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The Hydrology and Sediment Transport of Low-Gradient, Forested Headwater Streams

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THE HYDROLOGY AND SEDIMENT TRANSPORT OF LOW-GRADIENT, FORESTED HEADWATER STREAMS

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TABLE OF CONTENTS

ACKNOWLEDGMENTS ii

LIST OF TABLES v

LIST OF FIGURES vii

ABSTRACT xi

CHAPTER 1. INTRODUCTION 1

CHAPTER 2. LITERATURE REVIEW 6
- 2.1 Hydrology of Headwater Streams 6
- 2.2 Sediment Transport in Headwater Streams 10
  - 2.2.1 Suspended Sediments 11
  - 2.2.2 Dissolved Solids 13
- 2.3 Ponding in Forested Headwater Streams 15
  - 2.3.1 Debris Dams 15
  - 2.3.2 Beaver Dams 17
- 2.4 Hydrologic Simulation 19
  - 2.4.1 Spatial Modeling 19
  - 2.4.3 Soil and Water Assessment Tool (SWAT) 20

CHAPTER 3. METHODS 23
- 3.1 Site Description 23
- 3.2 Streamflow Measurements, Water Sampling and Weather Observation 27
- 3.3 Development of Stage-Discharge and Sediment Rating Curves 32
- 3.4 Hydrologic Modeling 34

CHAPTER 4. RESULTS 37
- 4.1 Hydrology 37
  - 4.1.1 Seasonal Conditions 37
  - 4.1.2 Stormflow Hydrology 43
- 4.2 Suspended Solids 50
  - 4.2.1 Baseflow Total Suspended Solids (TSS) 50
  - 4.2.2 Stormflow TSS 55
- 4.3 Dissolved Solids 58
  - 4.3.1 Baseflow Total Dissolved Solids (TDS) 58
  - 4.3.2 Storm TDS 63
- 4.4 Hydrologic Modeling 66
  - 4.4.1 Streamflow Initial Simulation and Calibration 66
  - 4.4.2 Simulation Accuracy 71

CHAPTER 5. DISCUSSION 75

5.1 Hydrologic Responses in the Flat Creek Headwaters 75
5.2 Sediment Transport in the Flat Creek Headwaters 78
5.3 Applicability of the SWAT Model 86

CHAPTER 6. CONCLUSIONS 91

REFERENCES 93

VITA 104

LIST OF TABLES

3.1. Descriptions of stream monitoring locations (sites) where stream discharge was measured, and water samples were collected. ... 28

3.2. Discharge, Total Suspended Solid (TSS) and Total Dissolved Solid (TDS) r-squares from log-linear regression. Discharge (m^3/s) is related to stream depth (m) where TSS loading (kg) & TDS loading (kg) is related to discharge ... 34

3.3. Parameters adjusted in the Soil and Water Assessment Tool (SWAT) during model calibration. Ranges are recommended, and default values given are from the initial model run, before calibration. ... 36

4.1. Amount of precipitation converted into runoff with wet and dry antecedent conditions, in order of increasing drainage area. Use of one weather station to measure precipitation assumes uniform precipitation, and may result in errors from unknown spatial variation... 41

4.2. Descriptive statistics of daily streamflow (L/s) for all sample sites. ... 43

4.3. Dates of sampled storms with "x" denoting a storm sample at the respective site. Missing storm samples were due to variation in individual site response, equipment malfunctions, or laboratory testing problems ... 44

4.4. Storm hydrograph characteristics for all intensive sites in response to a 34.0 mm precipitation event, occurring on 02 Feb 2006. ... 45

4.5. Stormflow recession constants for sites with increasing drainage areas. Coefficients of determination (r^2) are calculated between predicted recessions using the individual equation, and observed streamflow recessions. ... 48

4.6. Stream Total Suspended Solid (TSS) concentrations determined from monthly baseflow water sampling over the study period. Dashed (-) values represent no flow during monthly sampling. ... 51

4.7. Log transformed regression coefficients of determination between Precipitation (mm), Average Storm Intensity (mm/hr), and TSS (mg/L) for all intensive sites ... 58

4.8. Stream Total Dissolved Solid (TDS) concentrations determined from monthly water baseflow sampling. Dashed (-) values represent no flow during monthly sampling. ... 59

4.9. A comparison of stream flow characteristics from monthly sampling performed on 21-22 Feb 2007, in order of increasing drainage area. ... 60

4.10. Stormflow and storm sample Total Dissolved Solid (TDS) characteristics for site I4 ... 66

4.11. Soil and Water Assessment Tool characteristics for each subwatershed. ... 67

4.12. Land Use and Soil Distribution 68

4.13. Statistical comparison of monthly simulated and observed results for I1 and E4, using the Nash-Sutcliffe efficiency (NS_e), Mean Absolute Error (MAE), and Relative Error (RE). .. 74

5.1. Soil test results for selected ionic species (±SD). 85

5.2. Observed and SWAT simulated runoff percentages for the entire 17 month study period.. 88

LIST OF FIGURES

1.1. Location of the coastal plain region in the southeastern US (USFS 1969). 2

3.1. Location of the Flat Creek Watershed in North Central Louisiana. 23

3.2. Land use categorization of the Flat Creek Watershed, analyzed from a 2006 LandSat 5 TM image. Upland evergreen and bottomland deciduous forests dominate over 90% of the land in the watershed. 24

3.3. Observed mean monthly temperatures recorded at the weather station in the Flat Creek Watershed, compared with the long-term (1971-2001) averages at the NCDC Winnfield 2W weather station, located approximately 23 km south. 25

3.4. Elevations range from 21 to 92 meters above mean sea level, and land slopes range from 0% to 23% in the Flat Creek Watershed. Details on sampling sites are given in Section 3.2 and Figure 3.5. 27

3.5. A map of the 369 km^2 Flat Creek Watershed showing sample sites, weather station, and stream locations. Site E4 is used as the watershed outlet, as access to the actual watershed outlet at site E6 was unavailable. 29

3.6. Methods used for determining stage-discharge relationships. Flow measurements for discharge determination (left), and inserting the water level logger in the stilling well on a bridge pylon (right). The stage gage is also visible on the adjacent pylon in the background. 33

4.1. Monthly observed and average (1971-2001) precipitation for the 17-month study. 37

4.2. Total monthly discharge for all study sites where flow could be determined. E4 discharge is on the right y-axis due to higher magnitude of streamflow. 38

4.3. Coefficient of Variation (CV) for monthly streamflow (mm) generally decreases with increasing drainage area. Streams draining smaller areas tend to respond more quickly to variations in precipitation than streams draining larger areas. When compared with monthly precipitation (mm) CV, streamflow in several smaller streams is more variable than precipitation and less variable in larger streams. 39

4.4. Streamflow variability of Turkey Creek between dry and wet seasons, downstream of site N1 39

4.5. Percent of total precipitation over entire study period (1632 mm) converted to runoff at each site. Runoff is the total discharge measured at each stream site, divided over the drainage area. Remaining precipitation is assumed to be lost to evapotranspiration due to negligible groundwater recharge. 40

4.6. Flow Duration Curves (FDCs) for all sites analyzed. FDCs provide a way to compare sample sites using mean daily discharge (L/s), showing here that site I1 had the most continuous flow and site E2 had the least continuous flow. 42

4.7. Percentage of baseflow, or groundwater, contributing to stormflow at sites I1 and I4. Site I4 shows higher proportions of baseflow contributing to stormflow than at site I1. 46

