EVENT-DRIVEN SEDIMENT TRANSPORT IN A HIGHLY RESPONSIVE LOWLAND RIVER AS INFLUENCED BY CLIMATE AND LAND-USE CHANGE, HAW RIVER, NORTH CAROLINA, USA

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ABSTRACT

SPENCER SAMUEL PERKINS: Event-driven sediment transport in a highly responsive lowland river as influenced by climate and land-use change,
Haw River, North Carolina, USA
(Under the direction of Brent A. McKee)

Anthropogenic activities have dramatically altered river systems from their natural state. Not only has population growth enhanced the magnitude of human impacts such as contaminants, it has also led to an increasingly direct link between a river and its basin. Land-use change has increased available material by mobilizing large quantities of sediment, while impervious surfaces and storm drains have intensified discharge events by more efficiently directed runoff to stream channels. In central North Carolina, the hydrologic response to precipitation events has intensified 22-91 percent. Yet, this change is shown to have occurred during a period when precipitation and temperature remain normal compared to historical baselines.

Sediment is an efficient vehicle for transporting contaminants, which are known to decouple and become bioavailable upon deposition in these reservoirs. This is particularly problematic because of the increasing number of reservoirs built along rivers and utilized for drinking water. Sixty-one suspended sediment samples were collected between April 2008 and June 2010 in the Haw River, a lowland river located in a high-population growth area of the Piedmont of North Carolina. Radioisotope measurements identify excess sediment from human impacts (construction) present primarily during peak discharge of a hydrologic event. Such human impacts have implications not only for ecosystems and public health but also for

the utilization of radioisotopes to elucidate sediment transport. While there is a global focus on climate change, this study illustrates how land-use change is already having significant consequences that will only be exacerbated by the intensified hydrologic cycle predicted to result from global warming.

ACKNOWLEDGEMENTS

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Thank you to my other committee members, Dr. Tony Rodriguez and Dr. Larry Band, for your input and perspectives, which helped give this research the breadth it needed to accurately tell the whole story and in a manner capable of comprehension across all fields.

Pulling up all that water from the Bynum Bridge and spending the hours processing it, my arms would have completely fallen off were it not for the help of those in the McKee lab, especially Sherif Ghobrial, John Biddle, Rebecca Reese, Kristen Jarman, Cameron Houser, Grainne O'Grady and the other graduate students in the department.

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1. INTRODUCTION

As global population has increased in recent centuries, rivers have responded dramatically to the combination of increasing human and climate pressures (Leopold 1973; Trimble 1974; Vorosmarty et al., 2003). Climate change is expected to impact river discharge by altering the timing and magnitude of precipitation (Arora and Boer, 2001; Milly et al., 2005). Human impacts and pressures alter river content as well as discharge timing, magnitude and routing. These human impacts can come in the form of urban development, manufacturing, and engineering for diversions and reservoirs (Walling 2006; Vorosmarty et al., 2003). Lands adjacent to rivers are highly populated and extensively utilized because of the ecosystem services that rivers provide (i.e., freshwater, hydropower, transportation) (Small and Cohen, 2004). Such proximity has made direct human impact inescapable.

The research community has focused extensively on climate change as a driver of river system alterations (Nijssen et al., 2001; Palmer et al,. 2008; Trenbeth 2011). However, human impacts and their importance relative to climate change should also be considered in evaluating past, present and future river alterations, particularly in order to better allocate efforts to mitigate impacts. The study presented here examines the evolving impact of human activities and climate change on water and sediment discharge in a lowland river in North Carolina (Haw River; Figure 1).

FIGURE 1. Haw River basin and local counties. Source: Elon University

Primary questions are:

- What are the ages/sources of sediment being transported in the Haw River?
- What are the relative influences of direct human impacts and climate change on the hydrology and sediment discharge for the Haw River?
- Can radioisotopes be used to evaluate basin-scale sediment ages/sources during transport events? How useful is the $^{7}Be/^{210}Pb_{xs}$ ratio?

Milliman and Syvitski (1992) define lowland rivers as having maximum elevations between 100 and 500 meters. The research presented here incorporates river samples collected at a site just above a major reservoir, as well as current and historic gauge data from the United States Geological Survey (USGS) and data from the U.S. Census Bureau and other government agencies on population growth – and potential for human impact.

River geomorphology, hydrology, biogeochemistry and water quality are all sensitive to both human and climate pressures. Modern river geomorphology in the eastern United States strongly reflects the impact of human activity, especially land-use changes. In the 18th and 19th centuries, tilling and poor erosion control from agriculture associated with European settlement completely changed the nature of sediment transport in river systems, ultimately also affecting basic hydrology and biogeochemistry (Leopold 1973; Trimble 1974; Walter and Merritts, 2008). Today, the introduction of contaminants – including excess sediment loading (‘excess’ being the result of human activity), nutrients and synthetic chemicals – into this already transformed system has significant biogeochemical and water quality consequences. In addition to sourcing, contaminant transport and fate is something further impacted by humans through river engineering (i.e., dams, reservoirs) or by climate change through enhanced/depleted precipitation patterns. Understanding these processes and what controls them has strong water quality implications, both for river ecosystems as well as for humans withdrawing water from the system for drinking, irrigation or manufacturing.

Mountainous rivers, especially along active margins, have garnered research attention as sediment sources, the initial chemical weathering of which also removes atmospheric carbon dioxide (Milliman and Syvitski 1992; France-Lanord and Derry 1997; Syvitski and Milliman 2007). Coastal plain rivers have also been a longtime research focus, where the emphasis has primarily been given to processes in the estuarine portion of these systems. Consistently neglected are the intermediate lowland rivers, which are critical zones of transition and human impact. In the eastern United States, this region is known as the Piedmont (translated literally as 'at the foot of the mountains'). This Piedmont region links steep-sloping, fast-moving, small mountainous streams and flat, slow-moving, wide coastal plain rivers. One reason early European settlement in the Piedmont was extensive was because of the stream power of the rivers within the region.

Stream power (Ω) is the rate at which a stream can do work and is equal to $Q * \rho * S$, where:

Q = water discharge;
ρ = water density; and
S = channel slope.

The addition of waters from tributaries results in water discharge (Q) increasing with distance downriver toward the ocean.

While mountainous rivers have more elevation change (larger S) and faster-moving water, stream cross-sectional area and Q are relatively small and therefore so is stream power. In the coastal plain, where water discharge is greater (larger Q), the lack of elevation change (smaller S) limits stream power and the river's capacity to carry sediment. Piedmont rivers, with their combination of slope and water discharge, can readily provide stream power for mills or turbines. This enhanced stream power is also very important for driving sediment transport.

Downriver portions (the coastal plain) of lowland rivers are typically the focus of research. However, lowland rivers are not uniform in any sense from origin to terminus, and the variation in slope is a prime example. Hydrology in particular will vary with slope, and the stream power dictated by slope will influence all other processes associated with the river. As an example, the elevation change within the Haw River (the Piedmont region of the Cape Fear) facilitates the focusing and rapid delivery of water that contributes to flash floods typical to the region (Figure 2). In this Piedmont portion of the lowland river – almost half the total river distance – the slope changes 1.38 m/km.   In the coastal plain, elevation only changes 0.07 m/km. For the entire Cape Fear River basin, this means 94 percent of the elevation change occurs within the first 44 percent of the river.

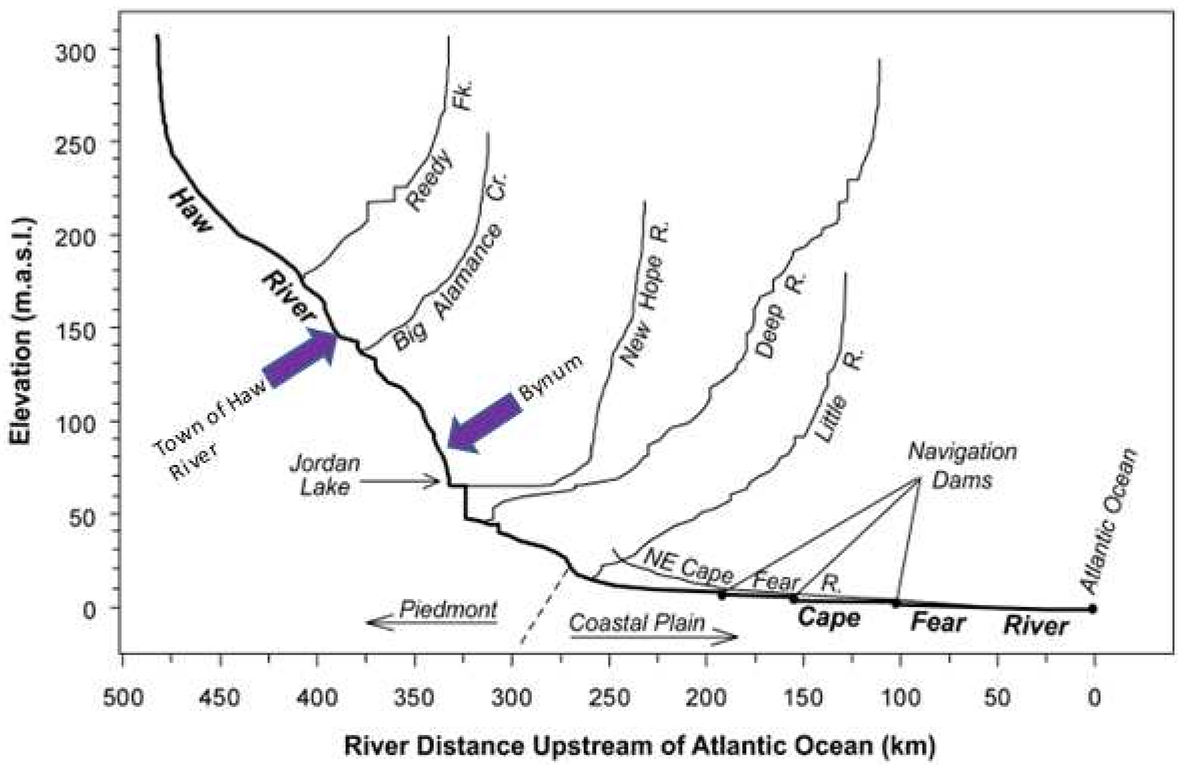


FIGURE 2. Elevation change in the Haw River and Cape Fear River. Modified from Benedetti et al. (2006).

Hydrographs rise and fall sharply compared to downriver sites in the coastal plain (Figure 3). Given the combination of relief and channelized water, the Haw River can respond quickly to precipitation events, at Bynum increasing as much as 10,000 cfs in one hour during rising-limb periods during this study. Because of this rapid response, Piedmont rivers have earned a reputation of being ‘flashy’ or responding quickly to rainfall events (Figure 4).

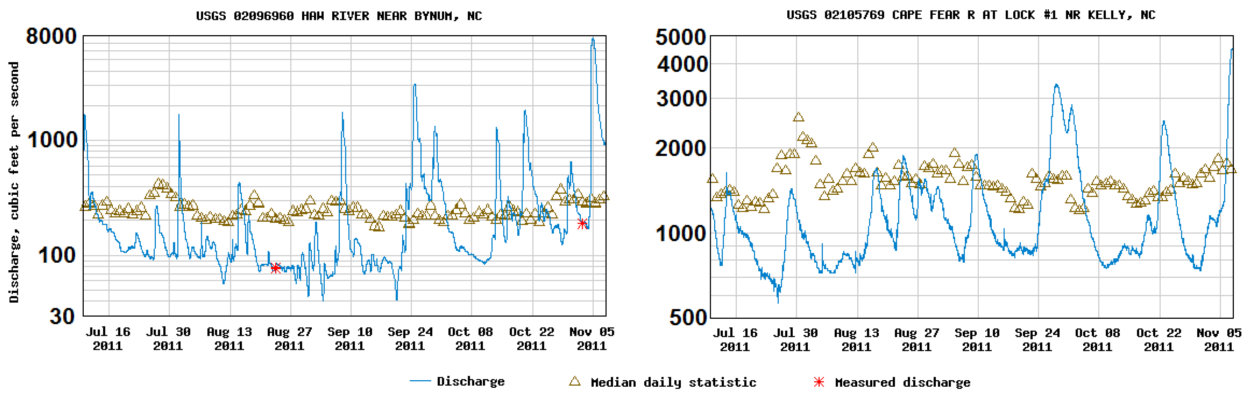


FIGURE 3. A hydrograph for the Haw River near Bynum (left) and hydrograph over the same time period for the Cape Fear River just prior to its terminus at the Atlantic Ocean (right). Note that the sharper, narrower hydrographs for the Haw River. Despite the Cape Fear hydrograph being located at a site draining a majority of the overall basin, peak discharge for precipitation events are very similar for the two, emphasizing the relatively 'flashy' nature of the Piedmont portion (Haw River) of the Cape Fear River.

FIGURE 4. Looking upriver from Bynum Bridge. At left, the Haw River on 8/13/2008 at typical, low summer discharge (86 cubic feet per second) and turbidity (5.81 mg/L). At right, the river during a major discharge event two weeks later (8/28/2008; discharge and turbidity measured 28,500 cfs and 288.36 mg/L).

Large volumes of fast-moving water have the power to exert significant shear stress and at the same time the capacity to carry a larger load of sediment and other mobile material.

In addition to sediment (itself classified by the EPA as a contaminant), many important elements and chemicals have been documented to be transported primarily in the particulate phase (Shuman et al., 1978; Mayer et al., 1998; Meybeck 1982; Seitzinger et al., 2005). This makes sediment a valuable, more easily-measured proxy for determining the presence and transport of other contaminants important in studying water quality. As major reservoirs are constructed to collect and supply drinking water for surrounding municipalities, this becomes of concern. If sediment is transported to reservoirs and concentrated there with extreme efficiency (Vorosmarty et al., 2003), then, as previous studies indicate, the same can be said for contaminants. Within these storage reservoirs, contaminants can become decoupled from the particulate phase and become more bioavailable (Mayer et al., 1998; Meybeck, 1982; Seitzinger et al., 2005). Both sediment and its associated contaminants have considerable biological and biogeochemical consequences. Deposition stemming from high sediment loads is capable of burying and suffocating benthic life, exacerbating the water's already impacted biogeochemistry.

Human development has also increased the connectivity of point contaminant sources to rivers and reservoirs by means of impervious surfaces and drainage systems that efficiently focus runoff and associated contaminants (Arnold and Gibbons, 1996; Paul and Meyer, 2001). Typically, the materials transported by rivers have numerous stages of storage and subsequent transformation prior to arriving at the river's terminus (Stallard 1998; Allen 2008). Changes in the residence time of particulates within storage reservoirs downriver can have major implications regarding the quantity and character of what is transported to the ocean (Blair et al., 2004). In essence, human activities throughout the river basin directly impact what is stored in alluvial deposits such as reservoirs and what is exported to the ocean.

Furthermore, the increased presence of impervious surfaces within a watershed usually facilitates more direct and rapid delivery of runoff to the river, which results in a larger peak discharge and carrying capacity. This, combined with storm drainage systems, greatly reduces groundwater recharge and the gradual release of water into a river channel via subsurface flow (Arnold et al., 1996). More water is able to quickly reach the river channel. Material transport becomes much more efficient and less prone to depositing particles out of suspension. The quantity of transported material also increases with the addition of excess sediment provided by urban development and poor erosion controls (Wolman and Schick, 1967; Leopold 1973).

Changes to river transport dynamics has typically been considered in terms of climate change, specifically focusing on the key source of water to rivers – precipitation events and their magnitude and frequency (Arora and Boer, 2001). Multiple current trends indicate the beginnings of increased global climate change that became identifiable in the 20^{th} century. The past decade produced 10 of the 11 warmest years on record (National Climatic Data Center). Such a temperature change is purported to intensify the global hydrologic cycle, though there will be regional variability in the effects (Labat et al., 2004). Global climate cycles such as the El Niño Southern Oscillation (ENSO) have been credited to be key drivers of global precipitation, temperature and overall weather patterns (New et al., 2001).

2. BACKGROUND

2.1 Previous Research

2.1.1 River Systems and Processes

River research has long focused on understanding sediment flux and its influences. With increased accuracy and spatial distribution of datasets, natural river systems and their processes have been increasingly considered on a global scale (Milliman and Meade 1983; Milliman and Syvitski 1992; Syvitski 2005; Syvitski and Milliman 2007). The relative importance of certain types of rivers to sediment flux has long been debated. Beginning with Milliman and Meade (1983), studies primarily focused on rivers with the greatest discharge in order to describe sediment flux on a global scale. A decade later, Milliman and Syvitski (1992) emphasized the important role of small mountainous rivers in global sediment discharge to the ocean. In constraining how much sediment reaches ocean, both studies emphasized the importance of considering numerous natural factors such as basin area, geomorphology, tectonics, lithology, climate and runoff.

However, in attempting to improve models and estimates since then, researchers have also had to increasingly consider the role human influences on river systems. The processes of many systems – once believed to be operating naturally and in stationarity – could not be accurately and precisely constrained without additional factors. Mulder and Syvitski (1996) revisited the data of Milliman and Syvitski (1992), improving correlations by removing river systems deemed to have been heavily impacted by humans. Other research has also demonstrated difficulty explaining, predicting and constraining natural trends on multiple spatial and temporal scales. It is therefore important to consider human influences and acknowledge the immense variability they can cause, as we improve our understanding of rivers and explain outliers in data sets (Vorosmarty et al. 2003; Syvitski et al. 2005; de Vente et al. 2007; Syvitski and Milliman 2007; Milliman 2008).

Agriculture has long been considered an important human impact on erosion. American agricultural practices of the mid-Atlantic and Southeastern U.S. through the late 19^{th} and early 20^{th} centuries mobilized immense quantities of sediment, which resulted in floodplain deposits (meters in thickness) that are still present today and are identified as 'legacy' sediments. Trimble (1974) documented the evolution of erosive land use between 1700 and 1970, focusing especially on the 19^{th} century agriculture that mobilized the sediment that would become the legacy layer. This research revealed a rapid increase in agriculture in the late 18^{th} century, followed by a period of intensive land erosion between 1860 and 1920 as cotton, tobacco and mixed-use agriculture was at its peak in the Southeast. While this study primarily used historic land-use and agricultural records, it also looked at some effects of the high sediment loads of the period, noting rapid accretion over floodplains and especially behind dams. Walter and Merritts (2008) studied this legacy sediment layer throughout the mid-Atlantic Piedmont, sampling legacy sediment layer thickness at numerous sites. They stimulated much discussion on the issue, asserting that their findings "show that most floodplains along mid-Atlantic streams are actually fill terraces, and historically incised channels are not natural archetypes for meandering streams."

