: The Water-Budget Myth. Studies in Geophysics. Scientific Basis of Water-Resource Management National Academy Press, Washington, DC. P 51-57.

Brown, P.M., Burt, E.R., Carpenter, P.A., Enos, R.M., Flynt, B.J., Gallagher, P.E., Hoffman, C.W., Merschat, C.E., and Wilson, W.F., 1985. Geologic Map of North Carolina. NC Department of Natural Resources and Community Development. Map.

Burns, D.A., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J., and Kendall, C., 2005. Effects of suburban development on runoff generation in the Croton River basin, New York, USA. Journal of Hydrology. 311: 266-281.

Cawthorne, J., 1970. Soil Survey of Wake County, North Carolina. US Department of Agriculture, Soil Conservation Service. 118 pages plus map plates.

CDM, 2003. Wake County: Comprehensive Groundwater Investigation, Final Report. http://online2.cdm.com/wakecgi/Final.htm. 147 pages.

Chang, H., 2007. Comparative streamflow characteristics in urbanizing basins in the Portland Metropolitan Area, Oregon, USA. Hydrological Processes. 21: 211-222.

Chapman, M.J., Bolich, R.E., Huffman, B.A., 2005. Hydrogeologic Setting, Ground-Water Flow, and Ground-Water Quality at the Lake Wheeler Road Research Station, 2001–03. US Geological Survey Scientific Investigations Report 2005–5166. 99 pages.

Cheng, S., Wang, R., 2002. An approach for evaluating the hydrological effects of urbanization and its application. Hydrological Processes. 16: 1403-1418.

City of Raleigh, 2008. City of Raleigh, Public Utilities Department. http://www.raleigh-nc.org/portal/server.pt/gateway/PTARGS_0_2_306_204_0_43/http%3B/pt03/DIG_Web_Content/dept/public/Dept-AboutUs-PubUtil.html

Clark, T.W., Blake, D.E., Stoddard, E.F., Carpenter, P.A., III, and Carpenter, R.H., 2004. Preliminary bedrock geologic map of the Raleigh 30' x 60' quadrangle, North Carolina. North Carolina Geological Survey Open-file Report 2004-02.

Colson, T.P., 2006. Stream Network Delineation From High-Resolution Digital Elevation Models. Dissertation, North Carolina State University. 241 pages.

Daniel, C.C., 1989. Statistical Analysis Relating Well Yield to Construction Practices and Siting of Wells in the Piedmont and Blue Ridge Provinces of North Carolina. U.S. Geological Survey Water-Supply Paper 2341-A. 27 pages.

Daniel, C.C., 1996. Ground-Water Recharge to the Regolith-Fractured Crystalline Rock Aquifer System, Orange County, North Carolina. USGS Water-Resources Investigation Report 96-4220. 59 pages..

Daniel, C.C., and Dahlen, P.R., 2002. Preliminary Hydrogeologic Assessment and Study Plan for a Regional Ground-Water Resource Investigation of the Blue Ridge and Piedmont Provinces of North Carolina. U.S. Geological Survey Water-Resources Investigations Report 02-4105. 60 pages.

Dano, K.E., 2002. Geochemical and Geophysical Determination of the Fate of Septic Tank Effluent in a Mountain Watershed, Colorado. Geological Society of America (GSA) 2002 Denver Annual Meeting (October 27-30, 2002).

Dingman, SL., 2002. Physical Hydrology, Second Edition. Prentice Hall, NJ. 646 pages.

Epperson, D.L., Johnson, G.L., Davis, J.M., and Robinson, P.J., 1988. Weather and Climate in North Carolina. Agricultural Extension Service, North Carolina State University. 48 pages..

FACE, 2008. Duke University Free-Air CO_2 Enrichment Experiment. http://face.env.duke.edu/main.cfm

Godfrey, J.E., 1978. Some Studies Relating Water Well Yields to the Geology and Geomorphology of the Triassic Basin in Wake, Chatham, and Durham Counties, North Carolina. Unpublished report submitted to the Wake County Health Department. 16 pages.