4.8. Precipitation event and associated stream response for all intensive sites on 25-26 Apr 2007. Stream depth instead of discharge was used in order to compare all sites, as discharge was unable to be determined at sites I2, I5, and I6. The lack of response at site I2, shown in red, shows the potential for variation in storm responses between stream sample locations. 47

4.9. Comparison of stormflow recession curves of sites with different drainage areas. Discharge and time were normalized using peak discharge (Q_p) and total time of recession (t_r). Details of the recession constant (k_1) are in table 4.5. 49

4.10. Storm hydrograph characteristics of Lag Time (T_L) and half-flow period ($t_{0.5}$) increase with drainage area. 50

4.12. Box and whisker plots of Total Suspended Solid (TSS) concentrations for all sites. Boxes show values in the middle 50%, bounded by the first and third quartiles (Q1&Q3), and sites are arranged from lowest to highest drainage area. Variations in sample numbers (n) are due to dry periods where no surface flow existed at the site and samples were not collected. ... 52

4.13. Comparisons of monthly discharge with monthly Total Suspended Solid (TSS) concentrations (A&B) and loadings (C&D) for sites I1 and E4, the smallest and largest drainage areas, over the 17-month study period. 53

4.14. Monthly Total Suspended Solid (TSS) loading for all sites. Site E4 values are listed on the right y-axis, with all other site values located on the left y-axis. Zero values occur at no flow periods during monthly sampling. 54

4.15. Average monthly Total Suspended Solid (TSS) loading and flux over the 17-month study. TSS loading increases and TSS flux decreases with increasing drainage area.................... 55

4.16. Box and whisker plots of Total Suspended Solid (TSS) concentrations for storm samples collected during the study period from intensive sites. Boxes show values in the middle 50%, bounded by first and third quartiles (Q1 & Q3), and sites are arranged from lowest to highest drainage area. Connected points show the trend of average TSS with increasing area. Variations in sample numbers (n) are due to variable stream responses not triggering all automatic samplers or equipment malfunction. 56

4.17. Seasonal variation in storm sample Total Suspended Solid (TSS) concentration levels..... 56

4.18. Relationships of streamflow to Total Suspended Solid (TSS) concentrations and loadings at I1 and I4. Data points are direct values, but regression r^2 values are for log-transformed data. 57

4.19. Box and whisker plots of monthly baseflow Total Dissolved Solid (TDS) concentrations for all sites during the study period. Boxes show values in the middle 50%, bounded by first and third quartiles (Q1 & Q3) and sites are arranged from lowest to highest drainage area. Variations in sample numbers (n) are due to dry periods where no surface flow existed at the site and no sample was collected. 60

4.20. Monthly Total Dissolved Solid (TDS) loading for all sites. Site E4 values are listed on the right y-axis, with all other site values located on the left y-axis. Zero values represent no flow during monthly sampling. 61

4.21. Comparisons of monthly discharge with monthly Total Dissolved Solid (TDS) concentrations (A&B) and loadings (C&D) for sites I1 and E4, the smallest and largest drainage areas, over the 17-month study period. 62

4.22. Box and whisker plots of storm Total Dissolved Solid (TDS) values for all sites. Boxes show values in the middle 50%, bounded by the first and third quartiles (Q1 & Q3), and sites are arranged from lowest to highest drainage area. Connected points show the trend of average TDS with increasing area. Variations in sample numbers (n) are due to variable stream responses not triggering all automatic samplers or equipment malfunction. 63

4.23. Seasonal variation in storm sample Total Dissolved Solid (TDS) concentration levels. ... 64

4.24. Daily stream depth and Total Dissolved Solid (TDS) Concentrations at site N1 on Turkey Creek in August 2006. 65

4.25. Subwatersheds used for the Soil and Water Assessment Tool simulation based upon sites where discharge was measured, to compare observed and simulated streamflows. 67

4.26. Monthly (A) and daily (B) streamflow simulation results, compared to observed streamflow at site I1, the site with the smallest drainage area. 71

4.27. Monthly (C) and daily (D) streamflow simulation results, compared to observed streamflow at site E4, the Flat Creek Watershed outlet. 72

5.1. Riparian flooding at site I6 along Turkey Creek. 76

5.2. Beaver Dam located downstream of site I6 on Turkey Creek. 77

5.3. Box and whisker chart, modified from Figure 4.19 to include a Total Dissolved Solid (TDS) concentration from samples collected in pools of water on intermittent streams. 79

5.4. Monthly average Total Dissolved Solids (TDS) concentrations from previously analyzed non-pooled sites and pooled (I2, I5, I6) sites, with standard deviations marked by dashed lines. No standard deviations exist for two months (Sep, Oct 2006) of the non-pooled sites, as only one site was flowing. 81

5.5. Monthly average Total Suspended Solids (TSS) concentrations of previously analyzed non-pooled and pooled (I2, I5, I6) sites, with standard deviations marked by dashed lines. No standard deviations exist for two months (Sep, Oct 2006) of the non-pooled sites, as only one site was flowing........ 82

5.6. Average monthly baseflow and storm sample concentrations of Total Suspended Solids (TSS) for all intensive sites, with standard deviation bars........ 83

5.7. Average monthly baseflow and storm sample concentrations of Total Dissolved Solids (TDS) for all intensive sites, with standard deviation bars. 84

5.8. Comparison of observed and SWAT simulated average daily streamflow at site I1. Baseflow is consistently underestimated, with frequent overestimation of stormflow peaks. Note the premature flow peaks also present in the earlier storms. 87

ABSTRACT

Understanding stream hydrology of headwater regions is critical in effective land management for downstream water quantity and quality. Although extensive research has been performed on headwater streams in topographically variable areas, fewer studies examine low-gradient headwater stream systems, such as those existing on much of the southeastern coastal plain. This study aims to investigate spatial and temporal variation of headwater stream hydrology in a low-gradient forested watershed, quantify mass loading of suspended and dissolved solids in the watershed, and assess the applicability of a spatially distributed model in predicting hydrologic responses of a flat terrain landscape. Stream discharge and sediments were monitored for 17 months (Dec 2005 – Apr 2007) throughout the Flat Creek Watershed, a 369 km^2 basin located in north central Louisiana. Containing 1st, 2nd, and 3rd order streams, land slopes average 3.9% and channel slopes are less than 1%. Results show that streamflow variability throughout the study period was highest in the 1st order streams, but ranged from intermittent conditions to water levels exceeding bankfull height throughout the watershed. Evapotranspiration in the watershed was high, exceeding 80% of the precipitation in most areas, and was partly due to low levels of rainfall. Suspended and dissolved solid loading was mainly controlled by discharge levels, as concentrations of solids did not vary extensively throughout the study period. Sediment yields in the Flat Creek Watershed were also lower than many other regions in the United States. Additionally, hydrologic simulation of streamflow using the Soil and Water Assessment Tool (SWAT) did not perform well, suggesting this type of model may not be applicable to the complex runoff processes created by the flat terrain. Representation of the water budget for the 17 months was reasonably close, but streamflow timing was off with

consistent overestimation of storm peaks and underestimation of baseflow discharge. Physical watershed characteristics including the low slopes, elevated water table, beaver/debris dams, and stream geomorphology combine to increase water storage and residence time, reduce peak stormflows, sustain higher baseflows, and influence sediment loading rates in the low-gradient forested watershed.