Significant human impacts on sediment processes generally occur within a relatively small spatial footprint compared to basin area. Thus, in-depth research on the subject has occurred primarily on local and regional levels. Some of the earliest investigations on human impacts focused on rivers in the mid-Atlantic U.S. (Wolman and Schick 1967; Leopold 1968; Leopold 1973; Walter and Merritts 2008). Impervious surfaces and storm drainage quickly concentrate runoff in stream and river channels, impeding runoff loss via seepage into soils (groundwater recharge) and evapotranspiration. This results in larger, more frequent flood events, which are capable of transporting more sediment (Leopold 1973; Hollis 1974; Colosimo and Wilcock 2007). Impervious surfaces also cause 'flash' floods to become more intense, as has been demonstrated by a decreased lag time between precipitation and peak discharge (Leopold 1968; Leopold 1991).

While improved tilling and erosion control have (in concert with overall agricultural decline) reduced soil loss, construction has proven to be an even more powerful driver of erosion. During the initial phases of construction, local erosion rates can increase as much as 40,000 times over pre-disturbance erosion rates; at mid-Atlantic sites, basin sediment yield increased 45-300 times over background (Leopold 1968; Chin 2006; Colosimo and Wilcock 2007), with much of the variation depending on the magnitude and progression of development. Wolman and Schick (1967) calculated sediment yield to increase 700-1,800 tons per 1,000 increase in population.

What happens to this sediment is one of the modern challenges to calculating sediment budgets. Syvitski et al. (2005) estimate large rates of modern soil erosion and at the same time decreasing sediment flux to coastal zones due to dams. Large dams have been increasingly installed to provide hydropower, freshwater for human use, flood control and irrigation. The reservoirs behind dams are extremely efficient at trapping particles by slowing water flow and causing them to fall out of suspension. Vorosmarty et al. (2003) estimates that as much as 30 percent of global sediment flux is intercepted by registered reservoirs. This estimate may be a conservative one since the number of small, unregistered impoundments is not well-constrained (Downing et al., 2006).

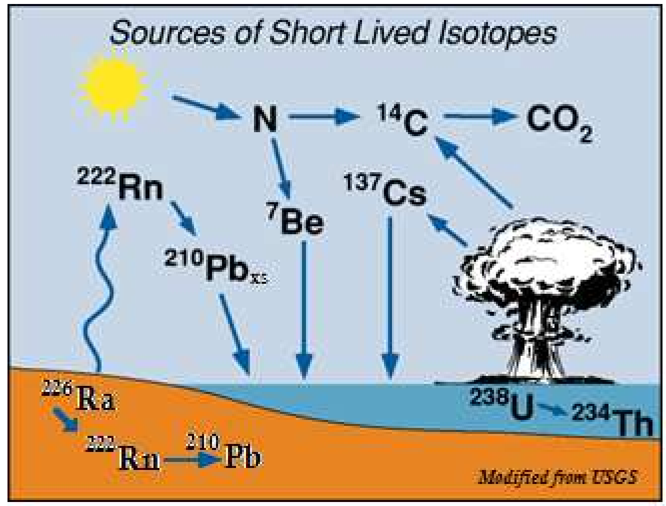
Sediment not intercepted by dams can deposit on floodplains when discharge overbanks. Excess sediment loading and deposition can also cause significant aggradation in and around the river channel. This has serious consequences for river ecosystems. High sediment concentrations can inhibit respiration, block sunlight critical for photosynthesis, deliver excess contaminants (i.e., nutrients, pollutants) associated especially with urban-sourced sediment, and even bury flora and fauna (Wolman and Schick 1967; Morse et al. 2003; Wheeler et al. 2005; Cianfarni et al. 2007). In fact, this sediment deposition can happen to such an extent that it entirely changes the geomorphology of the river (Walter and Merritts, 2008).

In research that was applied directly to the Haw River basin, Phillips (1991) documented sediment source, transport and fate dynamics in central and eastern North Carolina rivers. Using the Universal Soil Loss Equation and surveys from the 1970s and 1980s, this study calculated erosion, stream supply and yield figures for sediment. It concluded that approximately two-thirds of sediment supplied to streams was stored as alluvium. It also noted that these "rivers are transport-limited and aggrading, in that more sediment is supplied to the stream by upland or channel erosion than the river system is capable of transporting."

Benedetti (2006) analyzed alluvium throughout the entire Cape Fear River basin using similar approaches and methods (soil surveys, field inspection of deposited samples, mineralogy), and also include data from previous work that was performed in the early 1990s and earlier. In agreement with previous studies, it concluded "little Piedmont-derived material reaches coastal waters because of deposition and dilution by coastal plain material."

2.1.2 Radioisotope Tracers (Radiotracers)

Certain radioisotopes with known source and deposition cycles can be utilized to fingerprint and track particles. ^{7}Be and ^{210}Pb are two naturally occurring radioisotopes that can potentially be used to determine the age (since previous exposure to the atmosphere) and source of sediment. ^{7}Be is the product of constant cosmic ray spallation in the upper atmosphere and has a short half-life (53.3 days). It reaches the Earth's surface through wet fallout. On land, it rapidly sorbs onto soil particles and is generally found only in surface soils. ^{210}Pb, a product in the ^{238}U decay series, has a longer half-life (22.3 years) and is also delivered via wet fallout, although it has a more complicated pathway than ^{7}Be. Because of its significantly longer half-life, ^{210}Pb is typically found deeper in soil profiles than ^{7}Be (more surficial soils presumable having been more recently exposed to the atmosphere).



^{238}U and its daughter products undergo alpha and beta decays within the Earth's crust until producing ^{226}Ra (solid phase), which decays to form the noble gas ^{222}Rn, some of which escapes to the atmosphere, where it decays (3.83-day half-life) along with subsequent short-lived daughter radioisotopes to produce ^{210}Pb. Atmospheric ^{210}Pb is then also introduced to surface soils and sediments via wet fallout.

Like ^{7}Be, ^{210}Pb is rapidly sorbed onto particle surfaces. Particles also contain ^{210}Pb that is supported by ^{226}Ra decay in their mineral lattice. Excess ^{210}Pb (^{210}Pb$_{xs}$) is calculated by subtracting the ^{226}Ra supported background ^{210}Pb activity from the total ^{210}Pb activity of the particle. The individual activities of both ^{7}Be and $^{210}Pb_{xs}$ in wet fallout can vary spatially and temporally, but their ratio to one another as delivered in wet fallout remains relatively constant for a locale. Because ^{7}Be decays much more rapidly than ^{210}Pb, the ^{7}Be /$^{210}Pb_{xs}$ ratio on particulates will decrease with time, once the particles are no longer directly connected to the atmospheric radionuclide source. For example, one year after a sediment particle is tagged with both radioisotopes, ^{7}Be will have decayed through seven half-lives, leaving less than one percent of the initial ^{7}Be activity on the particle, while $^{210}Pb_{xs}$ will remain practically unchanged.

The ^{7}Be /$^{210}Pb_{xs}$ ratio has been used for "sediment fingerprinting" during the past decade. Matisoff et al. (2005) proposed using the ^{7}Be /$^{210}Pb_{xs}$ ratio to directly quantify sediment age one of two ways. Let

$$
\begin{aligned}
A &= (^{7}\mathrm{Be})_{\mathrm{sample}} \\
A_o &= (^{7}\mathrm{Be})_{\mathrm{source}} \\
B &= (^{210}\mathrm{Pb}_{\mathrm{xs}})_{\mathrm{sample}} \\
B_o &= (^{210}\mathrm{Pb}_{\mathrm{xs}})_{\mathrm{source}}
\end{aligned}
$$

If the value of the individual radioisotopes (and thus the ratio) in precipitation is known, the activity in the precipitation represents the source. Sediment sample activities and the ^{7}Be/$^{210}Pb_{xs}$ ratio are given by

$$
\begin{aligned}
A &= A_o\, \mathrm{e}^{-(\lambda_{^{7}\mathrm{Be}} t)} \\
B &= B_o\, \mathrm{e}^{-(\lambda_{^{210}\mathrm{Pb}} t)}
\end{aligned}
\qquad\qquad
\frac{A}{B} = \frac{A_o}{B_o}\, \mathrm{e}^{-(\lambda_{^{7}\mathrm{Be}} - \lambda_{^{210}\mathrm{Pb}})t}
$$

The decay constants are 0.01300 d^{-1} for ^{7}Be and 8.50999 x 10^{-5} d^{-1} for ^{210}Pb. Sediment age (the time since the particles were last tagged by the tracer) is therefore

$$
t = \frac{-1}{(\lambda_{^{7}\mathrm{Be}} - \lambda_{^{210}\mathrm{Pb}})} \ln\left(\frac{A}{B}\right) + \frac{1}{(\lambda_{^{7}\mathrm{Be}} - \lambda_{^{210}\mathrm{Pb}})} \ln\left(\frac{A_o}{B_o}\right)
$$

However, there are complications in making definitive conclusions based solely on the ratio. Initial activities (source material) must be known, and assumptions are required that: (a) radioactive decay is the only factor that changes the ratio of a source material; and (b) the sediment source is from the upper part of soil profiles still in contact with atmospheric inputs. To account for mixing of sediment containing both radioisotopes with ^{7}Be-dead sediment, two methods are presented for calculating percent 'new' sediment, though each still requires initial activities:

$$\% \text{ 'new' sediment} = 100 \times \exp\left[-(\lambda_{^{7}\mathrm{Be}} - \lambda_{^{210}\mathrm{Pb}})t\right] \qquad \% \text{ 'new' sediment} = 100 \times (A/B)/(A_o/B_o)$$

When tracking the ^{7}Be /^{210}Pb$_{xs}$ ratio and its variation, Matisoff et al. (2005) acknowledges that two scenarios exist for a given ratio and its measured change.

"…decreases in the ^{7}Be/^{210}Pb$_{xs}$ ratio in suspended sediments can be caused by two end- member scenarios. First, the decrease in the ^{7}Be /^{210}Pb$_{xs}$ ratio may reflect an increase in the time since the sediment was tagged with atmospherically derived ^{7}Be and ^{210}Pb$_{xs}$ since ^{7}Be decays faster than ^{210}Pb$_{xs}$. Alternatively, a decrease in this ratio can be caused by dilution of ^{7}Be -rich sediment with ^{7}Be -deficient (but not ^{210}Pb$_{xs}$-dead) sediment."

2.2 Objectives and Approach

Given its history and population growth, North Carolina – especially the Piedmont – is a perfect study site for comparing and contrasting both human and climate environmental stressors. The overall objective of this research is to examine how the Haw River has responded (and continues to respond) to human impacts and climate change.

In determining exactly how and to what extent humans have impacted river response, the specific activities relevant to runoff must be considered. Population data provide a quantitative assessment of growth within the area and the corresponding increase in human pressure. Lane-mile data (not just miles of road but miles of individual lanes) directly quantifies impervious surface area, and while it does not encompass all impervious surfaces, its increase is nonetheless an indicator of the increase of other impervious surfaces.

Current and historical hydrologic data, some records going back as much a century, provide valuable information about events that occur during the period of observations as well as a means to compare present events with those that occurred decades before. In conjunction with discharge data, precipitation data is useful to document decadal-scale changes in climate.

As explained above, sediment from different sources and with different histories may have different radioisotope signatures, making radiotracers valuable tools for determining sediment source. However, radiotracer data must be considered in the context of both natural processes and human activity. Temporal variations in radiotracer values should also be determined (on time scales ranging from hourly to decadal) when examining a river's response to historic, seasonal and event-scale changes.

2.3 Study Area

2.3.1 Land Description

The Piedmont is a physiographic province in the eastern United States located between the base of the Appalachian Mountains and the fall line, which defines the beginning of the coastal plain.

Several large and rapidly growing metropolitan areas – from Atlanta, Georgia, to Washington, D.C. – are located within this region. In the North Carolina Piedmont, this includes areas known as The Triangle (Raleigh, Durham and Chapel Hill), The Triad (Greensboro, Winston-Salem and High Point) and Metrolina (Charlotte area), all of which have experienced some of the nation's most significant growth in during the past two decades.

The Haw River, located in central North Carolina, has a basin size of 4,217 km^2. Together with its similar-sized neighbor, the Deep River, it comprises the Piedmont portion of the Cape Fear River basin (Figure 5), which has no mountainous origin, unlike other large river systems on the eastern seaboard. The Haw River begins in Forsyth County, arching north and east toward the North Carolina-Virginia border before continuing southeast through central North Carolina to Jordan Lake, which is a reservoir behind an earthen dam completed and filled in the early 1980s.

A few kilometers below exiting Jordan Lake, the Haw River merges with the Deep River to form the Cape Fear River. Many rapidly-growing municipalities, including Greensboro, Durham, Chapel Hill, Burlington and Pittsboro, are located within the Haw River basin.

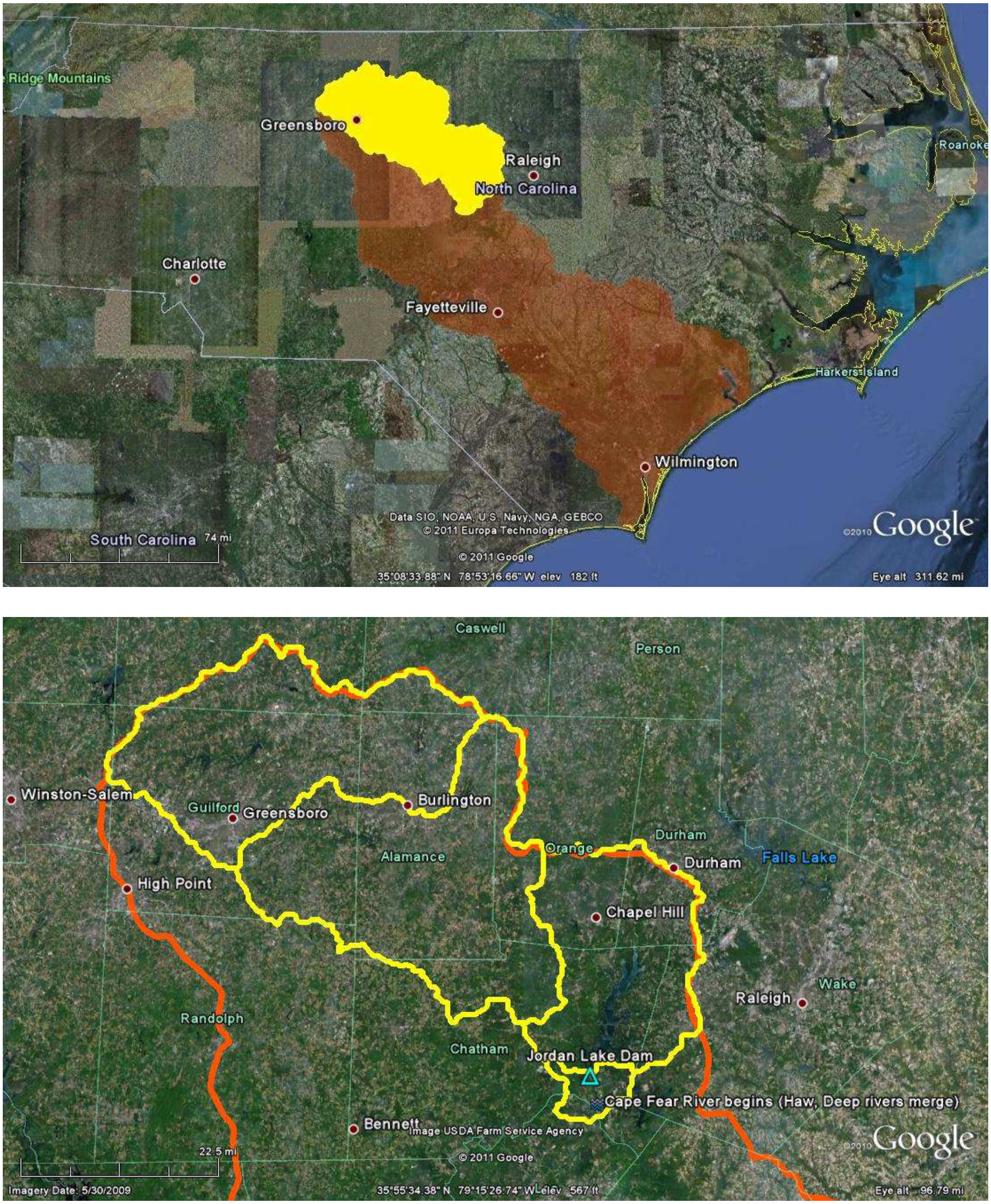


FIGURE 5. The Haw River basin is located in the northern portion of the Cape Fear River basin. It comprises approximately half of the Piedmont portion of the CFRB and contains multiple cities, such as Greensboro, Chapel Hill, Durham and Burlington.

2.3.2 Early History and Legacy Sediment

The geomorphology along much of the eastern United States has been immensely transformed over the past four centuries. Prior to European settlement, Sissipihaw Indians inhabited the Haw River basin. European settlers arrived in the 17th century and settlements flourished in the 18th and 19th centuries. This temperate area was ideal for agriculture, including corn, cotton and tobacco, which were important staples both for sustaining colonies as well as exporting for profit (Trimble 1974). Thus, agriculture was extensive, but so too were its consequences. Modern tilling practices and erosion control measures generally preserve soil within an agricultural area. But in early America, farmers simply tilled the land, churning and breaking up soil to soften it for successful agriculture. Breaking up soil – especially the fine, compacted, cohesive clay particles of the Piedmont – renders it easily mobile. Farming practices in colonial times also resulted in highly weathered soils such that ultimately, during precipitation events, this sediment was transported into water channels in concentrations much higher than those prior to European settlement (Trimble 1974). As a result, sediment deposited in river and stream channels and floodplains, quickly accreting over the course of a couple of generations (Walter and Merritts, 2008).