Goulden, M.L., Munger, J.W., Fan, S., Daube, B.C. and Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. Global Change Biology. 2: 169-182.

Gremillion, P., Gonyeau, A., and Wanielista, M., 2000. Application of alternative hydrograph separation models to detect changes in flow paths in a watershed undergoing urban development. Hydrological Processes. 14: 1485-1501.

Guilford County, 2007. Guilford County Well rules, Chapter 3 Section 5. Guilford County Board of Health. 46 pages.

Heisig, P.M., 2000. Effects of Residential and Agricultual Land Uses on the Chemical Quality of Baseflow of Small Streams in the roton Watershed, Southeastern New York. US Geological Survey Water-Resources Investigations Report 99-4173. 15 pages.

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., 2004. Estimated Use of Water in the United States in 2000. Reston, Va., U.S. Geological Survey Circular 1268. 46 pages.

Kalf, F.R.P., and Woolley, D.R., 2005. Applicability and methodology of determining sustainable yield in groundwater systems. Hydrogeology Journal. 13: 295-312.

Komatsu, H., 2005. Forest categorization according to dry-canopy evaporation rates in the growing season: comparison of the Priestley-Taylor coefficient values from various observation sites. Hydrological Processes. 19: 3873-3896.

Lindsay, J.B., 2003. Terrain Analysis System. The University of Manchester, UK. http://www.sed.manchester.ac.uk/geography/research/tas/

Maimone, M., 2004. Defining and Managing Sustainable Yield. Ground Water. 42 (6): 809-814.

May, V., and Thomas, J.D., 1968. Geology and Ground-Water Resources in the Raleigh Area, North Carolina. North Carolina Department of Water and Air Resources, Bulletin 15. 135 pages.

NCAC 18C, 2004. Rules Governing Public Water Systems – Subchapter 18C – Water Supplies. North Carolina Administrative Code, Title 15A. 295 pages.

NC CGIA. North Carolina Center for Geographic Information and Analysis, NC OneMap data distribution website. See GIS References for specific layer information. http://www.nconemap.com/.

NC CRONOS. North Carolina Climate Retrieval and Observations Network of the Southeast Database. State Climate Office. http://www.nc-climate.ncsu.edu/cronos/.

NC DEH, 2005. Public water supply water sources. NC Department of Environment and Natural Resources, Division of Environmental Health, Public Water Supply Section. GIS shapefile, see GIS References – CWS wells.

NC DEH, DWW. Drinking Water Watch. NC Department of Environment and Natural Resources, Division of Environmental Health, Public Water Supply Section. https://www.pwss.enr.state.nc.us/NCDWW/

NC FMP. North Carolina Floodplain Mapping Program. http://www.nccrimecontrol.org/Index2.cfm?a=000003,000010,000176

NC FMP, 2003. LIDAR and Digital Elevation Data. North Carolina Cooperating Technical State Flood Mapping Program. 6 pages.

NC FMP, 2002. LIDAR Accuracy Assessment Report – Wake County. North Carolina Cooperating Technical State Flood Mapping Program. 5 pages.

Oren, R., Hsieh, C., Stoy, P., Albertson, J., McCarthy, H.R., Harrell, P., and Katul, G.G., 2006. Estimating the uncertainty in annual net ecosystem carbon exchange: spatial variation in turbulent fluxes and sampling errors in eddy-covariance measurements. Global Change Biology. 12: 883-896.

Reilly, T.E., Dennehy K.F., Alley W.M., and Cunningham W.L. 2008. Ground-Water Availability in the United States. U.S. Geological Survey Circular 1323. 70 pages. http://pubs.usgs.gov/circ/1323/

Sherlock, M.D., McDonnell, J.J., Curry, D.S., and Zumbuhl, A.T., 2002. Physical controls on septic leachate movement in the vadose zone at the hillslope, Putnam County, NewYork, NY. Hydrological Processes. 16: 2559-2575.

Sophocleous, M., 2000. From safe yield to sustainable development of water resources – the Kansas experience. Journal of Hydrology. 235: 27-43.

Sophocleous, M., and Perkins, S.P., 1993. Calibrated models as management tools for stream-aquifer systems: the case of central Kansas, USA. Journal of Hydrology. 152: 31-56.