CHAPTER 1. INTRODUCTION

Early studies on forested watershed hydrology were established in Central Europe during the late 19th century as a response to alpine flooding and landslide disasters, suspected to be a result of widespread forest clearing (e.g., McCulloch and Robinson 1993). In the United States, investigations of forested headwaters began in the first decade of the 20th century, leading to the passage of the Week's Act of 1911 (USFS 2007). Passage of this act authorized federal purchase of forest land in headwater regions for protection of navigable streams showing that even in the early 1900's, the strong physical connection of headwater streams to larger rivers was already recognized. Over the past few decades, studies on the relationship between headwaters and downstream receiving waters has transitioned from simple water quantity, expanding to nutrient transport, sediment delivery, and biogeochemical cycles within large basin systems and at the land-ocean interface (e.g., Likens & Bormann 1974; Mulholland & Kuenzler 1979; Meybeck 1982; Stieglitz *et al.* 2003).

Although forested headwaters have been intensively studied for over a century, few studies exist on the unique processes of the southeastern coastal plain in the U.S. (Figure 1.1). This gap in research and knowledge is especially important, as forests cover approximately 55% of the land cover in the southeast (Flather *et al.* 1990), occupying a large portion of headwater areas. The region has low average land slope (3.9%) and very low channel slopes (≤ 1%), creating extensively meandering streams with very low velocities and seasonally inundated backwaters. Complexities created by the low-gradient topography and shallow ground water located in many areas of the region can make quantification of surface hydrology difficult. Understanding hydrologic characteristics of

these low-gradient watersheds is ultimately critical for effective water resources management and water quality protection in the region.

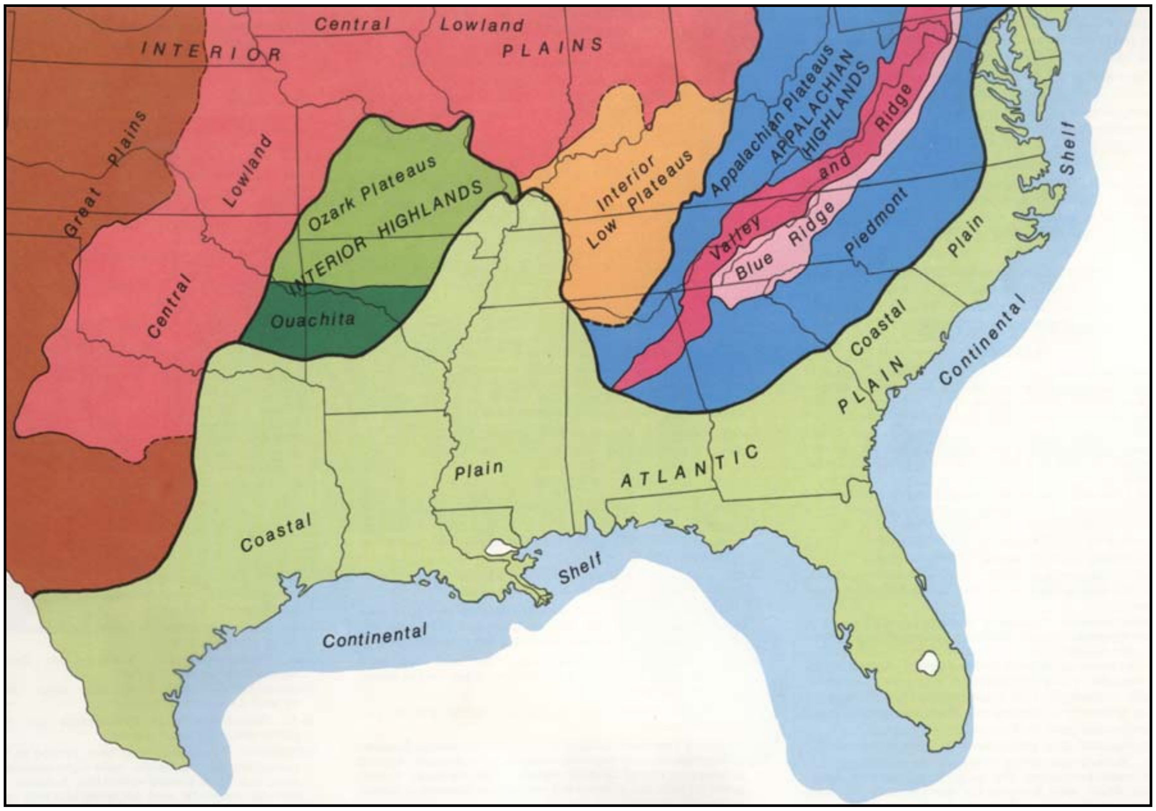

Figure 1.1. Location of the coastal plain region in the southeastern US (USFS 1969).

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Ecologically, the southeastern coastal plain of the United States include extensive hilly upland pine forests, bottomland hardwoods, riverine swamps and marsh complexes along the Atlantic and Gulf coasts. Initially well drained upland pine plantation forests in sandy loam soils slope down to bottomland hardwoods along the flat stream floodplains, where surface ponding occurs from low permeable clays. Hupp (2000) suggests a "rigorous relationship between vegetation and hydrogeomorphological processes," as small variations in elevation on the flat topography can affect hydrologic processes, altering vegetation types, and even creating a complete change in habitat. Beaver activity

also establishes a biological influence on stream hydrology. By damming the streams, beavers create ponds, increase water storage and residence time, and make the low streamflow even more variable along the entire stream network. Geomorphologically, stream position on the flat landscape, in-stream debris, and channel characteristics can vary extensively throughout this type of watershed, causing large variations in flow and sediment delivery spatially and seasonally.

Stream response and sediment transport characteristics from headwaters to the larger watershed outlet is necessary to understand the effects of these physical controls present at different scales. Processes occurring in a small drainage area may affect the watershed outlet, but may not be directly visible at the larger watershed scale. The streams in this region become intermittent in the dry summer season, but this does not directly start in the headwaters and move down to the larger streams due to the interactions described above. Water released from a beaver dam, for instance, can create flow upstream of a dry bed existing further downstream. Sections of the stream flowing through an area of elevated local groundwater will also have higher sustained baseflow and take longer to become intermittent.

Sediment yield from forested areas is generally considered to be lower than most types of land use. However, it is the primary pollutant to streams from forest dominated land (Patric *et al.* 1984). Among forested areas in the US, southeastern coastal plain forests typically contribute lower sediment delivery to streams, due to the low land gradients (Beasley and Granillo 1988). However, higher rates of erosion can occur after forest harvesting operations, leading to reduced water quality. Sediment yield can also be

increased when harvesting operations on saturated soil can cause extensive compaction, rutting, and disturbance in areas with a high water table.

Dissolved solid levels are also important to stream water quality. High concentrations of dissolved solids can decrease the suitability of aquatic habitat for plants, fish, macroinvertebrates and other aquatic species. Streams in the study watershed are currently considered impaired for high levels of dissolved solids (>100 mg/L, LDEQ 2001) after assessment in accordance with the EPA's Total Maximum Daily Load (TMDL) program. Potential sources for this condition are brine discharge onto the land around oil wells and naturally high groundwater levels (USEPA 2002). The contribution of groundwater and stormflow to the stream is then critical in determining the cause of high stream TDS.

Hydrologic models are used to simulate and predict changes in the quantity and quality of water in a stream with changes in land use. A spatially distributed, calibrated model for the watershed can be used to assess stream effects of forest harvesting in this watershed, as well as land management variables affecting non-point source pollution. Distributed models have the advantage of incorporating both spatial and temporal variations, whereas lumped hydrologic models only assess variation with time. Integrated into the EPA's BASINS modeling framework for assessing TMDLs, the Soil and Water Assessment Tool (SWAT) is a widely used hydrologic model that will newly be applied in a lowland forested watershed.