This accretion was meters thick in some areas. As a result, rivers had to re-incise through channels filled in with sediment until bedrock – resistant to erosion – was reached. The end result was – and remains to this day – a 'legacy' sediment layer that resulted in channels with much higher banks. One consequence is that these river channels are much less frequently overbanked. This legacy layer is visible in the exposed banks of many Piedmont river and stream channels. Most of the bank from the top down will be a lighter, reddish color indicative of nutrient-poor red clay. Below this, if visible, will be a darker (black/gray), thinner layer, which is the organic-rich soil. The boundary between the two represents the pre-settlement surface prior to the deposition of legacy sediments.

2.3.3 Dams

Settlers also constructed numerous mill dams throughout the basin, especially in the 19th and 20th centuries. The back-up effect from dams decreases water velocity, diminishing its carrying capacity and causing suspended sediment to settle out, creating a sediment trap for as far as a dam's back-up effect extends. Only a few major dams remain intact on the Haw River. These are (in order from upriver to downriver): Saxapahaw dam, first constructed in 1782 and in its current 30-foot high, concrete form since 1938; Bynum dam, a 10-foot concrete dam built in its current form around the beginning of the 20th century; and Jordan Lake dam, an earthen dam with a 50-60-foot head completed for flood control and recreation (though also now used for drinking water) in 1982 (U.S. Army Corps of Engineers).

The Bynum dam site (Figure 6) is the focus of sample collection for this study as the dam is the final structure before the Haw River flows into Jordan Lake. The primary sampling site for this study is a pedestrian bridge 0.5 kilometers downriver from the Bynum dam. At this site, the river is 150 meters wide. This is considerably narrower than the river's width at the dam, which is 300 meters. Less than 2.0 kilometers upriver from the dam, beyond influence of the backed up water behind the dam, the river width is 50 meters. The back-up effect from Jordan Lake and its dam begins approximately 6.0 kilometers downriver from the sampling site. From there upriver to Bynum, considerably more bedrock is exposed than is typically visible upriver from Bynum, and the width of the river varies, roughly between 60 and 200 meters.

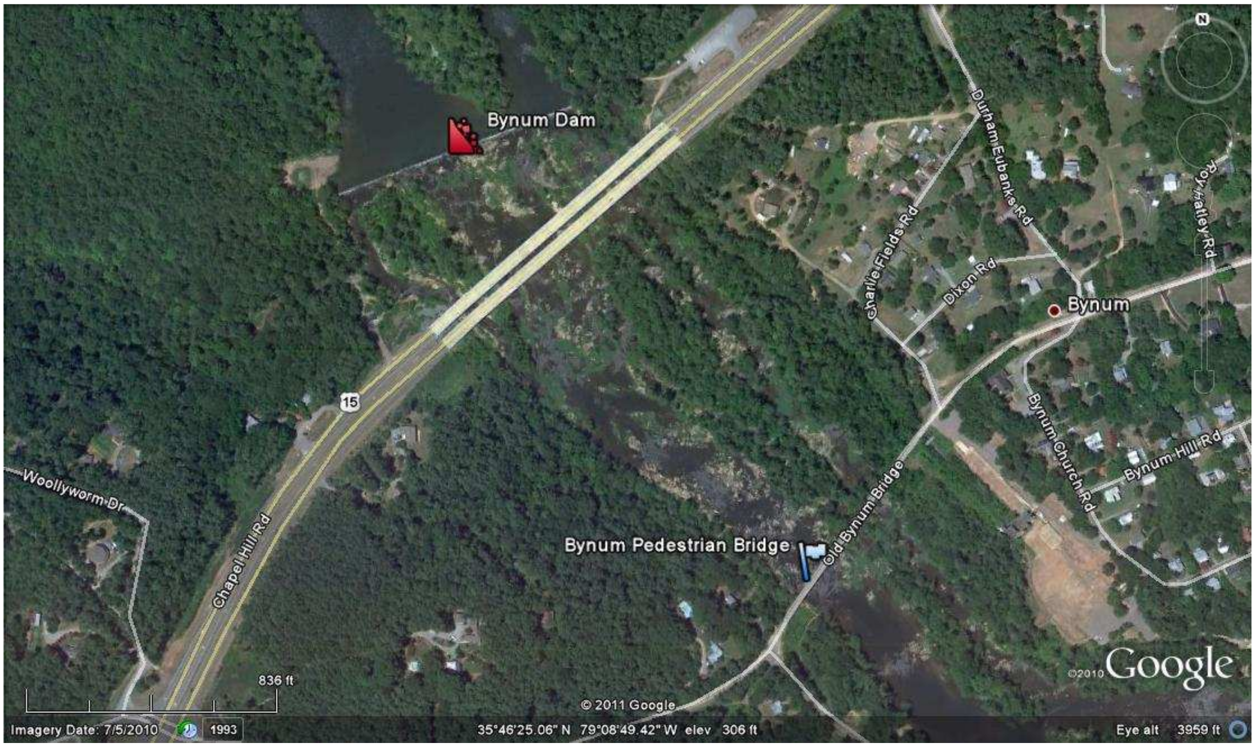


FIGURE 6. Bynum Dam and Sampling Site

2.3.4 Modern History

Since the 1990s, major population growth throughout the Haw River basin (as well as the entire state) has increased the human pressures on the river system. North Carolina's population has steadily increased, and growth has accelerated in recent years. From 1980 to 2010, the state's population increased 62 percent. Of the top 20 counties (North Carolina has 100 total) with the largest population growth, seven were in the Haw River basin (U.S. Census Bureau). Extensive construction and overall development to accommodate the growth has both churned soils (priming them for transport in large concentrations) and replaced permeable ground with impervious surfaces. In addition to sediment, fertilizers and other anthropogenic contaminants are readily mobile in the system. Delivery of this material from the landscape is facilitated by impervious surfaces and storm drainage systems that rapidly divert water and suspended material away from developed areas and into channels and reservoirs.

3. METHODS

3.1 Sampling Routine

From May 2008 through June 2010, the Haw River was sampled for suspended sediment at the pedestrian bridge in Bynum, N.C., approximately 0.5 kilometers downriver from Bynum Dam and 6.0 kilometers upriver of the back-up effect of Jordan Lake and its dam. Gauge height during this time span ranged between 2.62 and 15.00 feet; discharge ranged between 27 and 37,300 cfs.

Suspended sediment samples were collected from the bridge using a rope and a 12-liter plastic bucket. Surface waters were collected into two to six Nalgene carboys, each with a volume of approximately 33 liters. The volume of water collected was based on an estimate of sediment concentrations in the water to ensure an adequate mass of sediment for analysis. Two one-liter Nalgene bottles were also collected for measurements of total suspended matter (TSM). All materials were thoroughly rinsed with the river water before sampling, and the sampling equipment was rinsed after all containers filled.

The sampling frequency was, on average, once every two weeks, but trips were also made during/after precipitation events. Initially, event sampling targeted rising flow (rising-limb) and peak flows, tracked using USGS data from a gauge at the site, as the highest sediment concentrations was expected to be associated with these flow regimes. Intra-event sampling was added to the project, to examine variation within a hydrologic event. Targeted flows during hydrologic events included: base flow (prior to an event); rising-limb (accelerating flow); peak flow; falling-limb (decelerating flow); and sometimes post-event base flow.

3.2 Hydrologic, Human Impact and Climate Data

Hydrologic data was obtained from the USGS National Water Information System. Real-time discharge data for the gauge at Bynum (NWIS ID# 02096960) is available in 15-minutes intervals. Archived historical data for the Bynum site and the Town of Haw River gauge site (approximately 70 km upriver; NWIS ID# 02096500) were also obtained. The Town of Haw River gauge, located in the center of the basin (near Burlington), has the longest record, with daily mean discharge reported back to 1928. Other discharge records (daily maximum/minimum discharge and 15-minute interval discharge data) were not kept until recent years. The Bynum station gauge was not installed until 1973. Precipitation data was obtained from the State Climate Office of North Carolina for four gauges around the basin (Greensboro, Reidsville, Chapel Hill and Siler City). The gauges are evenly spaced and are located in the western, northern, eastern and southern parts of the basin. This study uses the average of the daily observed rainfall for the four gauges. Population data was obtained online from the U.S. Census Bureau and road-mile data from the Federal Highway Administration.

3.3 Sample Processing and Total Suspended Material (TSM)

The one-liter bottle samples were each vacuum-filtered through a pre-weighed 0.22-micron, nitrocellulose filter. The filter was then dried in a 40^{o}C oven for approximately one day and weighed again to determine the TSM concentration.

3.4 Radioisotopes

To process samples for radioisotope activities, carboys of river water were first pumped through in a Heraeus Contifuge at 15,000 RPM. A one-liter outflow sample was taken during each run and processed in the same manner as TSM in order to make sure the contifuge captured all material. After all carboys had pumped through the contifuge and spun out their sediment into the titanium rotor-head chamber, the concentrated sediment was extracted using a 60 mL syringe, DI-water squirt bottle and, if necessary because of cohesion to the walls of the chamber, a silicone spatula. The extracted material was divided among three or four 250 mL Nalgene bottles and placed in a centrifuge at 4,000 RPM for 40 minutes. With the sediment concentrated in the bottom, most of the overlying water was decanted off. A small amount was left in the bottle and used to re-suspend the more concentrated sediment such that each bottle, now containing less volume, could be concentrated into one 250 mL Nalgene bottle and again centrifuged at 4,000 RPM for 40 minutes. Finally, the overlying water was decanted off from that final bottle, and the remaining wet sediment was placed in a freeze-dryer for 1-2 days. Once the sediment is completely dry, it is homogenized down to a fine powder in a small plastic bag using a rubber mallet. The sediment is next transferred into a pre-weighed plastic vial to a height of 30 millimeters or to the maximum height possible if there was very little sediment in the river during the sampling trip. When the vial is filled, it is re-weighed to determine the mass of sediment in the vial; sediment mass in a vial filled to 30 mm usually weighs in between 1.5 and 2.5 grams. The vial is then sealed at the sediment surface with a half-centimeter cap of epoxy and stored for two weeks to allow ^{210}Pb to equilibrate with its parent ^{226}Ra. If a sample is counted for ^{7}Be before the two-week equilibration period is over, it is re-counted for ^{210}Pb after at least two weeks. Gaseous ^{222}Rn is a decay intermediate between ^{210}Pb and its parent ^{226}Ra. The epoxy seal prevents radon escape from the vial. By allowing the sample to equilibrate for two weeks, the background supported ^{210}Pb can be measured directly by gamma counting ^{226}Ra. The activity of ^{226}Ra is subtracted from that of total ^{210}Pb activity to derive the excess ^{210}Pb activity ($^{210}Pb_{xs}$). Counts from the gamma detector are then processed to calculate activity in units of dpm/g. The short-lived isotope ^{7}Be is decay-corrected to the time of sample collection.

4. RESULTS AND INTERPRETATION

4.1 Precipitation and Discharge Analysis

Precipitation rates within the Haw River basin do not appear to have changed significantly during the past 20 years relative to rates measured over the past 80 years. Average precipitation for the period 1991-2010 was within 2% of that measured for the 1931-1990 baseline period (Table 1). Standard deviation was used as a measure of the variability of month-to-month precipitation patterns, an increase signifying more wet/dry extremes and a decrease signifying more evenly distributed precipitation throughout the months. For this, a decrease in variability was observed at Greensboro (4.86%), while Chapel Hill exhibited an increase (15.30%).

	Average (inches/month)		**Standard Deviation**	
	Greensboro	*Chapel Hill*	*Greensboro*	*Chapel Hill*
1931-1990	3.532	3.824	2.132	2.099
1991-2010	3.493	3.906	2.028	2.420
Difference	-0.040	0.081	-0.104	0.321
% Difference	-1.125	2.129	-4.864	15.296

TABLE 1. Monthly Basin Precipitation

Changes in precipitation patterns for individual months were investigated (Appendix A), and while there are increases and decreases depending on the month, the overall average as reflected in Table 1 indicates no overall significant change.

However, the response of the river to essentially the same amount of precipitation has significantly changed. Daily observed precipitation data (average of four sites throughout the basin) and the river's discharge response (mean daily discharge data) was compared for baseline (1930-1990) and modern (1991-2010) periods. A linear regression was run for discharge (dependent) versus precipitation (independent), with the slope of the line being the discharge response of the river to a known quantity of precipitation. The linear regression was used not only for being the best fit but also for the presumed direct relationship between discharge and precipitation given the limited possible sources/sinks and the mechanisms of their operation. Additionally, an r-value correlation was calculated, with a larger value indicating a more consistent response. This was performed for all precipitation events and then filtered to only include precipitation events greater than 0.5 inches (Appendix A) and then 1.0 inch. Finally, calculations were also performed with consideration of delayed discharge response. A 1-day calculation compares precipitation with the observed discharge response on that same day. A 2-day calculation compares the observed discharge response on a given day to the sum of precipitation observed that day as well as the day before; a 3-day calculation uses the sum of precipitation that day plus the two days before. For example, for the 4-day delay, the sum of precipitation from June 10 to June 13 is plotted against discharge on June 13. This was performed for up to six days of precipitation observed on plus prior to an observed discharge event (Table 2).

Precipitation Events ≥ 1 Inch							
		1-day	*2-day*	*3-day*	*4-day*	*5-day*	*6-day*
Slope (discharge increase per inch of precipitation)	*1930-1990 Baseline*	2357.974	2420.032	1984.597	1564.486	1080.411	1074.475
	1991-2010 Modern	4481.921	3233.013	2429.327	1920.123	1373.390	1338.206
	% Difference	**90.08**	**33.59**	**22.41**	**22.73**	**27.12**	**24.55**
Correlation (r)	*1930-1990 Baseline*	0.314	0.501	0.549	0.534	0.482	0.495
	1991-2010 Modern	0.566	0.584	0.563	0.543	0.494	0.500
	% Difference	**80.16**	**16.59**	**2.52**	**1.53**	**2.56**	**1.01**
Baseline N=442 Modern N=149							

TABLE 2. Response to precipitation events greater than or equal to one inch.

All precipitation events – including those filtered to be of a minimum magnitude – showed the greatest increase in response on the day of the precipitation event. This is especially true for events greater than or equal to one inch precipitation, for which river discharge – compared to observed precipitation that same day (1-day) – exhibited a 90% greater response over baseline (Figure 7). Using the trends in an example for a day during the baseline period with more than one inch precipitation, each inch of precipitation would yield an additional 2,358 cfs discharge as reflected by the river gauge. For the same example during the modern period, each inch of precipitation would yield an additional 4,481 cfs discharge as reflected by the gauge.

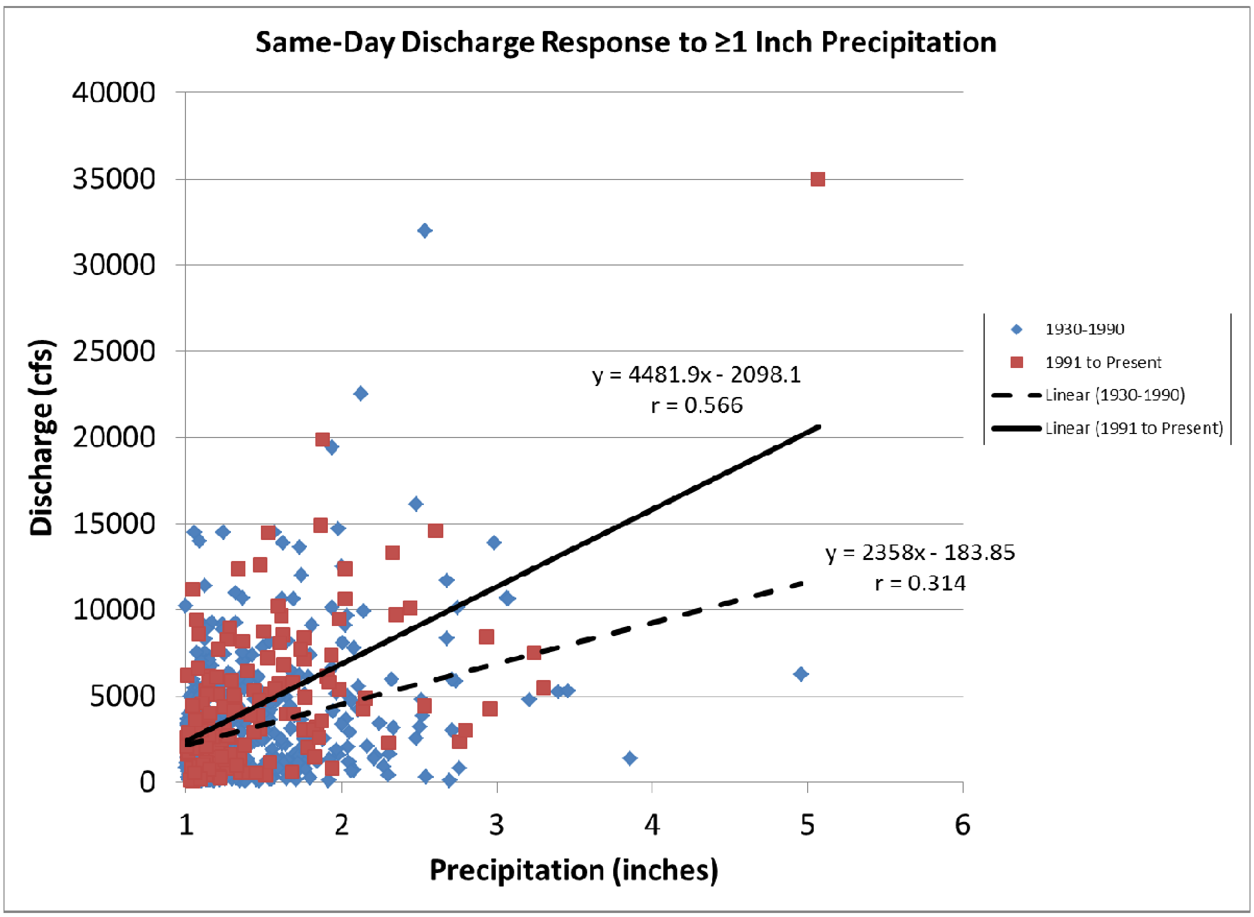
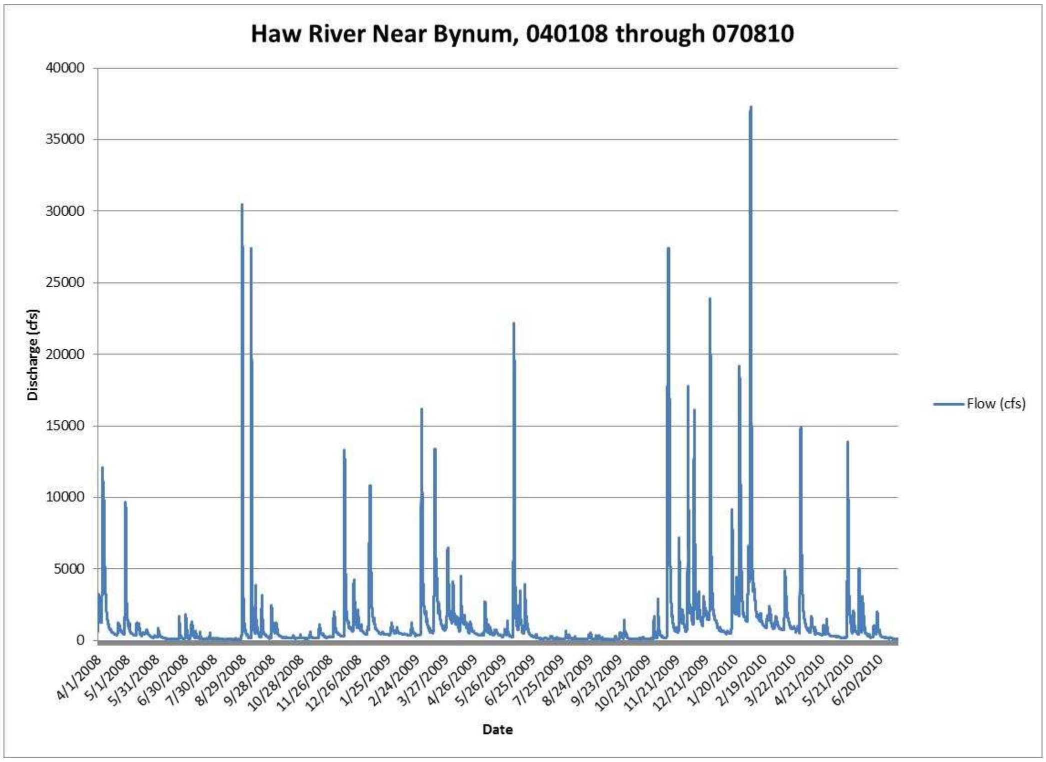