Stephenson, D., 1994. Comparison of the water balance for an undeveloped and a suburban catchment. Hydrological Sciences. 39(4): 295-307.

Stoy, P.C., Katul, G.G., Siqueira, M.B.S., Juang, J., Novick, K.A., McCarthy, H.R., Oishi, A.C., Uebelherr, J.M., Kim, H., and Oren, R., 2006. Separating the effects of climate and vegetation on evapotranspiration along a successional chronosequence in the southeastern US. Global Change Biology. 12: 2115-2135.

Stoy, P.C., Katul, G.G., Siqueira, M.B.S., Juang, J., Novick, K.A., McCarthy, H.R., Oishi, A.C., and Oren, R., 2008. Role of vegetation in determining carbon sequestration along ecological succession in the southeastern United States. Global Change Biology. 14: 1-19.

Tarboton, D., 2005. Terrain Analysis Using Digital Elevation Models in Hydrology. Utah State University. http://hydrology.neng.usu.edu/taudem/. 32 pages.

Taylor, J.R., 1997. An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements, 2nd ed. Sausalito, CA, University Science Books. 327 pages.

Terziotti, S., Schrader, T.P., and Treece, M.W., Jr., 1994. Estimated Water Use, by County, in North Carolina, 1990. US Geological Survey, Open-File Report 94-522. 102 pages.

Turner, R.D., 1992. Comprehensive Site Assessment: Gresham's Landing Facility. Turner Environmental Consultants, NC. 232 pages.

US Census Bureau, 1990. DP1. General Population and Housing Characteristics: 1990, North Carolina.
http://factfinder.census.gov/servlet/QTTable?_bm=n&_lang=en&qr_name=DEC_1990_STF1_DP1&ds_name=DEC_1990_STF1_&geo_id=04000US37

US Census Bureau, 2006a. State and County QuikFacts.
http://quickfacts.census.gov/qfd/states/37/37183.html

US Census Bureau, 2006b. American Community Survey, Wake County, NC. http://factfinder.census.gov/servlet/ACSSAFFFacts?_event=Search&_lang=en&_sse=on&geo_id=05000US37183&_county=Wake+County.

US EPA, 2008. Envirofacts information about Wake County, NC.
http://oaspub.epa.gov/enviro/ef_home3.html?p_zipcode=wake%2C+nc&p_type=county.

USDA, NRCS, 2004. Watershed Boundary Dataset. Water Information Coordination Program, Subcommittee on Spatial Water Data.
http://www.ncgc.nrcs.usda.gov/products/datasets/watershed/

USGS, 2008. Estimated Use of Water in the United States: County-Level Data for 2005 (draft).

USGS, NWIS. USGS Water Data for North Carolina, National Water Information Water System: Web Interface. http://waterdata.usgs.gov/nc/nwis/nwis

US Senate, 1996. Senate Committee Report on S.1316 Report 104 – 169: Section 24. Definitions. http://www.epa.gov/OGWDW/guide/sen104.html.

Wake County, 2007a. Population. http://www.wakegov.com/planning/demographic/dd_Population.htm.

Wake County, 2007b. Wake County Groundwater Sustainability Stakeholder Committee Report. http://www.wakegov.com/agendas/2007/august6/05%5Ccover.htm.

Wake County GIS: Mapping Services, Download data web page. See GIS References for specific layer information. http://www.wakegov.com/gis/gisdigitaldata.htm

Wake County iMaps. Wake County and the City of Raleigh's Online Mapping Service. http://imaps.co.wake.nc.us/imaps/

Weaver, C.J., 1998. Low-Flow Characteristics and Discharge Profiles for Selected Streams in the Neuse River Basin, North Carolina. US Geological Survey Water-Resources Investigation Report 98-4135. 101 pages.

Welby, C.W., 1983. Wake County Ground Water Study "Risk Level" Area. Department of Marine, Earth and Atmospheric Sciences, North Carolina State University. 20 pages.