This study was conducted to investigate hydrologic responses and sediment delivery of headwaters in a low-gradient, forest-dominated watershed in the southeastern gulf coastal plain. It is part of a larger research project that attempts to determine the

effectiveness of forestry best management practices in headwater protection for this region. Specifically, this study aims to achieve three main objectives: (1) determine spatial and temporal variation of headwater stream hydrology in a low-gradient forested watershed, (2) quantify mass loading of suspended and dissolved solids in the watershed, and (3) assess the applicability of a spatially distributed model in predicting hydrologic responses of a flat terrain landscape. In addition to accomplishing its own research objectives, this study provides data support for two other sub-studies of water quality and aquatic ecology, which are being completed by BryantMason (In Preparation) and Viosca (2007).

CHAPTER 2. LITERATURE REVIEW

2.1 Hydrology of Headwater Streams

First-order, headwater streams comprise over 77% of all streams in the United States, encompassing almost half of the total stream length (Leopold *et al.* 1964). Due to the overwhelming number of such streams, their contribution and importance to hydrological processes and water quality in all watersheds are considerable. As such, the protection of headwater streams can help maintain a more natural flow regime and benefit stream habitat over the entire river network (Saunders *et al.* 2002).

Creating definitive definitions of a headwater stream has been attempted using characteristics such as hydrology (first-order, intermittent, ephemeral, runoff-controlled), geomorphology (gradient, drainage area), and the resulting processes (sediment transport, debris flow) (Benda *et al.* 2005). However, most of these characteristics change with the geology, topography, and size of each stream network making a single quantitative definition extremely difficult if not impossible. Using Hack and Goodlett's (1960) description of headwater systems, where headwaters are comprised of hillslopes, zero-order basins, ephemeral or temporal channels, and first- and second-order stream channels, Uchida and others (2005) argue that hillslopes fall into zero-order basins because the hillslope area does not contain ephemeral and perennial flows. In the southeastern coastal plains of the U.S., Rheinhardt and others (1998) were able to positively correlate stream order with drainage basin size, floodplain width, and channel width.

Stormflow response in headwater streams can be highly variable depending on antecedent moisture conditions, affecting both the source and flow path of runoff (Sidle

et al. 2000). Church (1997) states that many studies have determined the major source of stormflow generated in forested catchments to be from pre-event (old) water, stored in the soil or groundwater reservoirs. Pearce and others (1986) found this to be true in the steep forested headwater catchments in the Tawhai State Forest of New Zealand, actually reversing the conclusions of an earlier study that had determined subsurface event flow to be dominant (Mosley 1979). However, Brown and others (1999) found that in the dry summer season, stormflow in headwater streams of the Catskill Mountains had high contributions from event water (precipitation). Elsenbeer and others (1995) also found forested headwater stormflow to be controlled by event water in the La Cuenca rainforest of western Amazonia.

Hewlett and Hibbert (1967) defined these variations in runoff flowpaths and sources due to rainfall amounts and antecedent moisture conditions as the Variable Source Area. Studying the Maimai watershed in New Zealand, McGlynn and others (2004) found runoff from a 27 mm storm in dry conditions to be mainly from headwater riparian zones, with runoff sources spreading out to the hillslopes and valley floor of the larger downstream river after a 70 mm storm in wet conditions. Brown and others (1999) also determined that increases in the size of catchments draining to headwater streams in the Catskills led to an increase in peak flow and the higher contribution of groundwater to summer storm events. While influenced by fluctuations in the variable source area, individual catchment characteristics, geographical location, and position in the watershed, disagreements remain on the origins of stormflow water.

Much of the literature on headwater streams is based upon studies in more topographically variable areas. As a result, some of those findings are applied or

interpreted with respect to the lowland characteristics of the coastal plain headwaters. In a review of several coastal forested watershed studies, Amatya and others (2005) comment on the limited number of hydrology and water budget studies in these complex and complicated areas, and expound on the need for long-term ecohydrologic monitoring to more fully determine the effects of forest management on water quality.

This type of system also has many labels throughout the literature - forested wetlands, bottomland hardwoods, flatwoods, forested lowlands, lowland coastal plains, and poorly drained loblolly plantations – among many others. All of them describe a portion, particular aspect, or general characteristic of this type of area. Some descriptions are interchangeable, some are distinct, but many exist without clear definitions. In this review, the labels are used as they are given, so as to keep consistent the author's intent when choosing how to describe a particular area.

Headwater streamflow in the forested lowlands of the southeastern United States depends largely upon the level of the local water table, as most flow results from saturated areas of the watershed (Amatya 2003). A report by Chescheir and others (2003) on 41 coastal lowland forested watersheds in eastern North Carolina determined that the major input to these streams is precipitation and the major outputs are evapotranspiration and stream outflow, with the highest outflows occurring in winter. Hewlett and Hibbert (1967) list soil depth, land slope, precipitation level, and land use as the most important factors, from highest to lowest, in determining stream runoff response in small humid watersheds.

Using long term hydrologic records, Sun and others (2000) determined that approximately 25% of annual precipitation leaves South Carolina forested wetland

watersheds through streamflow. This is comparable to the 27% in a similar Georgia watershed (Bosch 2006) and the 31% in analogous North Carolina watersheds, as quantified by Chescheir and others (2003), who also comment that loss to groundwater recharge is unsubstantial. Although Hewlett and Hibbert (1967) report that storm runoff amounts for watersheds in this area are usually less than 25%, with even the largest storm events rarely surpassing 50% of the precipitation.

Even though the average amount of runoff from precipitation was similar over all watersheds, the studies also found an extremely large range depending on the annual level of precipitation (wet vs. dry years). In addition to annual totals, results by Harder and others (2007) show that the size and timing of precipitation events, as well as the antecedent water table level, also have considerable effects on watershed outflow throughout the year. Due to these variable conditions, watershed outflows vary substantially more than precipitation (Amatya *et al.* 2006).

While antecedent conditions play a large role in runoff generation, Bracken and Croke (2007) state that base flow and subsurface storage in temperate humid catchments facilitates quicker revival of hydrologic connectivity, when compared to semi-arid or arid regions. Headwater streams in the humid sub-tropics, which often become intermittent in the dry summer season, can therefore quickly return to flowing reaches when storm runoff events return.

Sun and others (2002) compared hydrologic conditions in a southern flatwood watershed against a mountainous Appalachian watershed. Comparatively, the flatwood watershed had lower water yields with less continuous streamflow, which was largely due to higher evapotranspiration in the spring and summer. A strong seasonal variation

also exists in these southeastern coastal plain streams, alternating between low flow (Jun-Oct) and high flow (Nov-May) periods (Hupp, 2000). Low flow summer conditions can lead to streams becoming intermittent and disconnected. Intermittency initially occurs in headwater streams draining small areas, later moving to 2nd and 3rd order streams with larger drainage areas.

In their study on intermittent streams, Butturini and others (2002) found that precipitation only explained 25% of the runoff variability in the dry summer season, but 80% of the variability in the wet winter and spring seasons. The large amount of water use by mature trees within forested regions, compared to other vegetated areas, can additionally decrease water supply to the already low flow streams (Johnson 1998). Within a comprehensive review on low flow hydrologic conditions, Smakhtin (2001) covered a variety of ways to analyze low flow including flow duration, low-flow frequency, flow recession, and storage-yield analyses. Results from these analyses can then be interpreted and applied to many types of water resources engineering, science, and management issues such as reservoir storage and drought management.