FIGURE 7. Trend lines are shown for baseline and modern discharge responses for precipitation events. Here, the trend line is fit only with days on which ≥1 inch of precipitation was measured.

The correlation improvement was also greatest for this one-plus-inch subset of events. In fact, the baseline 1-day discharge-precipitation correlation was the smallest (r=0.314) of all calculated, while the same calculation for the modern period (r=0.566) was within the typical range of all other correlations (r=0.420 to r=0.655). This indicates that during the baseline period, runoff was much more buffered before it reached the main river channel. Large precipitation events (one-plus inch) didn't immediately result in larger discharge compared to today; the poor correlation indicates that response varied substantially relative to the magnitude of observed precipitation. Greater slope (response) increases were associated with less delay. Only increases (between 1991-2010 relative to 1930-1990) were observed, the smallest being a 22.87% response increase calculated for 6-day aggregate precipitation events greater than 0.5 inches (Appendix A).

Considering the sampling period of this study (April 2008 to June 2010), observed discharge hydrographs (Figure 8) demonstrate the typical variability in the region. The basin was relatively dry between April 2008 and October 2009 due in large part to the onset of a strong La Niña. While La Niñas are typically associated with droughts in the area, tropical storms are more likely to develop and deliver large quantities of precipitation (Shapiro 1987). An El Niño developed with the wet season spanning from November 2009 through May 2010, a time with frequent precipitation events. Two 12-month periods (June 2008 to May 2009; June 2009 to May 2010) are overlayed to illustrate the inter-annual variability typical of the region.



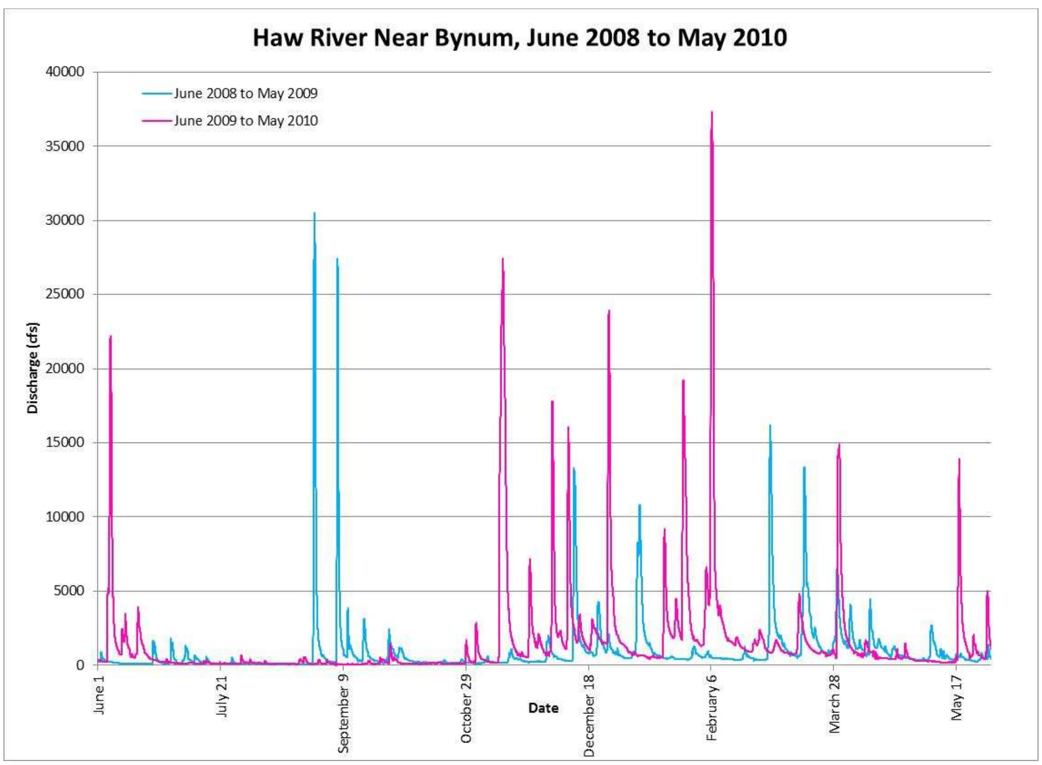


FIGURE 8. The top hydrograph covers the entire sampling span, from April 2008 through June 2010. The bottom hydrograph overlays two 12-month periods sampled, illustrating the inter-annual variability, especially with regard to summer events.

4.2 TSM

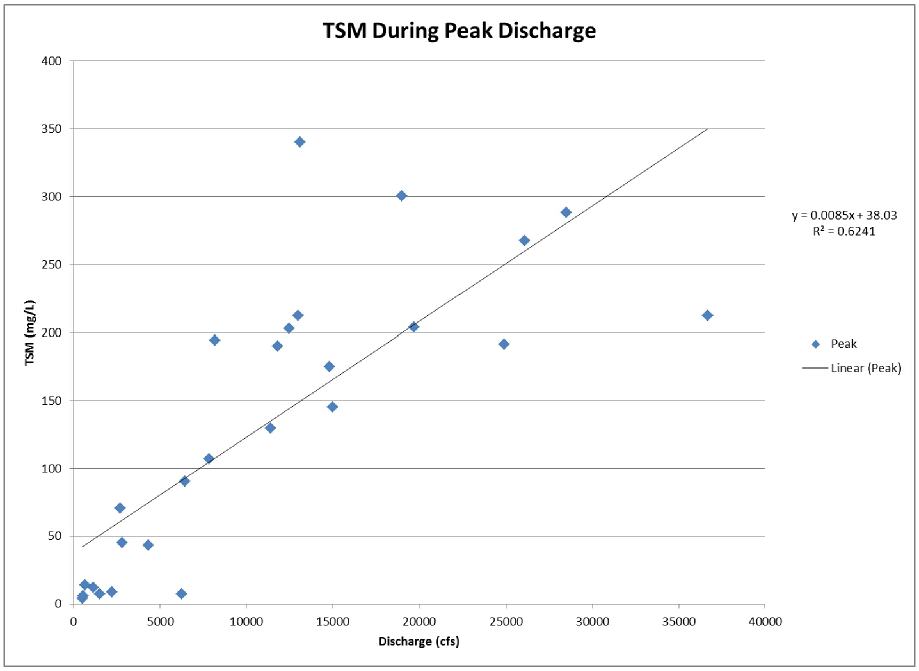
Total suspended material (TSM) concentrations varied substantially over the period of the study. Samples were categorized by their position on the hydrograph, approximating whether they were taken during base flow or the rising-limb, peak or falling-limb flows of an event. This categorization resulted in stronger linear correlations between discharge and suspended sediment concentrations than an analysis of TSM versus discharge including all samples. Base flows actually showed the poorest correlation.

	TSM min (mg/L)	TSM max (mg/L)	Discharge min (cfs)	Discharge Max (cfs)	Correlation (r)	Linear Slope
Baseline	2.49	16.48	86	1,020	0.645	0.0129
Rising-limb	32.94	443.30	3,380	10,700	0.798	0.0457
Peak	4.27	339.92	500	36,700	0.790	0.0085
Falling-limb	12.95	56.28	900	3,080	0.984	0.0178
Overall	2.49	443.30	86	36,700	0.743	0.0101

TABLE 3. Total Suspended Material relative to discharge. In addition to considering all samples together, samples were also categorized by hydrograph position. The correlation and slope are calculated for the relationship between discharge and TSM.

While variability made the presence of other variables for which a linear relationship does not account, linear relationships were generally good for fitting the data. One notable example is that of peak discharge, which, especially given the larger sample size, was better correlated (r=0.842) with a log function (Figure 9).

Considering all TSM data without certain hydrograph categories and fitting with power functions provided even better correlations. Plotting just base and falling-limb samples (Figure 10) provided a strong linear relationship, while plotting all data and power function-fitting just without rising-limb and then just without falling-limb illustrated strong relationships (Figure 11).



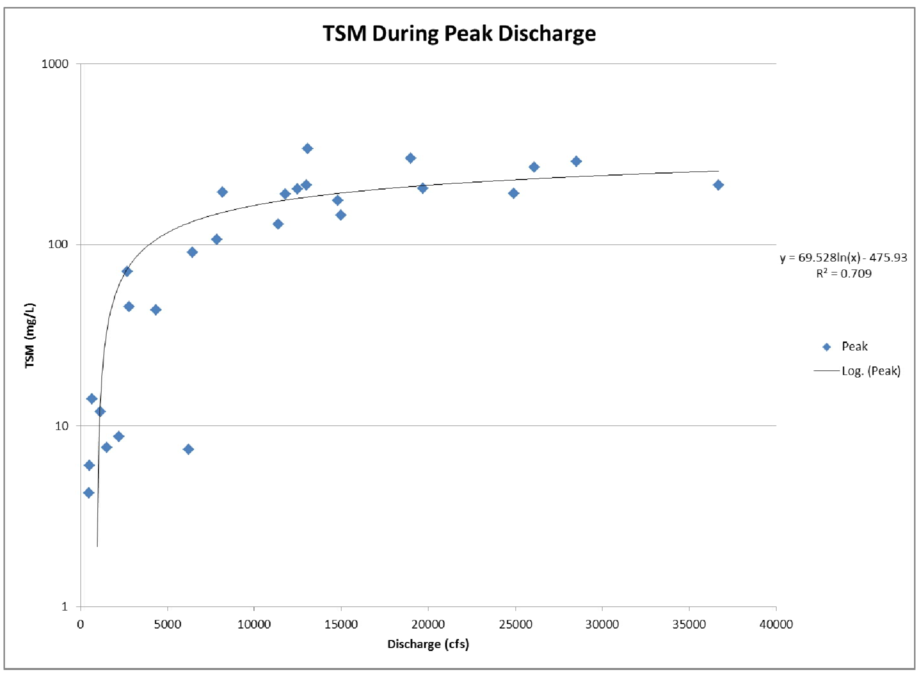


FIGURE 9. Observed TSM during peak discharge of an event. The same data is plotted with a linear (above) and log (below) fit.

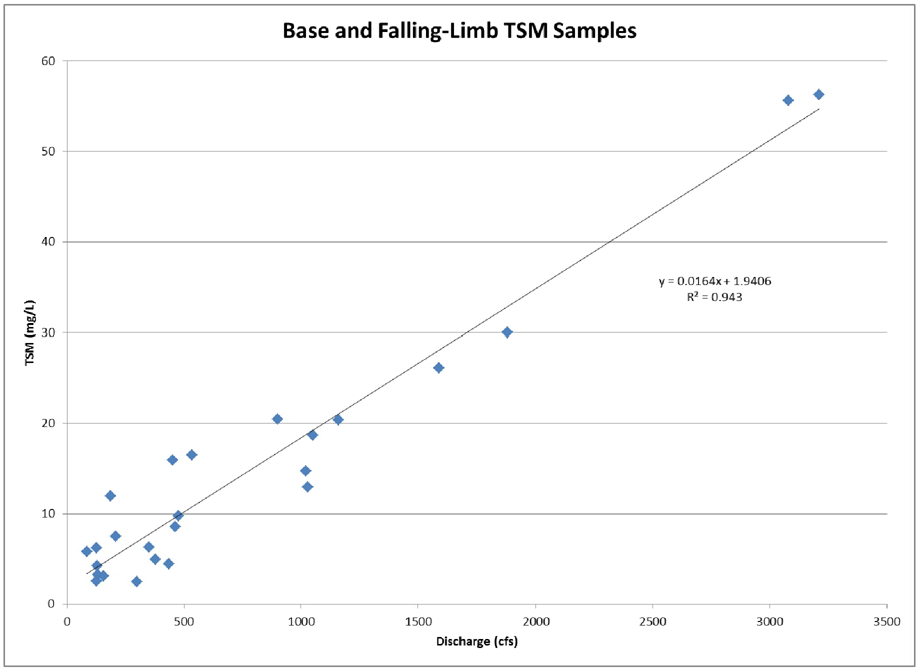
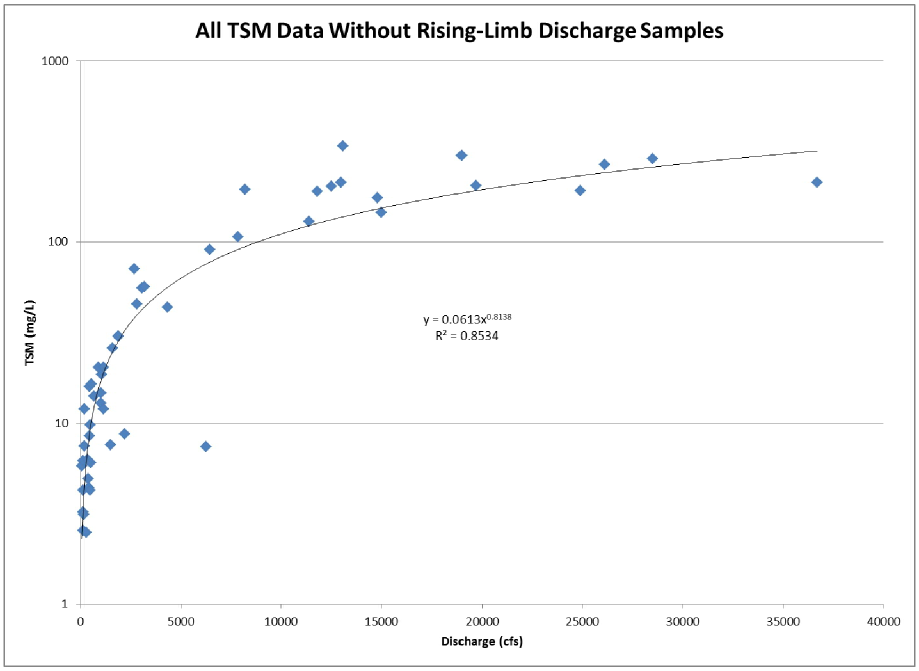


FIGURE 10. TSM samples collected only during base and falling-limb flows. The data here is best fit with a linear relationship (R^2=0.943). Mechanistically, these are the times (before and toward the end) of an event when sediment yielded as a result of variables other than discharge would be least prevalent.