Welby, C.W., 1984. Ground-Water Yields and Inventory for Land-Use Planning in Crystalline Rock Areas of Wake County, North Carolina. Water Resources Bulletin. 20(6): 875-882.

Welby, C.W. and T. M. Wilson., 1982. Use of Geologic and Water Yield Data from Ground Water Systems as a Guide for Ground Water Planning and Management. Water Resources Research Institute of the University of North Carolina Report No. 184. 110 pages.

GIS References

Category	data name	source	scale	Format
Climate - Precipitation and Evapo-transpiration	NC Climate Retrieval and Observations Network of the Southeast Database (NC CRONOS)	State Climate Office of North Carolina	Latitude and Longitude	shapefile
Framework - County Boundaries	cb100.shp	NC CGIA, NC OneMap, http://www.nconemap.com/Default.aspx?tabid=286	30 ft x 60 ft	shapefile
Framework - Rivers	hydromaj	NC CGIA, NC OneMap, http://www.nconemap.com/Default.aspx?tabid=286	1:100,000	shapefile
Framework - Roads - County	Streets.shp	Wake County GIS - http://lnweb02.co.wake.nc.us/gis/gismaps.nsf/WebGlobals!OpenView&ViewCat=shp	1:1200	shapefile
Framework - Roads - State	various - primary, secondary, county wide, state wide, more	NC Department of Transportation, GIS data, http://www.ncdot.org/it/gis/DataDistribution/DOTData/default.html		shapefile
Geology	Raleigh 100 K compiled geology (unpublished geodatabase)	NC Geological Survey	1:24,000	shapefile
Hydrogeology	hgmp500.shp	NC Center for Geographic Information and Analysis (CGIA), NC OneMap, http://www.nconemap.com/Home/tabid/262/Default.aspx		shapefile

GIS References (continued)

Category	data name	source	scale	Format
Land Class	parcel.shp	Wake County GIS - http://lnweb02.co.wake.nc.us/gis/gismaps.nsf/WebGlobals!OpenView&ViewCat=shp	1in = 100 ft	shapefile
Soils	soils.shp	Wake County GIS OR US Department of Agriculture, Natural Resource Conservation Service (USDA NRCS)	1in = 1320 ft	shapefile
Stream Discharge	usgsgages.shp	NC CGIA, NC OneMap, http://www.nconemap.com/Default.aspx?tabid=286		shapefile
Stream Discharge - Low Flow Partial Record sites		US Geological Survey, National Water Information System (NWIS), http://waterdata.usgs.gov/nc/nwis/inventory	latitudes and longitudes	
Watershed delineation	Watershed Boundary Dataset (unpublished)	USDA NRCS	1:24,000	shapefile
Watershed delineation	Lidar elevation data	NC Floodplain Mapping Program, http://www.ncfloodmaps.com/default_swf.asp	20 ft x 20 ft	raster
Wells - CWS users		Wake County Groundwater Information Management System (GIMS) http://imaps.co.wake.nc.us/gims_int/default.htm		match to parcel layer
Wells - CWS wells	pwsws.shp	NC DENR, Division of Environmental Health (DEH)	latitudes and longitudes	shapefile

GIS References (continued)

Category	**data name**	**source**	**scale**	**Format**
Stream Discharge - Low Flow Partial Record sites		US Geological Survey, National Water Information System (NWIS), http://waterdata.usgs.gov/nc/nwis/inventory	latitudes and longitudes	
Watershed delineation	Watershed Boundary Dataset (unpublished)	USDA NRCS	1:24,000	shapefile
Watershed delineation	Lidar elevation data	NC Floodplain Mapping Program, http://www.ncfloodmaps.com/default_swf.asp	20 ft x 20 ft	raster
Wells - CWS users		Wake County Groundwater Information Management System (GIMS) http://imaps.co.wake.nc.us/gims_int/default.htm		match to parcel layer
Wells - CWS wells	pwsws.shp	NC DENR, Division of Environmental Health (DEH)	latitudes and longitudes	shapefile
Wells - private wells		Wake County Groundwater Information Management System (GIMS) http://imaps.co.wake.nc.us/gims_int/default.htm		match to parcel layer