2.2 Sediment Transport in Headwater Streams

Studying the influence of headwater streams on water quality downstream, Alexander and others (2007) found that headwater streams directly contribute about 70% of the flow to all 2nd order streams in the northeast, with that rate falling to 55% in streams 4th order and greater. Headwater streams are not only important contributors of flow to downstream areas, but also largely influence the physical, chemical, and ecological characteristics of larger streams. Maintaining hydrologic connectivity, or the "water-mediated transfer of matter, energy, and/or organisms within or between elements

of the hydrologic cycle" as defined by Pringle (2001), in these small headwater areas is necessary to maintain ecological integrity at larger ecosystem or regional scales (Freeman *et al.* 2007).

Sweeny (1992) comments that the existence of trees, or lack thereof, along a stream might be the most critical factor affecting the structure and function of streams flowing into estuaries along the Atlantic coast. The same statement can be applied to the streams flowing into the estuarial waters bordering the Gulf coast where trees and other vegetation directly affect the input of woody debris and composition of stream chemistry. Further research and investigation into the hydrologic mechanisms of forested headwater streams in this area is especially important as forest cover is expected to be maintained at approximately 55% of the land in the southeast (Flather *et al.* 1990).

2.2.1 Suspended Sediments

The quantification of sediment yield in the coastal plain headwaters can be difficult. During high flow periods, overbank flooding and reconnection of backwater channels and oxbows complicates in-channel sources and sinks of sediments. Additionally, locally minor variations in topography and large woody debris create complex channel velocities, affecting individual site sedimentation characteristics (Hupp 2000). Conversely, in headwater streams with high slopes, Benda and others (2005) comment that the major sources of sediment are mass wasting events from the adjacent hillslopes, such as landslides. However, the researchers determined that even high gradient headwater streams have a high storage capacity for sediment, due to low fluvial transport capabilities of the stream.

In a study on suspended solid characteristics of 60 small catchments in southwest England, Ankers and others (2003) found a high degree of variability within catchments having similar geology and soil type, and suggest land use, topography, and sediment source as influential factors of site specific variation. Developing multiple regression equations for predicting sediment yield in the coastal plain of North Carolina, Calvo-Alvarado and Gregory (1997) found forest cover and ponding to be the most influential factors from 35 variables tested.

Stormflow can result in the highest rates of suspended solids loading due to increased erosion and the large volume of discharge water. Storm events in a forested catchment on Penang Hill, Malaysia accounted for only 12.7% of the streamflow throughout the year, but were responsible for 60% of the Total Suspended Solids (TSS) load (Ismail 2000). However, pre-existing conditions can play a large role in determining the amount of stormflow TSS. In that same Penang Hill study, stormflow events during the driest and wettest months of the year contributed 0.7% and 52.4% of the annual TSS load, respectively (Ismail 2000). Subsequently, in some catchments, increases in suspended sediment loading from forest harvesting may be more a result of elevated streamflow than increases in sediment sources (Gomi *et al.* 2005).

Marion (1993) found that sediment yield from a pine catchment was less than from hardwoods due to different leaf litter properties, and much of the existing yield may actually come from channel erosion. Ursic (1986), as reported in Marion (1993), found streamflow and sediment concentration to be unrelated in southern pine forests, determining instead that loading amounts have a linear relationship with flow. This observation is consistent with the lack of a seasonal TSS concentration pattern observed

in a lower North Carolina coastal forested watershed, as opposed to the stormflow-concentration response found in agricultural or mixed use watersheds of the same region (Birgand 2006). The bottomland hardwood/forested wetland portion of these forested areas, adjacent to the streambed, increases the surface roughness, further reducing the already slow stream velocity and creating the potential for trapping sediments being transported through the stream channel. One such system, the Coosawhatchie River in South Carolina, was found to deposit 0.02-0.20 cm of sediment annually, which translates into an average 24.5 kg ha^{-1} yr^{-1} (Hupp 2000).

2.2.2 Dissolved Solids

Monitoring of dissolved solids in streams is typically done by measuring Total Dissolved Solid (TDS) or conductance values. Both parameters give an indication of the amount of charged ionic content in solution (Hem 1985), and the relationship between them can be determined using a regression equation. Differences in chemical composition, and therefore ionic concentration, of source waters is determined by the chemical characteristics of the initial precipitation, the abiotic or biotic substances in a watershed, the abiotic reactivity or biotic activity of those substances, and the length of contact with them (Church 1997). Stream dissolved solid concentration variability is due to differences in levels and types of dissolved ions of each water source that creates storm discharge: precipitation/overland flow, soil/interflow, and groundwater (Nakamura 1971). Geochemical characteristics of groundwater can be traced to the catchment parent material, whereas ionic characteristics of water in the soil matrix are transferred through chemical weathering (Billett and Cresser 1996). Between carbonate and silicate source

rocks, carbonate weathering largely determines the chemical composition of stream water (Ryu *et al.* 2007).

It is well known that conductance values vary with stream discharge, particularly during storm events. Conductivity tends to be negatively correlated with stream baseflow, as Quinn and Stroud (2002) found in a New Zealand pine catchment. During stormflow, however, conductivity values form a hysteric loop with discharge due to differences in ionic concentrations based upon whether the stream is rising or falling (Evans and Davies 1998). By determining the ionic concentration of each individual water component, storm discharge and conductivity measurements can be used to separate out each phase contributing to stormflow (Caissie 1996; Nakamura 1971; O'Connor 1976).

A low flow stream chemistry study from catchments on the Mawheraiti River in New Zealand revealed variations in conductivity could be explained by site characteristics (32%), discharge (27%), seasonality (15%), and other unknown factors (Mosley and Rowe 1981). Mosley and Rowe (1981) also found that smaller catchments on the Mawheraiti had greater conductivity variability, with conductivity levels increasing downstream. Diurnal streamflow fluctuations during low flow periods, due to high rates of evapotranspiration on warm summer days, also affected the level of stream conductivity. Kobayashi and others (1990) determined that the ionic concentration of a headwater stream in northern Japan closely followed diurnal flow variation, with both variables falling during the day and rising in the nighttime. Using these observations, the researchers suggested transpiration was causing the daily flow fluctuation - as opposed to direct evaporation which would result in increased ionic concentrations during the day.

2.3 Ponding in Forested Headwater Streams

Dams created from beaver activity and woody debris can affect the hydraulic flow, sediment loading, nutrient transport, and biological functions of a stream, as well as development of the stream channel itself (e.g., Bilby and Likens 1980; Gregory 1985; Naiman *et al*. 1988; Woo and Waddington 1990; Gurnell 1998; Jeffiries *et al*. 2003). Just as the headwater streamflow greatly affects downstream conditions, these dams have the potential to impact areas much larger than their immediate vicinities. Gurnell (1998) comments that although one dam may not have a large effect, a series of dams will have significant effects on a stream network. The researcher cites a finding by Ehrman and Lamberti (1992) where water retention increased 1.5-1.7 times in 3rd-order streams with woody debris dams. Sun and others (2002) state that the low topography in the southern U.S. has a large effect on streamflow, storm peaks, and wetland development. Beaver and debris dams, as described below, exacerbate these low gradient conditions.

2.3.1 Debris Dams

Formations of debris dams are described by Bilby and Likens (1980), whereby a large piece of wood or a branch becomes lodged in the stream, catching smaller woody debris - eventually down to sticks and leaves - and creating an almost impermeable barrier. The pool formed upstream then causes sediments and organic debris to settle, similar to beaver dams. Not only do stream velocities decrease, but Trotter (1990) also found an increase in width and depth of streams where log dams were artificially constructed. Sediment storage from the dams was found to be up to four times any erosion resulting from the debris, transforming into a significant source upon breaching (Hart 2002). In their study of debris dams in headwater streams, Wallace and others

(1995) concluded that by creating abiotic diversity, such structures also increase the biotic diversity in these systems.