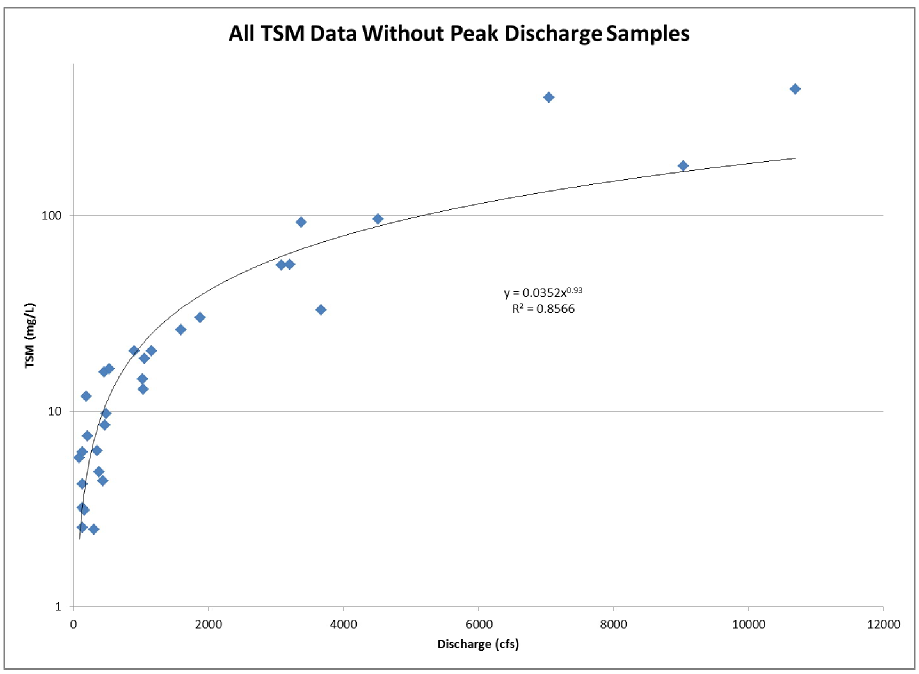


FIGURE 11. All TSM samples plotted with power functions, with data from certain hydrograph categories withheld. Compared to other functions used to fit the data, very strong relationships are seen using the power function. Rising-limb and peak discharge samples are more variable and likely have other variables affecting their yield. Dilution of sediment concentrations by the increasing volume of water is seen, but the system is clearly still supply limited as a decrease in concentration would expect to be seen if larger volumes of water were introduced but were unable to transport the sediment.

In plotting each category (Appendix D), outliers on the plot can be coarsely explained by hysteresis, or timing relative to previous events. Samples taken after separate events had recently occurred prior often explained disproportionately low TSM, while disproportionately high TSM coincided with events after a relatively long dry spell (inactive with regard to precipitation).

Looking at TSM change within events, rising-limbs often contained the highest sediment concentrations, though peak flow occasionally contained more. Very few USGS gauges continuously monitor turbidity or sediment concentrations. Even with good temporal resolution by sampling through an individual event's hydrograph, the quick river response makes it difficult to capture all the changes in transport dynamics that occur throughout the hydrograph of an individual event, and so peak sediment concentration could have been missed. This is illustrated in Figure 12, which compares TSM observed through the November 2009 event to the TSM response seen in the May 2010 event. Another event illustrating the change is from January 2010.

On January 25, 2010, measured discharge was 1,720 cfs at 01:15. By the first sampling at 09:45, flow was 10,700 cfs and TSM was 443.30 mg/L. At the peak sampling at 20:15, discharge was 19,000 cfs but TSM dropped to 300.56 mg/L. By January 28, 2010, at 12:15, flow had decreased to 3,080 cfs and TSM to 55.65 mg/L.

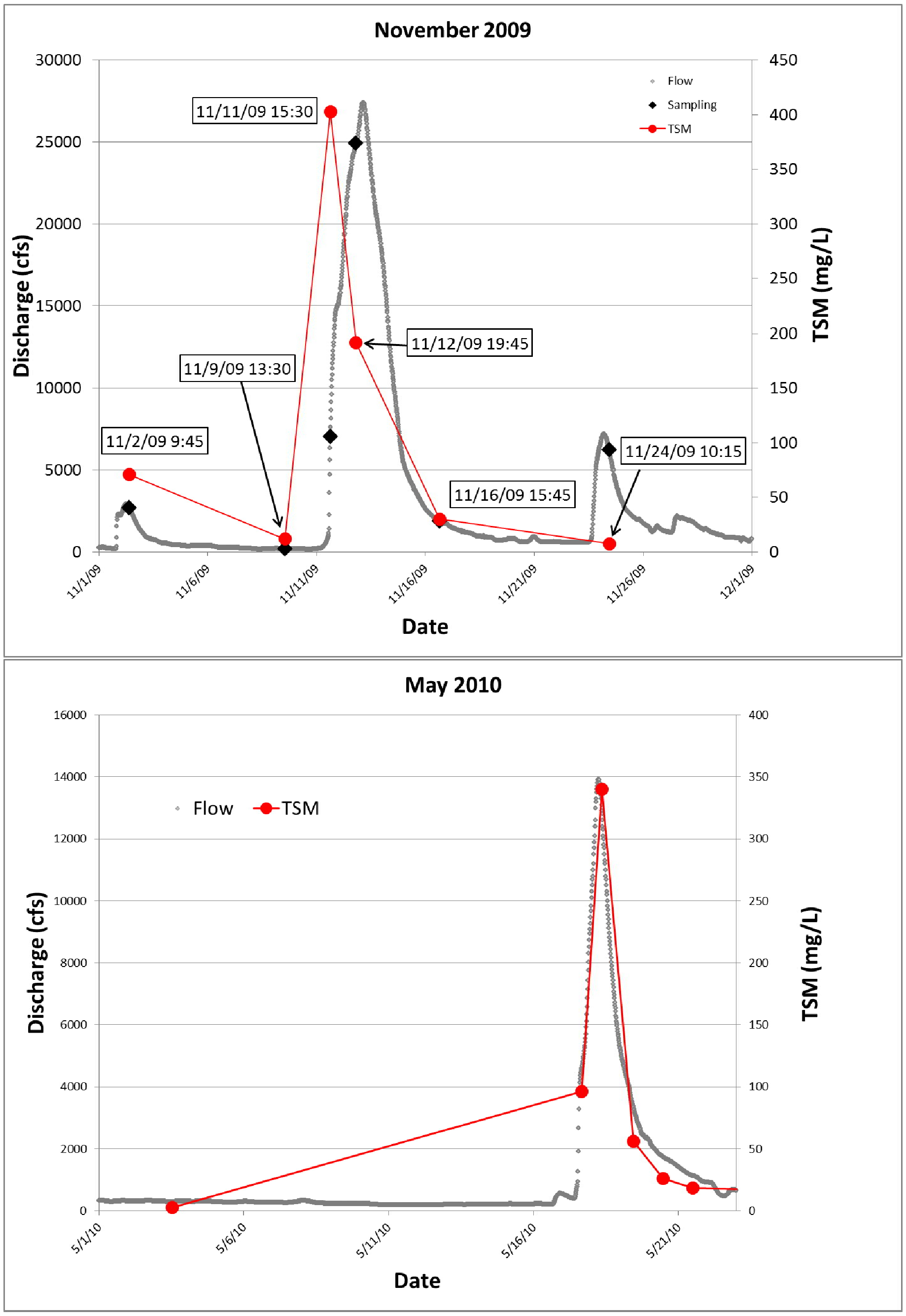


FIGURE 12. Two different examples of TSM responses throughout a hydrograph are illustrated to emphasize the rapid change that can occur. Rising-limb samples were taken relatively early in the rising-limb of both events, yet, timing of maximum TSM differed. While the lines connecting sampling points could portray an accurate picture of TSM change through the hydrograph, the position of maximum TSM in the November 2009 hydrograph raises the possibility that maximum TSM in May 2010 could have been in the narrow window between the rising-limb and peak discharge samples that were collected. Additional symbols for samplings are noted on the November 2009 hydrograph to help line up when samples were taken.

4.3 Radioisotopes

Activities of ^{7}Be, $^{210}Pb_{xs}$ and the $^{7}Be/^{210}Pb_{xs}$ ratio varied considerably during the study, most notably during periods of base flow, but exhibited trends on a hydrologic event scale. Hydrologic events in which samples were collected throughout the hydrograph – base (just prior to the event), rising-limb and peak flows – provided the best relationships between radiotracers, TSM and water discharge.

Figure 13 examines a November 2009 and Figure 14 a May 2010 discharge event in which samples were collected throughout the hydrograph.

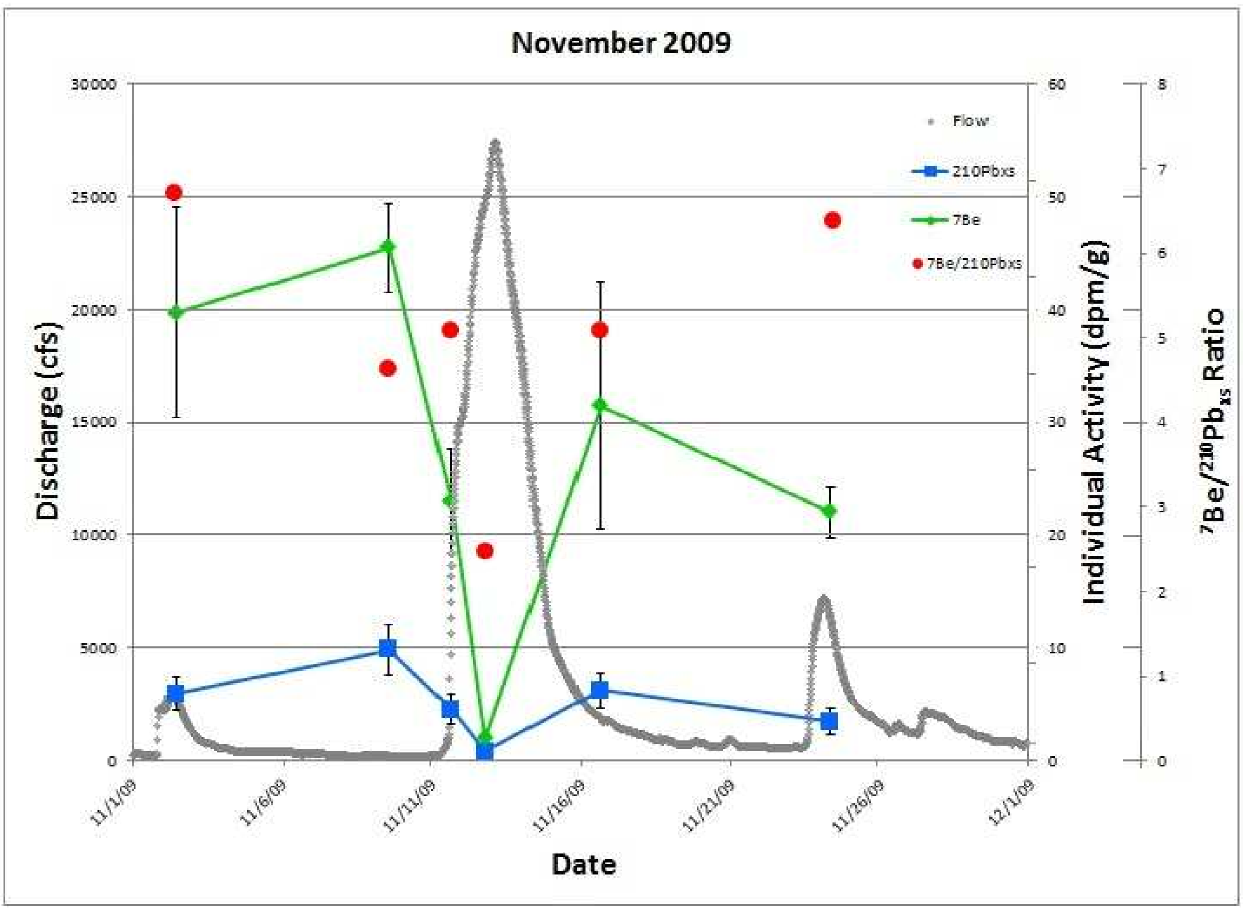


FIGURE 13.

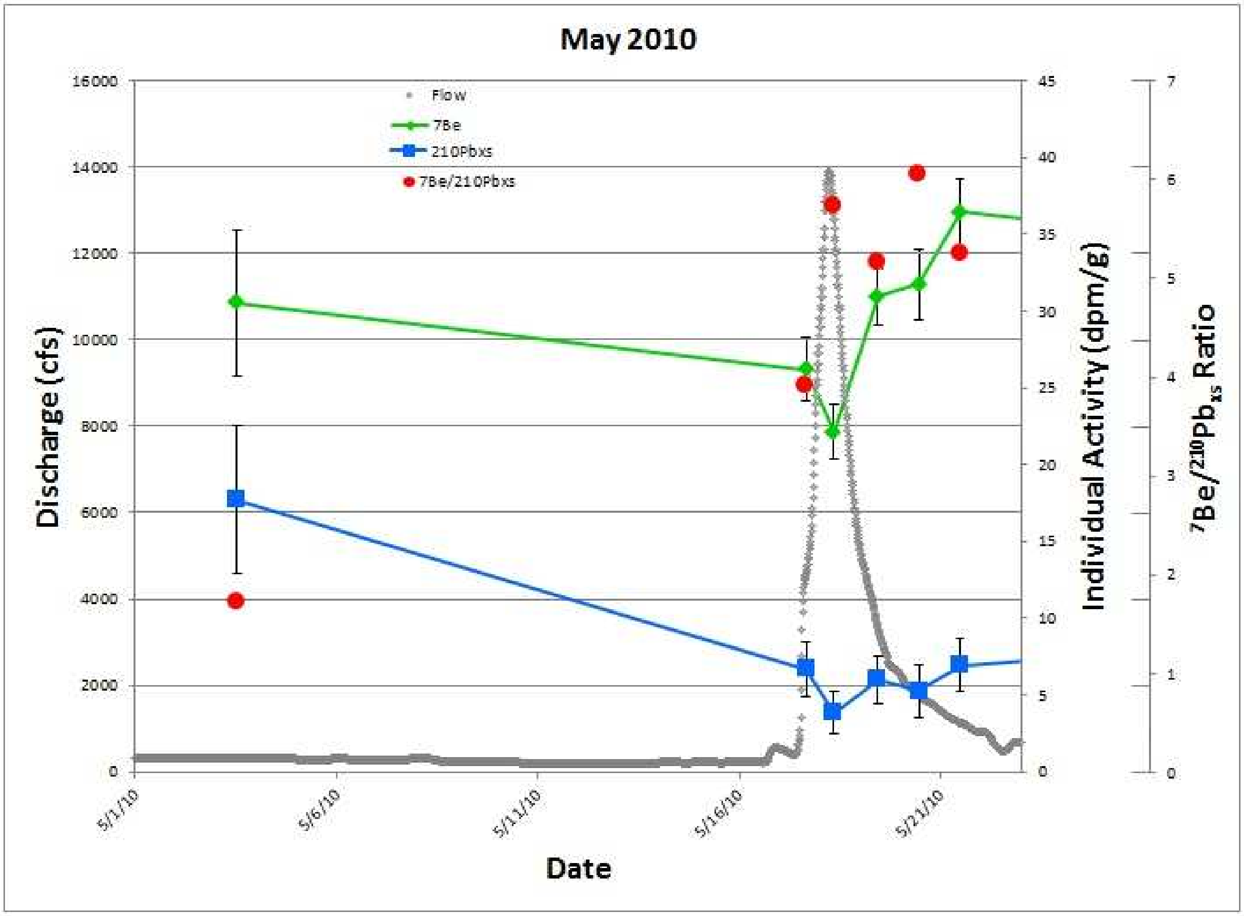


FIGURE 14.

For both events, the $^{7}Be/^{210}Pb_{xs}$ ratio increased through the rising-limb relative to the sample taken prior to the event. In November 2009, the peak flow $^{7}Be/^{210}Pb_{xs}$ ratio decreased significantly relative to the ratio at the rising-limb. However, in May 2010, the $^{7}Be/^{210}Pb_{xs}$ ratio remained elevated around the value observed during peak water discharge. While the $^{7}Be/^{210}Pb_{xs}$ ratio behaved differently between the two events, individual isotopes exhibited similar trends. In both events, individual activities for ^{7}Be and $^{210}Pb_{xs}$ decreased from baseline (pre-event) to rising-limb to peak measurements. Then during the falling-limb, individual activities increased back to typical baseline levels.

With events like May 2010 where a $^{7}Be/^{210}Pb_{xs}$ ratio decrease might have been expected but not observed, looking at the activities of the individual isotopes indicates dilution by older material that does not contain either isotope. For example, if sediment source A has activities of 40 dpm/g for ^{7}Be and 20 dpm/g for ^{210}Pb$_{xs}$. Sediment source B, being very old material, has zero activity for both isotopes. If half of a gram of each source is mixed together (forming sediment C), the product will have activities of 20 dpm/g for ^{7}Be and 10 dpm/g for ^{210}Pb$_{xs}$. The ratio (2.0) remains the same, but the material and individual signals have been diluted by an old material source where both isotopes have essentially decayed to where there is no detectable activity for either one. The ratio will only change if ^{7}Be-dead older material still contains ^{210}Pb$_{xs}$. Otherwise, the ratio will remain static as both individual isotope activities are equally diluted with neither receiving material with additional activity.

This dilution can be seen if radioisotope activities for all samples are categorized as either non-event (base flow) or event (rising-limb, peak, falling-limb) (Table 4).

	^{7}Be	^{210}Pb$_{xs}$	^{7}Be /^{210}Pb$_{xs}$	Discharge (cfs)	TSM (mg/L)
Non-event	69.35	18.29	3.76	338	7.81
Event	27.09	6.33	4.09	8,977	128.43

TABLE 4. Average sample values by event/non-event.

The ratio is almost identical between the two (event and non-event), while individual activities during events are only approximately 35 percent that of non-event activities. While all events show an activity decrease for individual radioisotopes, some show a ratio decrease while others do not. The difference is a proportionately greater ^{7}Be activity decrease compared to ^{210}Pb$_{xs}$, which also decreased.

In November 2009, two samples were taken in Cane Creek, a tributary to the Haw River approximately 20 km upriver from Bynum. The creek's drainage area – almost exclusively pasture and forest – is much less urbanized than the rest of the Haw River basin and represents an area much less impacted by human activity. The confluence of Cane Creek with the Haw River is located about halfway between the Town of Haw River and Bynum gauges, between which it took the hydrologic peak approximately 11 hours to travel for this event. This timing suggests the water mass from the first sample (11/11/09 11:45) would likely have entered Haw River at its rising-limb discharge for that location; the second sample (11/12/09 15:15) likely entered the river as it crested (peak discharge) at the site. Data for the samples are provided in Table 5.

	^{7}Be	^{210}Pb$_{xs}$	^{7}Be /^{210}Pb$_{xs}$	Discharge (cfs)	TSM (mg/L)
11/11/09 11:45	34.23 +/- 3.09	2.25 +/- 1.19	15.21	No gauge	263.94
11/12/09 15:15	20.92 +/- 2.01	5.70 +/- 1.41	3.67	No gauge	33.30

TABLE 5. Cane Creek samples.

The ratio for the first sample was more than double any ratio seen in November 2009. This larger ratio would be expected from a sub-basin dominated by natural erosion patterns contributing surface material from which ^{7}Be has not yet decayed. This material would likely have been present in the rising-limb sample collected at Bynum less than six hours later. Yet, that Bynum sample contained less ^{7}Be (26.79 +/- 5.45 dpm/g), more ^{210}Pb$_{xs}$ (5.79 +/- 1.50 dpm/g) and a much smaller ratio (5.07), though the ratio increased slightly over its baseline value (4.29). The peak-discharge sediment observed at Bynum purported to be partially composed of the second Cane Creek sample contained much less ^{7}Be (2.28 +/- 0.40 dpm/g) and ^{210}Pb$_{xs}$ (0.92 +/- 0.14 dpm/g) than what was observed at the tributary (ratio = 2.47). The trend of radioisotopic change at Cane Creek parallels that seen at Bynum, but much older material is diluting the signal of the tributary's material.

4.4 Human Pressures

Population and road lane-miles were two quantifiable human land-use change pressures calculated for the basin. Growth for Alamance and Guilford Counties, both of which are located almost completely in the basin, as well as for the entire state, is displayed here:

	1990 population	2000 population	2010 population	1990-2010 percent growth	2000-2010 percent growth
Alamance	108,213	130,799	151,131	40	16
Guilford	347,420	421,048	488,406	41	16
North Carolina	6,628,637	8,046,406	9,535,483	44	19

TABLE 6. Recent population growth in North Carolina.

State and county populations have roughly doubled during the past 50 years, with much of it having come in the past 20 years. The increase in impervious surface area associated with such growth is difficult to quantify. Data regarding road construction and lane widening has only been extensively kept in recent years. In North Carolina, unlike many other states, the state maintains all roads, which makes record keeping more easily accessible. As of 2008, North Carolina has the most state-maintained highway miles (80,214) of any state and second-most (behind Texas) state-maintained lane-miles (measures total miles of individual road lanes to better account for surface area increase). Change in lane-miles is calculated here as a figure expected to represent development likely to include other impervious surfaces (parking lots, buildings, sidewalks, storm drainage, etc). Between 2000 and 2008 (the earliest years for which data is available), lane-miles in North Carolina increased 26 percent, from 209,335 miles to 262,871 miles (Federal Highway Administration).

5. DISCUSSION

Significant climate changes were not observed in the Haw River basin over the past century. Analysis here, utilizing almost a century's worth of data, indicates no significant net change in recent (1991-2010) precipitation patterns compared to the 60 years prior. No long-term change in temperature (1895-2007) has been observed, either, according to the State Climate Office of North Carolina. If anything, there has been a slight warming trend since the mid-1970s. Thus, evapotranspiration is likely also unchanged or slightly enhanced, meaning soils would be, if anything, less saturated with water and more likely to absorb precipitation, ultimately losing more runoff to both the atmosphere and groundwater recharge. Overall, with similar precipitation patterns and a possible slight warming trend, discharge averaged over the entire modern period should be similar to discharge averaged over the entire baseline period. Yet, mean daily discharge increased from an overall average of 575 cfs (1930-1990) to 653 cfs (1991-2010). It is a 14 percent increase in observed discharge during a period without an observed precipitation increase.

Considering discharge responses to individual precipitation events, significant change in the Haw River basin is observed on multiple temporal scales and is parallel to increases in human impacts in the basin. The increase in the Haw River's discharge response to precipitation (22-90 percent more rapid compared to a 1930-1990 baseline) parallels substantial increases in human pressures in the basin during the past 10-20 years. The past two decades of rapid statewide population growth (44 percent) and lane-mile increase (26 percent in the last decade alone) illustrate the growing influence of human activities in the Haw River basin, which is an area of concentrated growth in the state. Both of these indicators are consistent with an increase in the percent of land covered with impervious surfaces and in the increased prevalence of storm water drainage within the basin, both of which serve to increase the speed and efficiency by which precipitation is delivered to river channels.

Enhanced river response has a number of implications. First, rivers experience more discharge extremes – higher maximum/peak discharge and lower minimum/base discharge. Higher peak discharge for a given quantity of precipitation means flood stages will be reached and exceeded more often. Since runoff is more focused and more rapidly passes through the system, it does not go through the natural route of permeating soil, recharging groundwater and gradually reaching the river channel, nor is it as exposed and susceptible to evapotranspiration. Without a steady, gradual supply of water to a river after a precipitation event, base flow between events can be expected to be lower.

Increased magnitude of peak discharges could increase the likelihood for overbanking, which was impeded by the higher banks from the accreted legacy sediment layer. This might promote more natural river/floodplain interactions. However, floodplains could significantly aggrade once again, ultimately building up banks and decreasing overbank likelihood.

In addition to an increase in the capability for sediments to be delivered to the Haw River, the TSM and discharge data indicate that there has been a concomitant increase in sediment supply. Two decades ago, prior to the increases in human pressures described here, Phillips (1991) classified North Carolina Piedmont rivers (and the Haw River specifically) as transport-limited. This was based on observations that the suspended sediment load was greater at upriver Piedmont sites than at sites near the Piedmont-Coastal Plain boundary. However, dams and reservoirs like those often constructed along the Piedmont-Coastal Plain boundary (including the case of the Haw River) can mask increased erosion and sediment yield. Calculating modern sediment budgets is complicated for reasons like this since these manmade structures can decrease sediment flux out of basin while erosion and overall yield is increased throughout the basin.

The large sediment loads observed during high discharge events appear to be capable of carrying sediments until they are deposited behind dams such as at Jordan Lake. Furthermore, the TSM-discharge relationship during events does not decrease even when several large discharge peaks directly follow each other. This observation leads to questions regarding the source of sediments in suspension during high discharge events in the Haw River. The possible sediment sources are: (a) sediments resuspended from the riverbed; (b) sediment eroded from river banks; and (c) sediments supplied via tributaries from the watershed.

The radiotracer data can be used in conjunction with observations to determine the likely source(s) of sediments in the Haw River. During multiple attempts to core the main river channel, no bed sediment was found and bedrock was primarily encountered.

The erosion of river banks is another possible source of soils 'dead' to ^{7}Be and ^{210}Pb$_{xs}$. Historic and recent aerial imagery does not indicate any widening of the channel, which means that laterally accessing bank sediments and releasing a substantial volume of 'dead' legacy sediments into the river is not likely. It is possible that old bank sediments contribute to the sediment load during peak discharges, but it is not likely to be a major contributor.

The most logical source of radiotracer-dead sediment is from the watershed via tributaries. The sediments collected during base flow and low discharge times exhibited high activities of ^{7}Be and $^{210}Pb_{xs}$ that is typical of surface soils in constant contact with the atmospheric delivery of these radiotracers. In contrast, the radiotracer signature of suspended sediments at peak discharge (highest TSM) was characterized by very low activities of both ^{7}Be and $^{210}Pb_{xs}$. Therefore, the supply of sediments during high flow has been out of contact with the atmospheric supply of these tracers for approximately five half-lives of the radioisotope. This is because natural radioisotopes decay to about 3% of their original activity after five half-lives if they are isolated from their source. For ^{7}Be, only 3% of its original activity is left after 266 days; for $^{210}Pb_{xs,}$ this decrease takes 112 years. Legacy sediments (in the drainage basin or in river banks) should therefore be dead to both ^{7}Be and $^{210}Pb_{xs}$.

The Cane Creek data demonstrates that the sediment supplied from undeveloped areas undergoing more natural erosional patterns have a distinctive signal that looks similar to surface soils that are constantly exposed to radionuclide depositional sources.

Another possible source within the watershed is from areas undergoing rapid development, which is extensive throughout the basin. The activities associated with construction and road building result in subsurface sediments (dead to both ^{7}Be and $^{210}Pb_{xs}$) being exposed on the surface and often poorly protected from being eroded and entering the river system.

On May 27, 2011, during a heavy precipitation event that resulted in flash flooding in the basin, samples of construction runoff were collected on the UNC campus. A construction site, approximately 750 square meters in area, exposed sediments from 5-10 meters below ground. Sediment mobilized during this storm event was visibly transported in two streams on top of impervious road and parking lot areas and directly to storm drains. Samples were collected at the storm drain. The TSM concentration for one stream measured 1.17 grams/L. The concentration of TSM from the other stream measured 21.26 grams/L. Materials from both streams were gamma counted, and samples were dead to both ^{7}Be and $^{210}Pb_{xs}$ (no activities for either were present). This kind of dilution of radiotracers was observed in Matisoff et al. (2002), which compared radiotracers in watersheds with tilled and untilled soils. With a linear relationship between ^{7}Be and $^{210}Pb_{xs}$ measured in a plot containing activities for radiotracers from both soil types, the ratio was the same for both tilled and untilled soils, yet individual activities for both were much lower in the tilled soils, where radiotracer-dead sediment was brought to the surface and evenly mixed with newly tagged sediment.

During a period when changes in precipitation rates and variability do not appear to have been substantial, human pressures resulted in (a) more rapid discharge response capable of transporting more sediment, and (b) accessing new sources of sediments (from construction and urban development). This additional sediment source and new mechanisms and routes to deliver it are also consistent with the somewhat variable timing and presence of this as seen in samplings. Point sources and associated small-scale transport are transferred more efficiently via storm drains, amplifying their impact on the main channel. However, these point sources, especially construction sites, are often ephemeral sediment sources with major spatial variability.

Relative to radiotracer signatures observed at Bynum, the urban runoff sediment contained a much older signature (both ^{7}Be and $^{210}Pb_{xs}$ had decayed beyond detection) that can dilute the signals of other sediments while not necessarily affecting the ^{7}Be /$^{210}Pb_{xs}$ ratio.

The rural Cane Creek sediment, on the other hand, contained the signature of fresh surface sediment that would be expected of more natural erosion patterns.

As explained above, sediment from different sources and with different histories may have different radioisotope signatures, making radiotracers valuable tools for determining sediment source. However, radiotracer data must be considered in the context of both natural processes and human activity. Temporal variations in radiotracer values should also be determined (on time scales ranging from hourly to decadal) when examining a river's response to historic, seasonal and event-scale changes.

Radioisotope data show a clear need to reevaluate sediment models using radiotracers to quantify the age and source of particulate materials delivered to rivers. The radioisotopic signatures of sediment vary considerably throughout the hydrograph both within and between discharge events. The use of the ^{7}Be /$^{210}Pb_{xs}$ ratio, as described by Matisoff et al. (2005) and other publications, requires additional context when utilized in environments impacted by human activity. Human impacts create multiple significant variables in sediment sources and transport that can be difficult to constrain spatially, temporally and mechanistically. The Matisoff model assumes that the material being supplied to rivers contain measurable activities of $^{210}Pb_{xs}$. In basins like the Haw River with significant urbanization, excess sediment loading from construction appears to contribute a significant portion of material. This is evident both in the measured TSM concentrations from the construction site (1-2 orders of magnitude more concentrated sediment compared the Haw River) entering storm drainage and the observed significant decreases in isotope activities. Sediment buried meters deep, accessed and made readily mobile by activities such as construction, will have no ^{7}Be activity and likely no measurable $^{210}Pb_{xs}$ activity. If the soil is located in an area of 'legacy' sediments associated with early American agricultural practices as documented by Trimble (1974), such land-use activities occurred 100-200 years ago. Some $^{210}Pb_{xs}$ could potentially remain, which would explain why a decrease in the ^{7}Be /$^{210}Pb_{xs}$ ratio was sometimes seen. Other times, the sediment was devoid of both radioisotopes and individual activities were very low, leaving the ratio and perceived sediment source/age observed as unchanged. The variability in these observations can be attributed to the ephemeral nature of the point sediment sources.

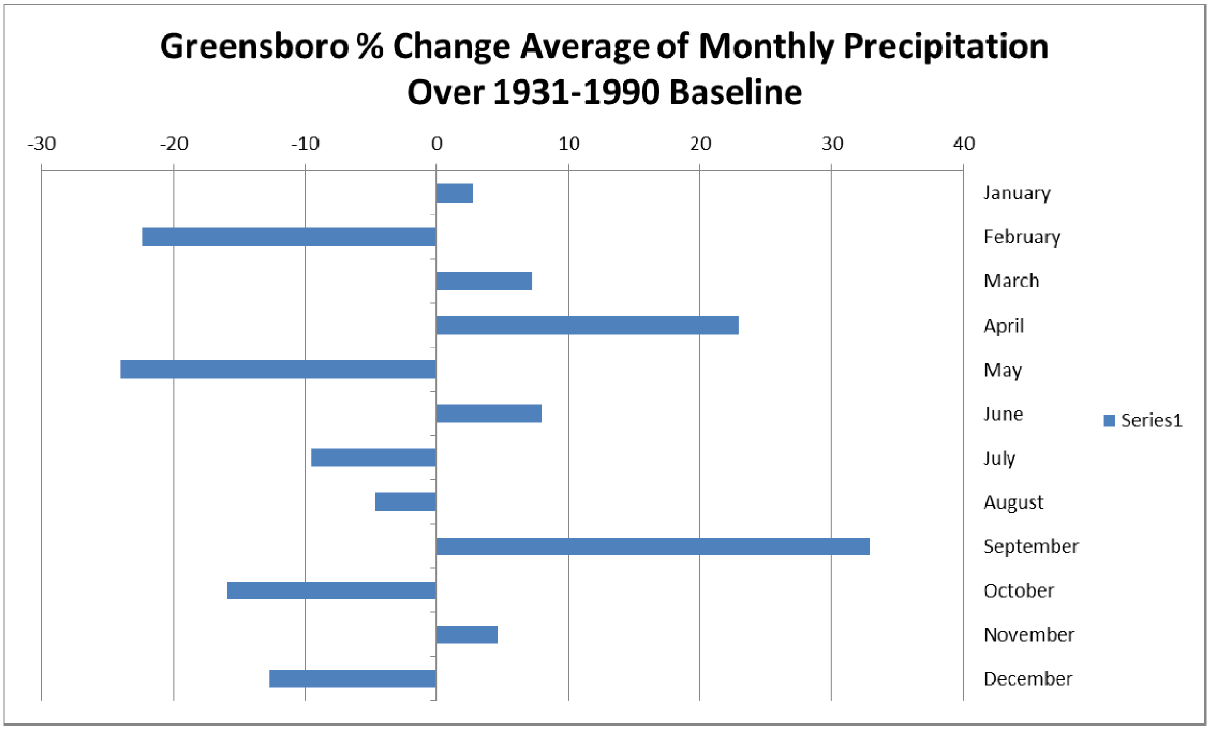
This study has contributed research on human-induced changes to a single river system in a much larger, more regional scale than is typically found in other studies. Rivers are typically considered in a global context with focus on the largest drainage basins with the most discharge and sediment yield. Studies set on a smaller scale are often multiple orders of magnitude smaller than the basin considered in this study (4,217 km^2). Furthermore, the in-situ radioisotope sampling provides detailed temporal resolution – both inter-event and intra-event – over the course of two years. The changes observed demonstrate a clear need for more extensive monitoring of river systems on much smaller time scales, especially prior to a reservoir. Finally, this study exemplifies the need for research on human pressures as immensely influential variables.