Geomorphic sources of woody debris to streams and processes that affect debris transport are discussed by Hassan and others (2005) for headwater and lower order streams in the Pacific Northwest. Adjusting these categories to fit a lowland headwater stream on the Gulf Coastal Plain (e.g. removing effects of snow accumulation and landslides), the major geomorphic sources of woody debris to headwater streams are both the riparian zone as well as the stream itself. Included in these sources are seasonally inundated backwater areas that are directly connected to the stream during periods of high flow. Physical processes that affect the transport of the debris in this area are mortality, wind throw, fluvial transport, bank erosion, and flooding. However, Jackson and Sturm (2002) comment that bank erosion in their coastal Washington headwater streams was inconsequential due to low fluvial power of the streams. In addition to this list of physical processes, biological influences such as beaver activity may be added, which not only elevates the amount of in-stream woody debris, but then also modifies both debris sources and transport processes.

Smaller bankfull widths of headwater streams, ranging from 0.5 m to 3.5 m wide, can hold a significantly greater amount of large wood pieces than wider downstream channels, as was discover by Gomi and others (2006) in their study on headwaters in southeast Alaska. This is expected as the wood pieces can more easily become lodged in the smaller widths and the force of streamflow is much less than in wider, downstream areas.

Channel stability is also increased by the presence of woody debris. Removal of woody debris in a headwater and 4^{th}-order Washington State stream induced scouring and filling, modifying the average bed elevation 3.28 cm and 25.41 cm in the headwater and 4^{th}-order streams, respectively, along with reducing the overall number of pools (Bilby 1984). Additionally, a large storm event over a Malaysian forested headwater catchment, dislodged 60% of the woody debris over a 300m stream reach, and was also one of two precipitation events that accounted for 11% of the suspended sediment load for the entire year. As such, channel instability can occur with the removal of woody debris, often after large storm events which can create the fluvial power to move larger objects than typically possible.

2.3.2 Beaver Dams

Although beaver populations were estimated to be in the range of 60 to 400 million prior to European settlement of North America, beaver trapping severely reduced those numbers. Populations of beaver have been recently estimated at 6 to 12 million, and are rapidly increasing (Naiman *et al.* 1988). In a review of studies on beaver (*Castor canadensis*), Gurnell (1998) found a range of densities from 0.08 to 1.25 colonies per river kilometer with dam densities ranging anywhere from 0.14 up to 19.0 per river kilometer.

Dams created from beaver activity result in ponding along the stream channel. Ponding from beaver dams reduces peak discharges following storm events and helps to maintain streamflow during dry periods, while raising the groundwater level in the adjacent riparian zone. By reducing stream velocities by 2% - 100% (no flow), beaver dams help reduce the suspended sediment load and improve water quality downstream

(Butler and Malanson 2005). Deposition of both organic and mineral sediments occurs when the flowing stream enters the beaver pond (Gurnell 1998). In a Maryland coastal stream, TSS concentrations were highly correlated with discharge before the creation of a beaver pond, with no significant relationship between the two variables for much of the year after pond development (Correll *et al.* 2000). Naiman and others (1988), cited in Butler and Malanson (2005), also comment that streams with beaver dams may reduce the impact of upstream disturbances on downstream water quality.

Quantitative effects of beaver dams on hydrology and sediment loading may vary extensively with the unique geomorphologic characteristics at each individual dam location, not just between regions. Due to the combination of different features at each location, there is no way to directly relate reduction in streamflow or sedimentation rates to characteristics such as bankfull width, slope, or dam depth. Therefore, each beaver pond would have to be assessed separately to determine its effect – an impossible and impractical task. In one such situation, a study in Glacier National Park, Montana determined sedimentation rates caused by beaver dams by measuring soil depth down to the gravel beds of the pre-dam stream (Butler and Malanson 2005). However, this method would not work in Louisiana since streambeds already primarily consist of very fine sediment and organic matter. The ability to incorporate small in-stream dam effects on streamflow (e.g., reduced storm peaks, increased channel storage) in a hydrological model would be an efficient and cost effective method for analyzing, assessing, and predicting changes in streams with beaver dams.

2.4 Hydrologic Simulation

2.4.1 Spatial Modeling

To further the understanding of hydrologic processes in a watershed, a model of the dynamic functions controlling the flow of water from precipitation to outflow points of streams and groundwater can be created. This type of hydrologic modeling can be especially beneficial in water resources management as it is often difficult and costly to track and measure the flow and flux of water throughout an entire watershed.

Modern mathematical modeling of surface water movement began in the 1930's with Horton's equation for estimating soil infiltration capacity, in order to determine overland surface runoff with time. However, this approach originated from a small scale experimental catchment (14.4 ha), where it has been suggested that subsurface flow may actually be an important contributor to runoff (Beven 2004). By the 1970's, the Soil Conservation Service (SCS) finished developing their Curve Number (CN) method, which calculates precipitation runoff (Singh 2002). Garen and Moore (2005) criticize use of the CN method for streamflow and water quality modeling (Garen and Moore 2005), as it extends the method beyond its original purpose for flood design engineering.

With the technological advances made in programming and computers, more complex and comprehensive models could be developed and run with greater ease. The Stanford Watershed Model (SWM) (Crawford and Linsley 1966) was the first comprehensive computer run watershed model, which has since evolved into the current Hydrologic Simulation Program-Fortran (HSPF) model (Singh 2002). Many more models have since been developed, often with a specific goal in mind or to answer a particular question not handled by general models.

The development of Geographical Information Systems (GIS) in the 1980's allowed hydrologic models to analyze spatial variation in addition to temporal variation (Martin *et al.* 2005). The ability to integrate relationships between spatially referenced elevation, soil, land use, and land management characteristics allowed for an additional level of model detail that was previously very difficult to incorporate. Interaction of GIS and hydrologic models range from loose coupling, where data is simply transferred back and forth between the entities, to a complete functional integration (Martin *et al.* 2005). Although problems of coupling GIS with hydrologic models, reporting model uncertainties, and model applications continue to exist (Sui & Maggio 1999), the benefits include improved accuracy, more flexibility, and greater model efficiency (Ogden *et al.* 2001).

Some of the most widely used models today are: Storm Water Management Model - SWMM (Metcalf and Eddy Inc. 1971), Areal Non-point Source Watershed Environment Response Simulation - ANSWERS (Beasley *et al*. 1980), Simulator for Water Resources in Rural Basins – SWRRB (Williams *et al*. 1995), MIKE SHE (Refsgaard and Sturm 1995), Hydrologic Model System – HMS (Yu 1996), and Soil and Water Assessment Tool – SWAT (Arnold *et al.* 1998). In this study, SWAT, which is supported by the EPA for use with the TMDL program, is used to determine its ability to simulate streamflow in a lowland forested watershed.

2.4.3 Soil and Water Assessment Tool (SWAT)

The SWAT model is integrated with the U.S. EPA's Better Assessment Science Integration point and Nonpoint Sources (BASINS) software program, a GIS interface for several modeling and support systems. Created in response to Total Maximum Daily

Load (TMDL) water quality requirements from section 303(d) of the 1972 Clean Water Act, BASINS incorporates spatial information into mathematical models to simulate complex hydrologic mechanisms (Di Luzio *et al.* 2002).