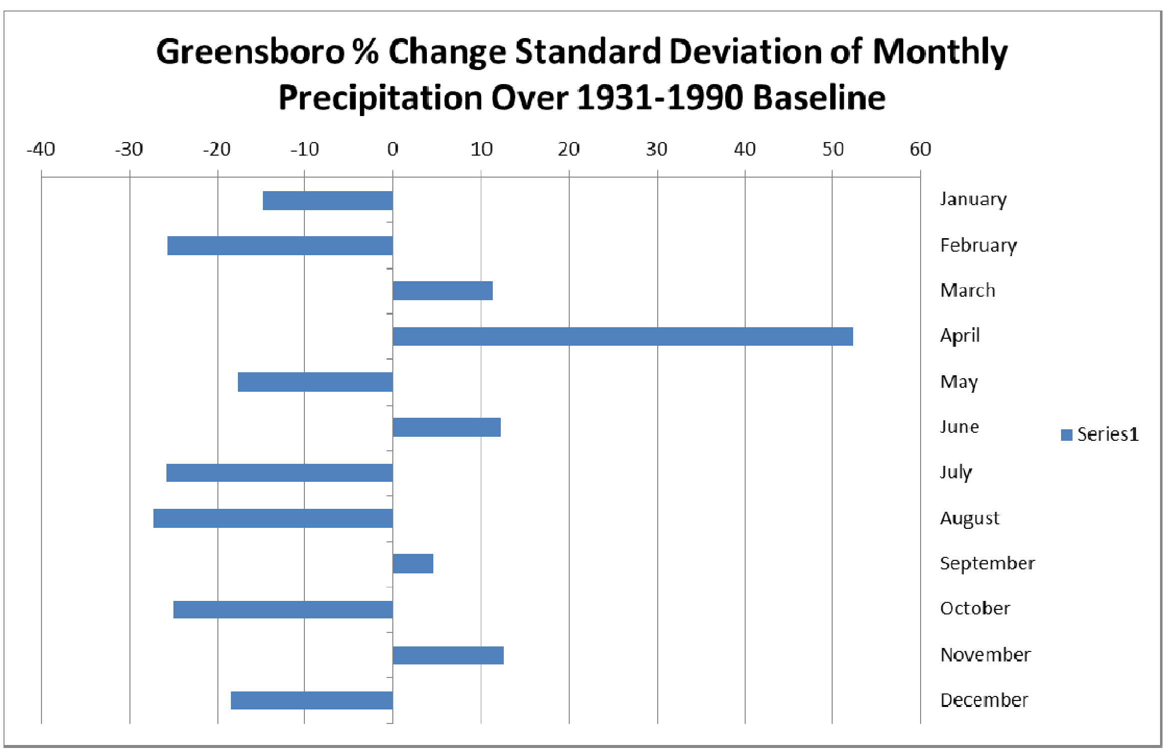
6. CONCLUSION

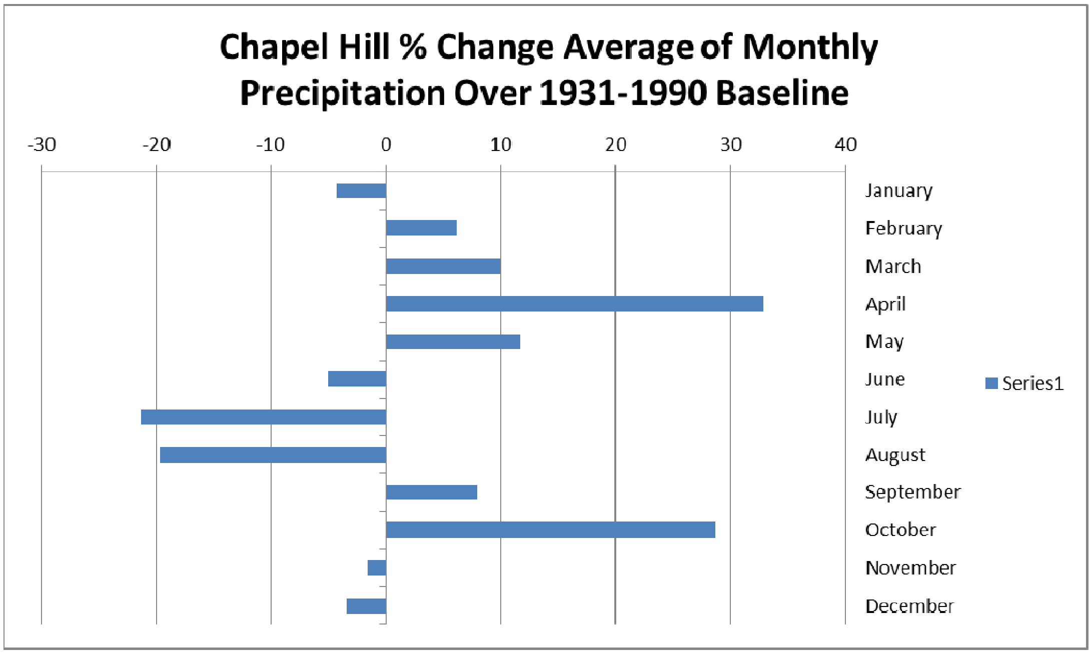
In only 20 years, land-use change has directly and significantly altered sediment transport processes in the Haw River, enhancing both the quantity of sediment and the ability to transport it. Population growth and changes to runoff pathways (impervious surfaces, storm drainage) associated with urban development coincide with a quicker and larger discharge response in the main channel of the Haw. In addition to enhancing the river's ability to transport material, radioisotopes indicate that the type of source material and load have also been enhanced. Previously buried sediment likely mobilized by construction activity is present during discharge events. However, in what had previously been deemed a transport-limited system, enhanced river response has outpaced the effect of excess sediment loading. More sediment is available in the system, and the system is now capable of transporting all of it, flushing it through the river system like a flume and not allowing it to settle as bed material or alluvial deposits. But excess sediment can go undetected since the type of sediment in transport varies through a hydrograph. Taking only a single sample during a discharge event – nonetheless a wet season or even year – is likely to yield a sample that is poorly representative of total transport throughout the event. Alternatively, this research has identified limitations with the use of radioisotope tracing methods – particularly the $^{7}Be/^{210}Pb_{xs}$ ratio – in areas with significant human impacts. Sediment buried meters deep for relatively long periods will be devoid of many radioisotopes that are commonly measured in studies of sediment transport. These sediments will dilute the signals of newer sediment accessed and transported by natural or at least clearly identified processes typical throughout a significant portion of the basin. The $^{7}Be/^{210}Pb_{xs}$ ratio must at least be used in conjunction with individual activities to determine if sediment is truly coming from relatively younger or older source(s). Generalized methods and formulas for examining river systems will become less universal and more difficult to apply to any given system without spatial and temporal context for a basin. Yet, regional and local scales are clearly in need of attention as this change has occurred without any significant change in local climate. Future climate change, should it introduce more runoff in the region as some predict (Milly et al. 2008), will only hasten this process.

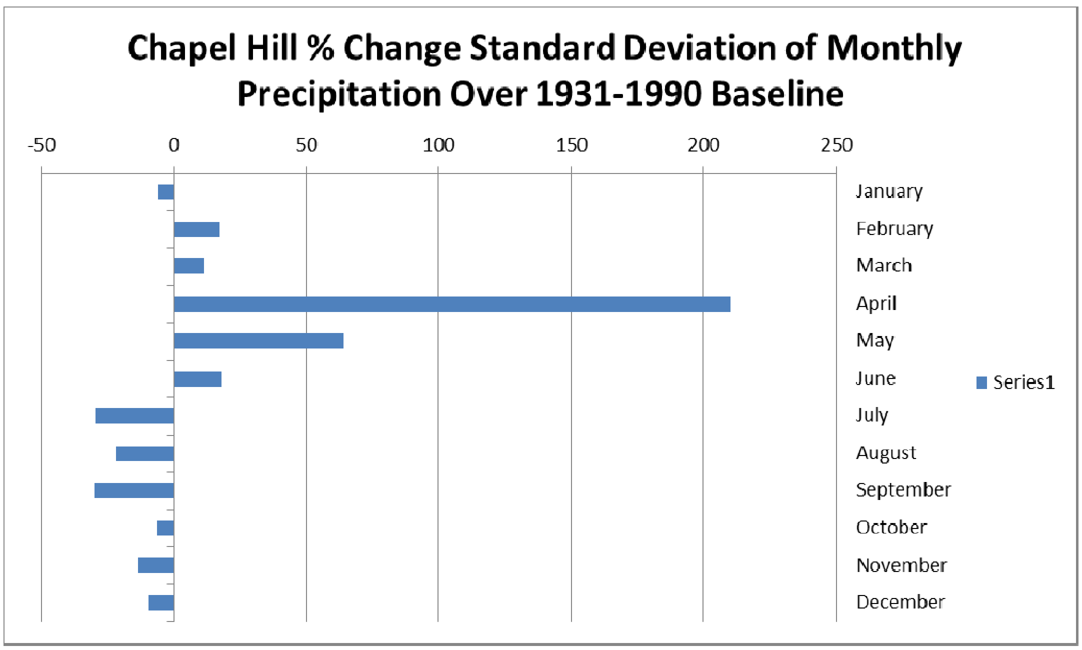
APPENDIX A

PRECIPITATION CHANGES FOR EACH MONTH






Chapel Hill % Change Average of Monthly Precipitation Over 1931-1990 Baseline
-30
-20
-10
0
10
20
30
40
January
February
March
April
May
June
July
August
September
October
November
December
Series1


Chapel Hill % Change Standard Deviation of Monthly Precipitation Over 1931-1990 Baseline
-50
0
50
100
150
200
250
January
February
March
April
May
June
July
August
September
October
November
December
Series1

APPENDIX B

PRECIPITATION AND DISCHARGE RESPONSE FOR ALL AND ≥0.5-INCH EVENTS

All Precipitation Events							
		1-day	*2-day*	*3-day*	*4-day*	*5-day*	*6-day*
Slope	*1930-1990 Baseline*	1674.992	1452.027	1212.681	1017.362	871.547	760.694
	1991-2010	2526.195	1935.205	1538.361	1265.381	1082.812	940.550
	% Difference	**50.82**	**33.28**	**26.86**	**24.38**	**24.24**	**23.64**
Correlation	*1930-1990 Baseline*	0.427	0.595	0.634	0.625	0.604	0.581
	1991-2010	0.528	0.650	0.655	0.631	0.606	0.578
	% Difference	**23.77**	**9.09**	**3.38**	**0.93**	**0.42**	**-0.38**

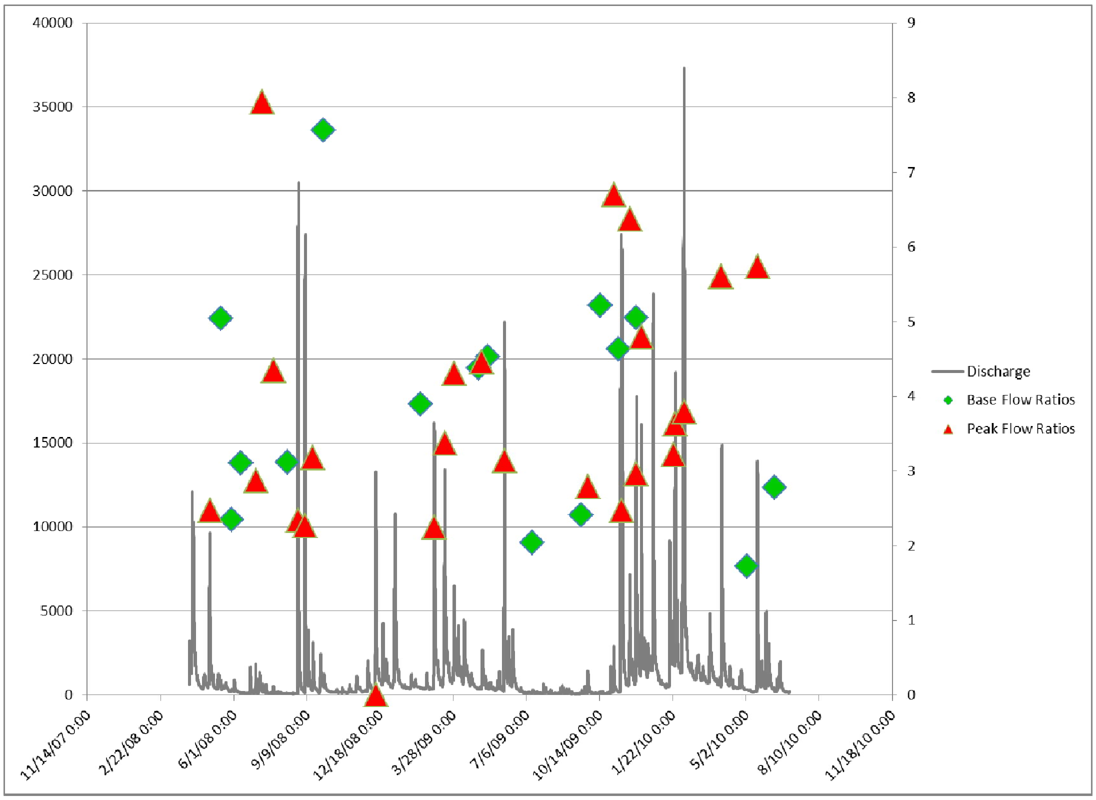
Baseline N = 22,279; Modern N=7,357

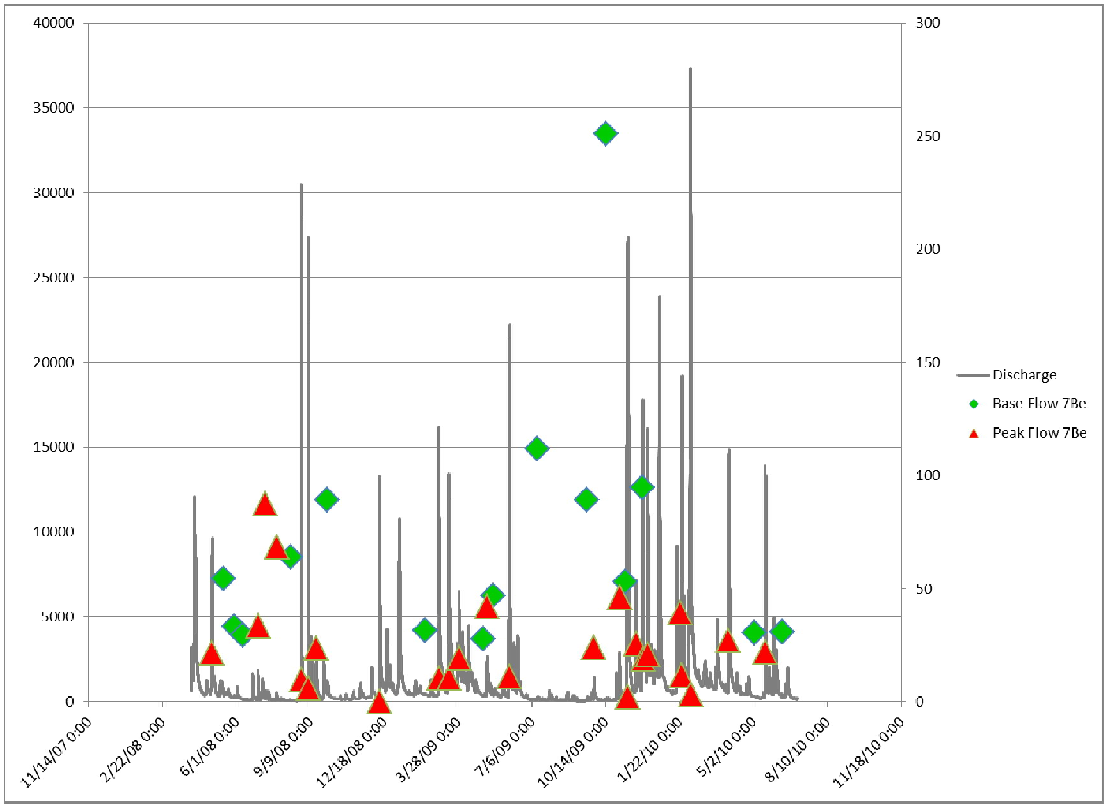
Precipitation Events ≥ 0.5 Inches							
		1-day	*2-day*	*3-day*	*4-day*	*5-day*	*6-day*
Slope	*1930-1990 Baseline*	2486.521	2154.385	1728.334	1043.099	973.562	955.011
	1991-2010	3880.388	2808.193	2123.962	1307.975	1206.321	1173.438
	% Difference	**56.06**	**30.35**	**22.89**	**25.39**	**23.91**	**22.87**
Correlation	*1930-1990 Baseline*	0.420	0.568	0.606	0.550	0.539	0.546
	1991-2010	0.591	0.633	0.613	0.550	0.536	0.542
	% Difference	**40.80**	**11.49**	**1.12**	**0.00**	**-0.65**	**-0.74**

Baseline N = 1,689; Modern N=561

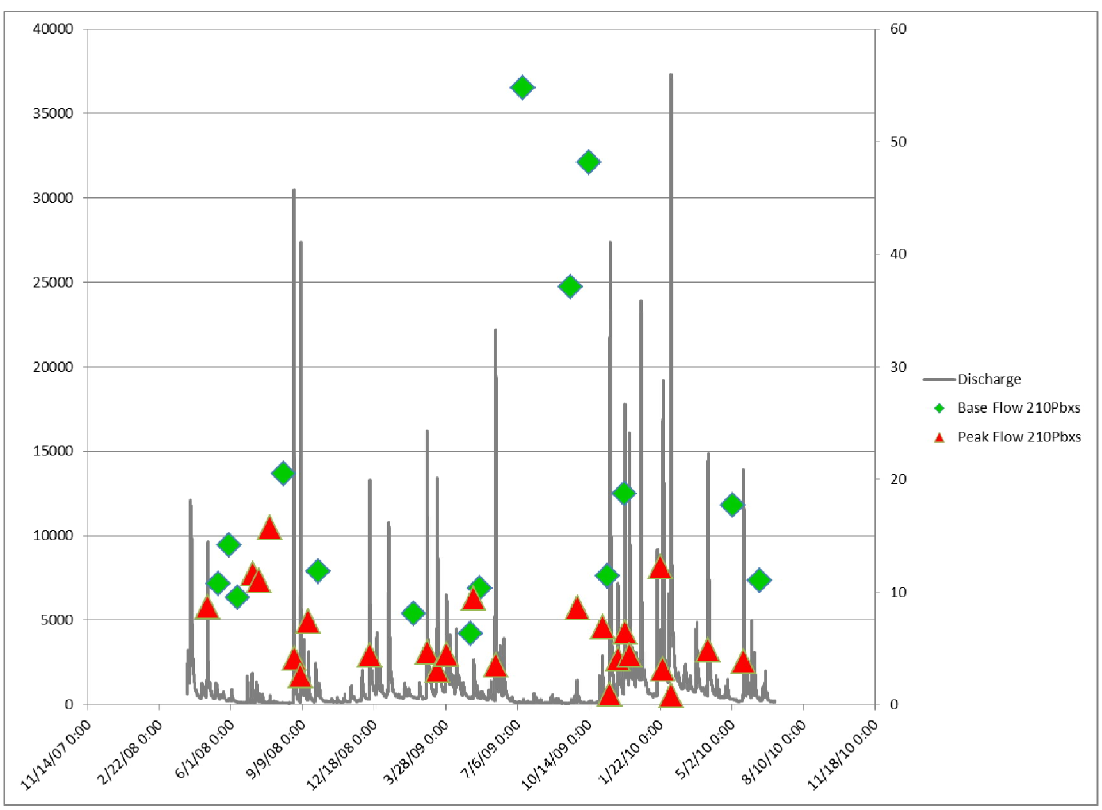
APPENDIX C

TOTAL SAMPLING PERIOD RADIOISOTOPE DATA, BASE FLOW VS. PEAK FLOW SAMPLES





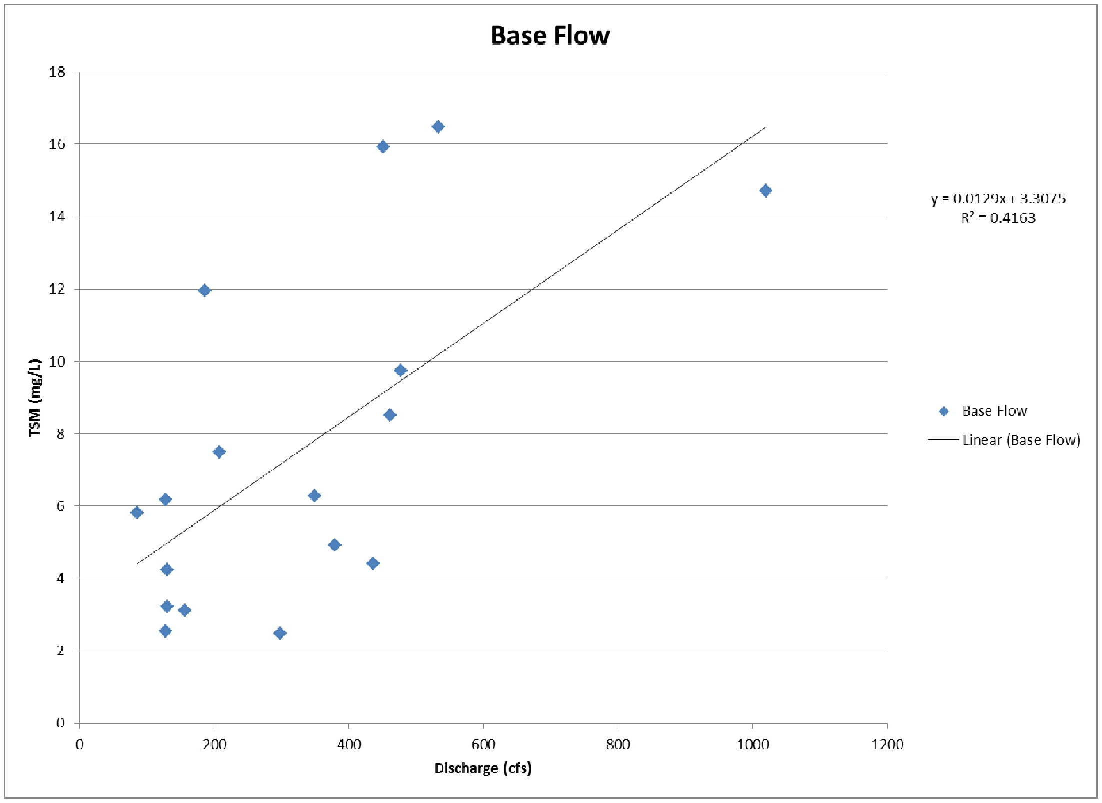
40000
35000
30000
25000
20000
15000
10000
5000
0
300
250
200
150
100
50
0
11/14/07 0:00
2/22/08 0:00
6/1/08 0:00
9/9/08 0:00
12/18/08 0:00
3/28/09 0:00
7/6/09 0:00
10/14/09 0:00
1/22/10 0:00
5/2/10 0:00
8/10/10 0:00
11/18/10 0:00
Discharge
Base Flow 7Be
Peak Flow 7Be

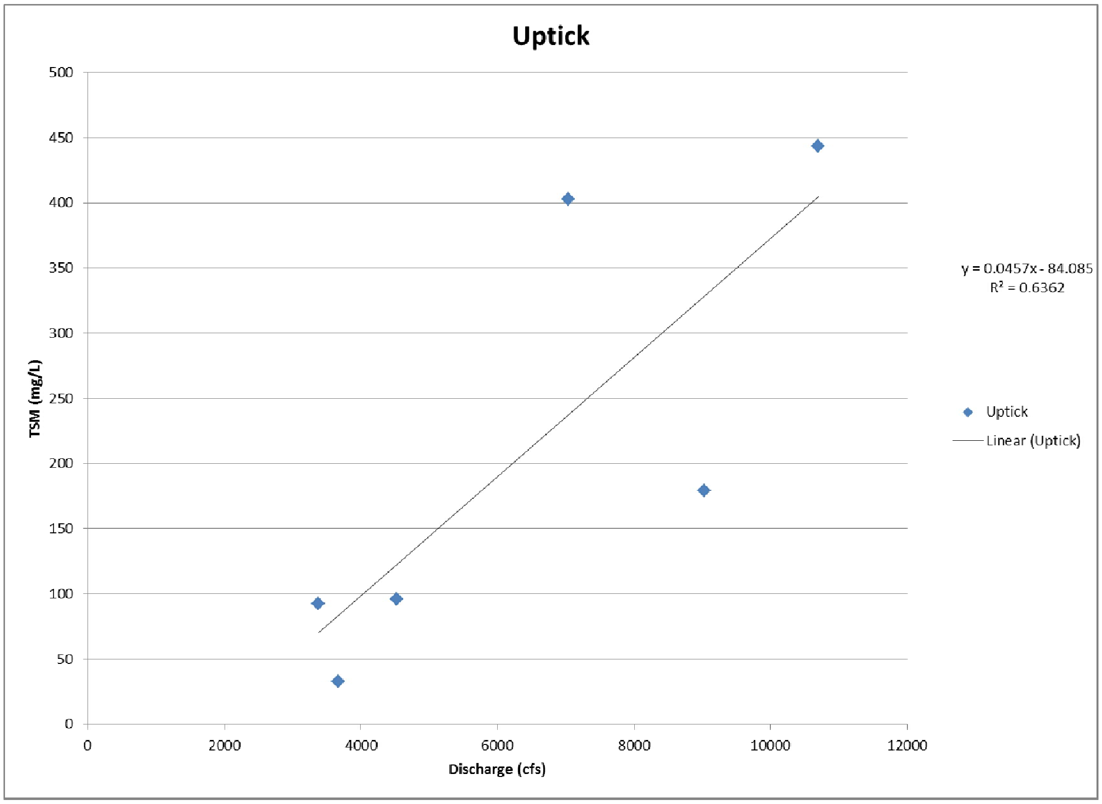


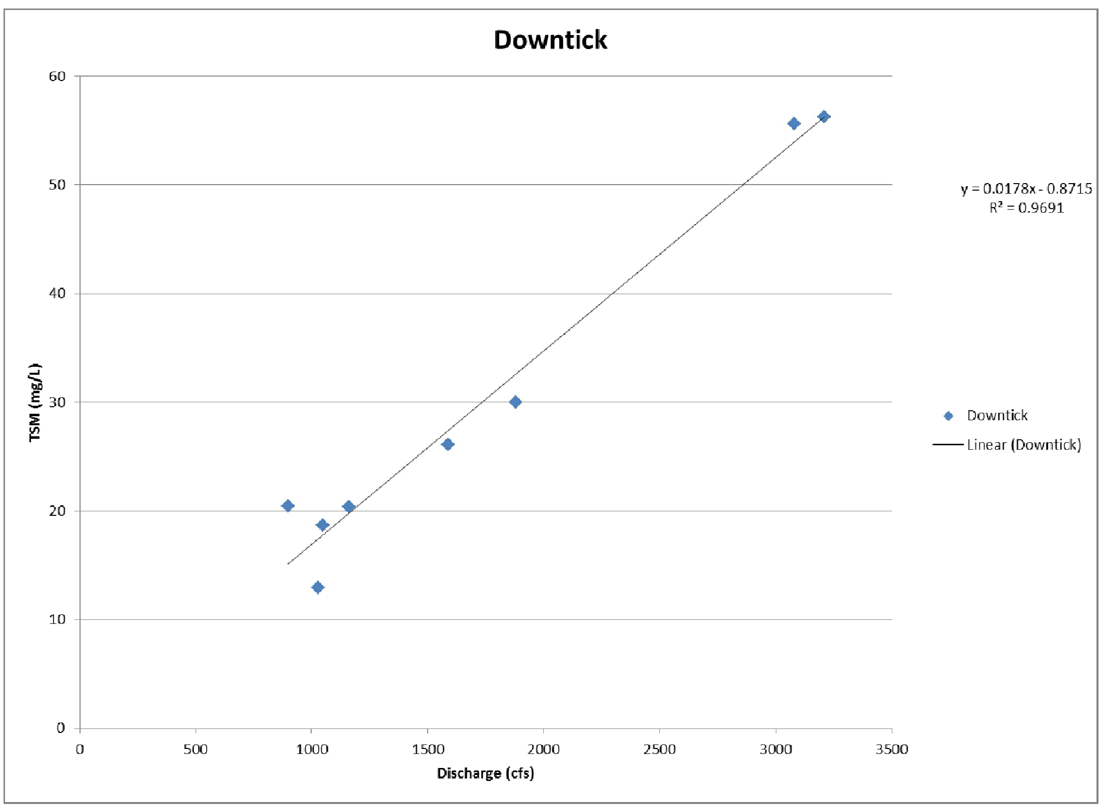
40000
35000
30000
25000
20000
15000
10000
5000
0
60
50
40
30
20
10
0
11/14/07 0:00
2/22/08 0:00
6/1/08 0:00
9/9/08 0:00
12/18/08 0:00
3/28/09 0:00
7/6/09 0:00
10/14/09 0:00
1/22/10 0:00
5/2/10 0:00
8/10/10 0:00
11/18/10 0:00
Discharge
Base Flow 210Pbxs
Peak Flow 210Pbxs

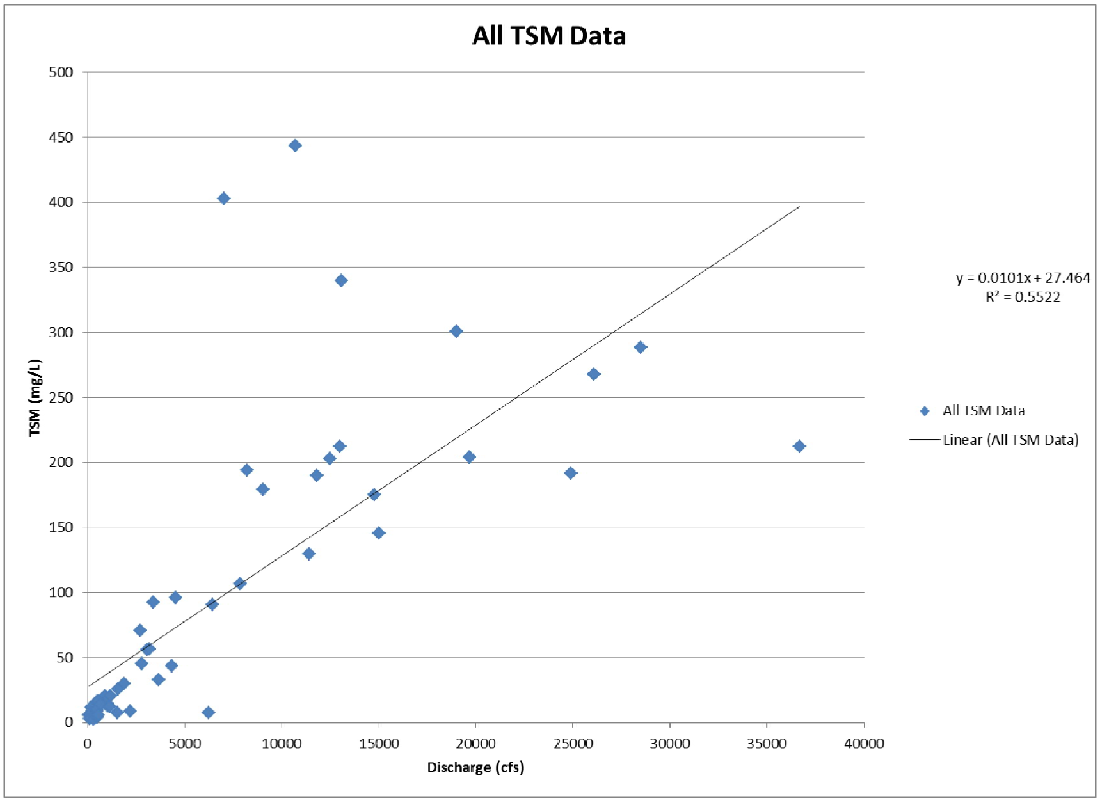
APPENDIX D

TSM VERSUS DISCHARGE PLOTS




Uptick
500
450
400
350
300
250
200
150
100
50
0
TSM (mg/L)
0
2000
4000
6000
8000
10000
12000
Discharge (cfs)
y = 0.0457x - 84.085
R² = 0.6362
Uptick
Linear (Uptick)


Downtick
60
50
40
30
20
10
0
TSM (mg/L)
0
500
1000
1500
2000
2500
3000
3500
Discharge (cfs)
y = 0.0178x - 0.8715
R² = 0.9691
Downtick
Linear (Downtick)


All TSM Data
500
450
400
350
300
250
200
150
100
50
0
TSM (mg/L)
0
5000
10000
15000
20000
25000
30000
35000
40000
Discharge (cfs)
y = 0.0101x + 27.464
R² = 0.5522
All TSM Data
Linear (All TSM Data)

APPENDIX E

SAMPLE DATA

Sample	Hydrograph	TSM (mg/L)	Flow (cfs)	$^{210}Pb_{xs}$ (dpm/g)	+/-	^{7}Be (dpm/g)	+/-	$^{7}Be/^{210}Pb_{xs}$
4/29/08 14:45	Peak	194.11	8200	8.692	1.685	21.510	1.881	2.475
5/14/08 10:30	Base flow	15.93	451	10.771	2.918	54.275	3.202	5.039
5/29/08 8:15	Base flow	6.28	350	14.170	2.596	33.286	15.353	2.349
6/10/08 8:00	Base flow	4.25	130	9.547	5.240	29.621	7.351	3.103
6/24/08 10:15	Falling-limb	12.95	1030	9.784	3.201	50.613	4.031	5.173
7/1/08 8:45	Peak	7.58	1520	11.651	2.840	33.406	3.646	2.867
7/7/08 15:00	Falling-limb	20.44	900	10.790	2.000	56.227	3.351	5.211
7/10/08 12:30	Peak	14.1	663	11.038	2.390	87.640	4.265	7.940
7/25/08 12:45	Peak	4.27	500	15.738	2.413	68.363	4.199	4.344
8/13/08 10:30	Base flow	5.81	86	20.487	4.294	63.952	4.993	3.122
8/28/08 12:00	Peak	288.36	28500	4.143	1.303	9.687	1.318	2.338
9/6/08 15:15	Peak	267.57	26100	2.540	1.331	5.770	1.127	2.272
9/17/08 11:00	Peak	45.25	2800	7.410	1.519	23.544	1.571	3.177
9/18/08 14:15	Falling-limb	20.36	1160	6.073	1.491	23.933	1.676	3.941
10/1/08 13:30	Base flow	16.48	534	11.817	2.583	89.346	4.258	7.561
12/11/08 15:00	Base flow	9.75	478	7.236	2.176	0.000	0.000	0.000
12/12/08 14:45	Peak	190.09	11800	4.380	1.578	0.000	0.000	0.000
2/11/09 11:30	Base flow	8.52	462	8.099	3.297	31.539	5.640	3.894
3/2/09 13:30	Peak	212.22	13000	4.633	0.649	10.391	0.710	2.243
3/16/09 10:30	Peak	129.66	11400	3.021	0.987	10.193	1.344	3.374
3/29/09 11:00	Peak	90.48	6450	4.474	1.772	19.258	2.056	4.305
5/1/09 11:00	Base flow	4.92	379	6.328	4.261	27.693	4.295	4.376
5/6/09 12:45	Peak	8.7	2210	9.449	2.232	42.145	2.537	4.460
5/14/09 15:00	Base flow	4.41	437	10.325	2.977	46.826	3.376	4.535
6/6/09 8:45	Peak	203.85	19700	3.528	1.594	11.056	1.803	3.134
7/13/09 14:45	Base flow	6.18	128	54.760	7.618	111.796	4.310	2.042
9/18/09 12:15	Base flow	2.54	128	37.090	7.690	89.340	8.990	2.409
9/28/09 9:45	Peak	11.99	1140	8.600	2.150	24.000	13.240	2.791
10/14/09 16:00	Base flow	3.22	131	48.150	8.870	251.160	11.950	5.216
11/2/09 9:45	Peak	70.77	2700	6.918	1.672	46.339	10.929	6.698

11/9/09 13:30	Base flow	11.96	186	11.450	2.670	53.070	4.630	4.635
11/11/09 15:30	Rising-limb	402.65	7040	5.279	1.500	26.792	5.453	5.075
11/12/09 19:45	Peak	191.67	24900	0.921	0.135	2.278	0.404	2.473
11/16/09 15:45	Falling-limb	30.01	1880	7.210	1.770	36.702	12.727	5.091
11/24/09 10:15	Peak	7.41	6250	4.024	1.309	25.652	2.526	6.374
12/2/09 16:15	Base flow	14.71	1020	18.734	2.952	94.588	3.505	5.049
12/3/09 2:00	Rising-limb	179.18	9030	4.778	1.284	20.677	2.013	4.328
12/3/09 14:45	Peak	174.83	14800	6.419	1.457	19.031	2.057	2.965
12/10/09 0:15	Peak	145.3	15000	4.374	1.252	20.971	1.916	4.795
1/22/10 13:30	Rising-limb	32.94	3670	9.362	2.144	34.278	1.998	3.661
1/22/10 21:00	Peak	43.49	4340	12.260	2.293	39.506	3.917	3.222
1/25/10 9:45	Rising-limb	443.3	10700	0.637	0.101	1.787	0.108	2.806
1/25/10 20:15	Peak	300.56	19000	3.195	1.180	11.594	1.938	3.629
1/28/10 12:15	Falling-limb	55.65	3080	6.979	1.932	24.810	2.919	3.555
2/6/10 12:00	Peak	212.22	36700	0.828	0.115	3.142	0.115	3.795
3/29/10 14:45	Peak	202.8	12500	4.849	1.525	27.190	2.301	5.607
5/3/10 12:45	Base flow	2.49	298	17.700	4.830	30.550	4.770	1.726
5/17/10 16:00	Rising-limb	96.06	4520	6.681	1.768	26.181	2.057	3.919
5/18/10 8:15	Peak	339.92	13100	3.851	1.410	22.119	1.802	5.744
5/19/10 10:45	Falling-limb	56.28	3210	5.997	1.545	30.956	1.838	5.162
5/20/10 11:00	Falling-limb	26.09	1590	5.242	1.672	31.758	2.276	6.059
5/21/10 11:45	Falling-limb	18.64	1050	6.938	1.713	36.433	2.162	5.251
6/10/10 11:45	Base flow	7.49	208	11.045	3.121	30.674	3.027	2.777
TSM Only								
11/23/09 18:00	Rising-limb	92.55	3380					
6/29/10 10:00	Base flow	3.12	157					
7/29/09 15:15	Peak	6.03	532					
1/7/09 14:15	Peak	106.85	7860					

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