Developed to provide continuous time simulations of water, sediment, and agricultural chemical yields for large ungaged basins, SWAT operates on a daily time-step. To complete these objectives, the model (1) does not require calibration (not possible on ungaged basins); (2) is based on readily available inputs; (3) operates on large watersheds in an acceptable amount of time through computational efficiency; and (4) uses continuous simulation over long periods to compute the effects of management change (Arnold *et al.* 1998).

Georeferenced soil and land use layers are combined to create a series of Hydrologic Response Units (HRUs). Unique combinations of soil and land use that occur over the area being modeled, HRUs are incorporated with climatic and topographic inputs to compute water balances individually. There are four storage volumes in each HRU that represent the water balance: snow, soil profile (0-2m), shallow aquifer (~2-20m), and deep aquifer (>20m) (Di Luzio *et al.* 2002).

Models are used in conjunction with TMDLs to more efficiently estimate nutrient and sediment loadings created from anthropogenic activities such as urban development, mining, and agricultural and forestry operations. For these models to be useful in determining loadings, it is most essential that runoff and stream discharge estimates be highly accurate, as this is the major influence on fluctuations of loading. The Soil and Water Assessment Tool incorporated in the EPA's Better Assessment Science Integrating point and Nonpoint Sources (BASINS 3.1) software is one such model used to support

Total Maximum Daily Load development. While SWAT has been traditionally used in agricultural catchments (Bosch *et al.* 2004; Saleh *et al.* 2000), the model has found wide applications in many land use types (Wu and Johnston, 2007; Afinowicz *et al.* 2005; Miller *et al.* 2002), including forestry. In this study, SWAT will be tested for its applicability for a low-gradient forest-dominated watershed.

CHAPTER 3. METHODS

3.1 Site Description

Located in north central Louisiana (Figure 3.1), the Flat Creek Watershed drains an area of 369 km^2, and is characterized by relatively flat, low sloping forests and pastures. Elevation ranges from 24 m above Mean Sea Level (MSL) at the southern outlet, to a high of 91 m above MSL in the north. Land use in 2006, analyzed using a LandSat 5 TM image, shows evergreen forests dominating land use (51.4%), followed by deciduous forests (32.6%), regenerating harvested areas (1-3yrs) at 7.0%, recently harvested areas (<1yrs) at 5.0%, pasture (3.9%), and water (0.1%) (Figure 3.2). The evergreen forests are typically commercial loblolly (*Pinus taeda*) pine plantations with bottomland hardwoods making up the deciduous forests adjacent to the streams.

Figure 3.1. Location of the Flat Creek Watershed in North Central Louisiana.

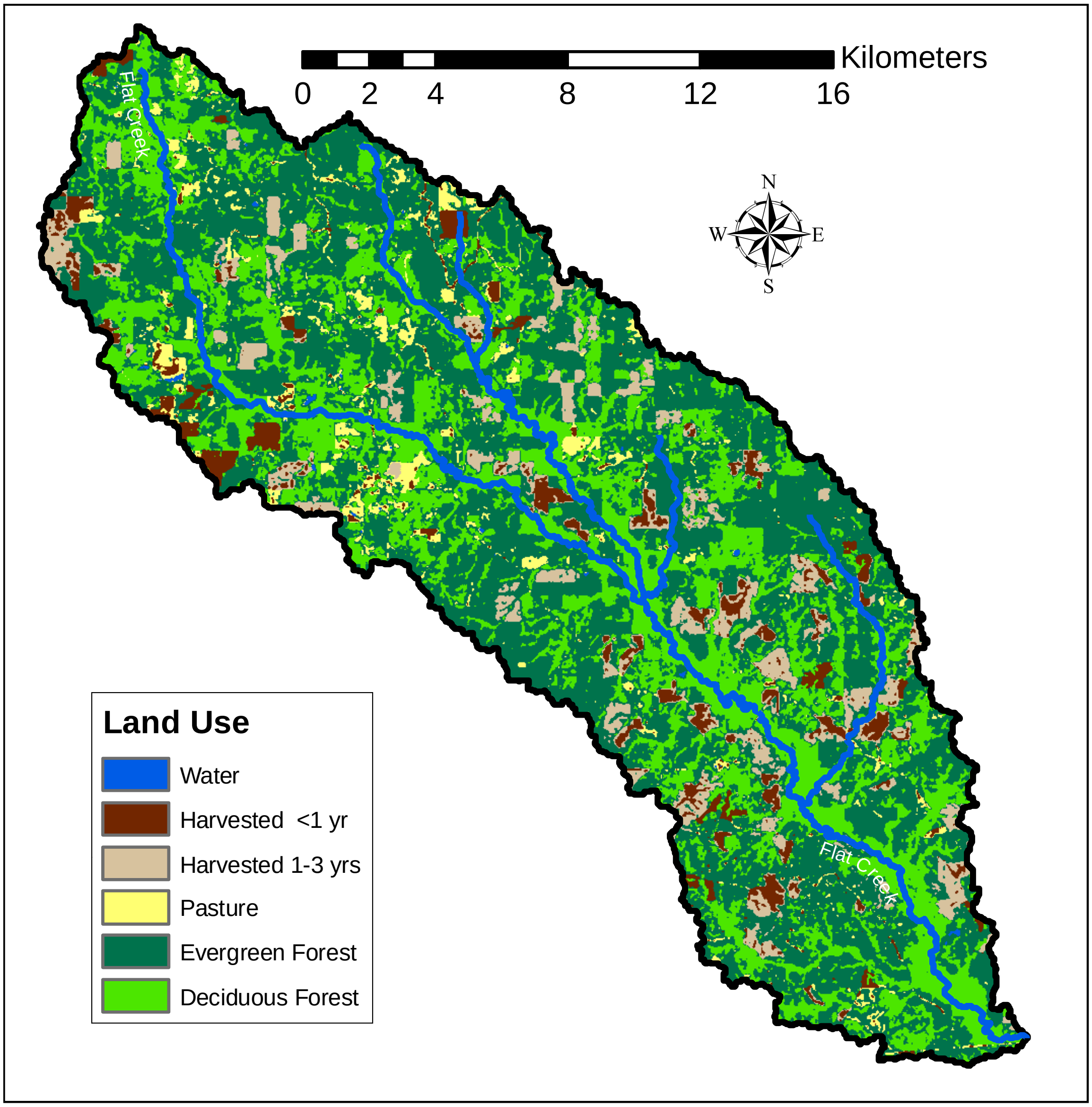


Figure 3.2. Land use categorization of the Flat Creek Watershed, analyzed from a 2006 LandSat 5 TM image. Upland evergreen and bottomland deciduous forests dominate over 90% of the land in the watershed.

Mean annual climatic data was obtained from the National Climatic Data Center (NCDC) Winnfield 2W station, approximately 23 km south of the study area (NCDC 2002). From 1971-2000, the average annual temperature in the area was 17.9 ºC, ranging from 7.2 ºC in January to 27.5 ºC in July. During our 17-month study, the mean monthly

temperature was 16.0 ºC ranging from 7.0 ºC to 27.8 ºC in January 2007 and August 2006, compared to a 17-month mean of 16.0 ºC (1971-2000) (Figure 3.3). Mean annual precipitation from 1971-2000 was 1508.0 mm with a low of 90.7 mm in September and a high of 157.7 mm in December. Precipitation measured with a HOBO weather station (4 Channel MicroStation, #H21-002; Onset Computer Corp., Bourne, MA) totaled 1632 mm during our study, ranging from 24 mm in June 2006 to 312 mm in October 2006, 74% of the long-term total of 2215 mm (1971-2000) for these 17 months.

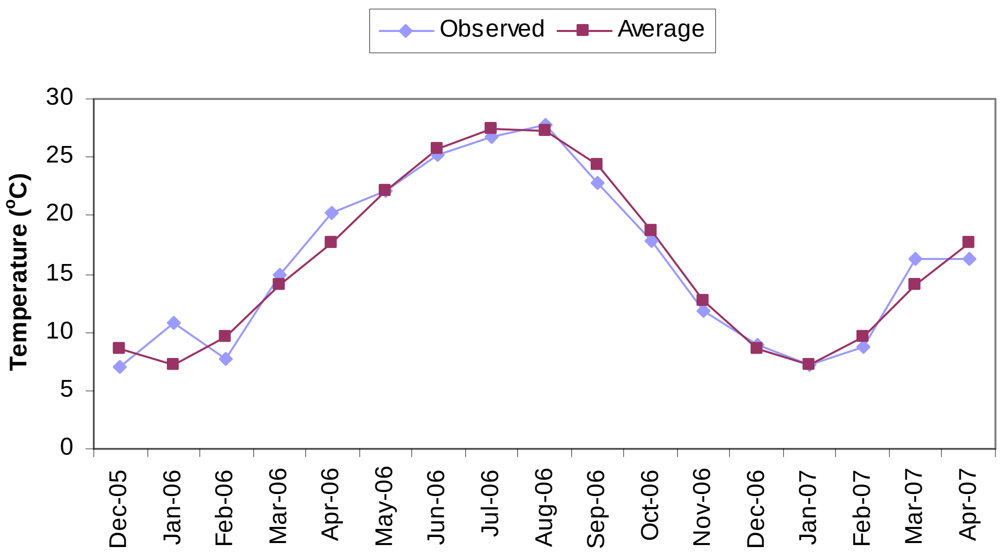


Figure 3.3. Observed mean monthly temperatures recorded at the weather station in the Flat Creek Watershed, compared with the long-term (1971-2001) averages at the NCDC Winnfield 2W weather station, located approximately 23 km south.

Soils in the area commonly consist of the Sacul-Savannah (fine sandy loam) soils in the upland areas, draining down to the Guyton (silt loam) series along the Flat and Turkey Creek floodplains. Sacul series soils are moderately well drained with slow permeability on forested land, having slopes of 1% to 40%. Savannah soils are also moderately well drained, slowly permeable, and are typically on pastures with slopes of 0% to 15%. The Guyton series is characterized by deep, poorly and very poorly drained

soils with slow permeability, and tend to have slopes of <0.5%. The slow permeable soils result in a seasonally high water table, from 0.5 m to 1.2 m below the surface in the Sacul-Savannah soils, and 0.5 m below the surface to ponding above the surface in the Guyton soils (Soil Survey Staff, 2007).

The streams in the Flat Creek Watershed are primarily first and second order, with a short time to peak flow, or lag time, after storm events. Beaver activity in the area has caused ponding along the rivers from the dams. Streams where beaver ponds are located have reduced stream depth variability from precipitation events or prolonged dry periods. The ponding from beaver dams reduces downstream peak discharges and maintains more constant water levels during dry periods. This ponding effect on the stream channel is most pronounced at sites I5 and I6 on Turkey Creek (Figure 3.5), where stream reaches never became visually intermittent and stage-discharge relationships could not be developed.

Land slope in the watershed was determined using a USGS 1 Arc Second (~30 m) National Elevation Dataset (NED) (Figure 3.4, Table 3.1). Using the NED, slopes were calculated with the ArcGIS 9.1 Spatial Analyst Extension Slope Tool, which determines the greatest elevation change between the cell and its nearest neighbors. Slopes for the entire watershed averaged 3.9%, ranging from 0% to 22.8%. Headwater streams in the upper portion of the watershed (I1, I3) had the highest mean overland slopes of 5.5% while a 2nd order stream in a lower part of the watershed (E5) also had the lowest mean overland slope of 3.6%. This follows the general trend of the highest slopes on uplands in the northern areas, decreasing to a very flat and wide floodplain at the southern watershed

outlet. Channel slopes ranged from 0.5% on Spring Creek upstream of I1, down to 0.1% on Flat Creek upstream of E4.

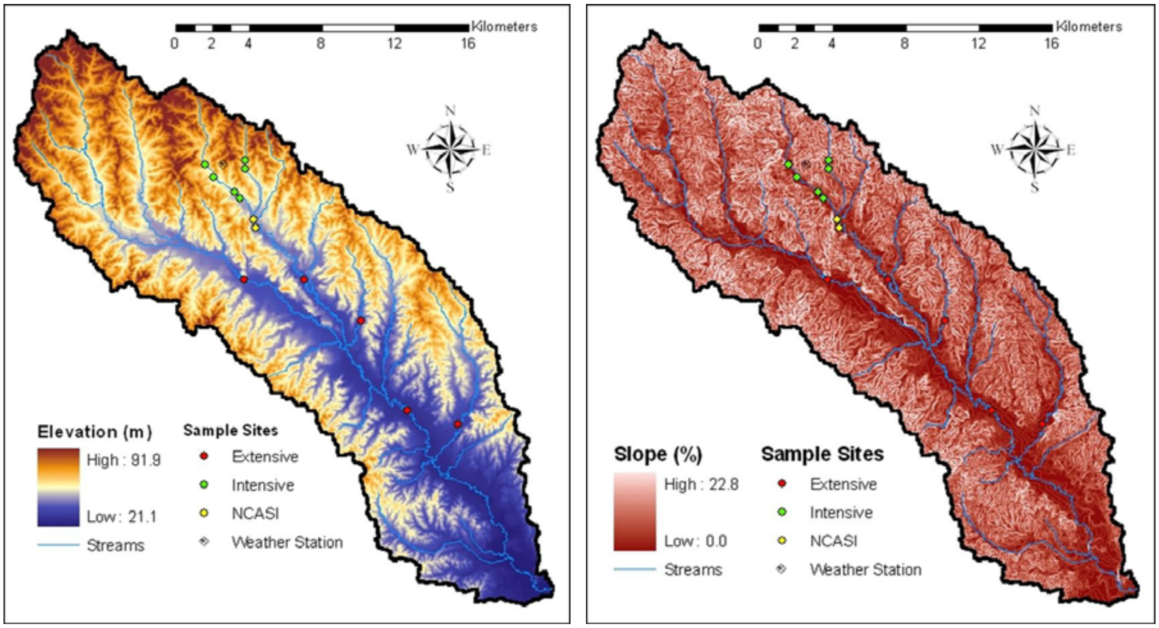


Figure 3.4. Elevations range from 21 to 92 meters above mean sea level, and land slopes range from 0% to 23% in the Flat Creek Watershed. Details on sampling sites are given in Section 3.2 and Figure 3.5.

3.2 Streamflow Measurements, Water Sampling and Weather Observation

A total of eleven initial stream sampling sites were selected to quantify both site and watershed characteristics in Flat Creek (Figure 3.5, Table 3.1). Six “Intensive” sites (I1-I6) were chosen to monitor changes in water quality from areas to be harvested. Two areas planned for harvesting in late 2007 along Turkey Creek had sites placed above and below each harvest area (above/below - I3/I4, I5/I6). In addition, another two sites (I1/I2) were placed on the adjacent Spring Creek as a control, to perform a paired-watershed study. Spring Creek, a headwater stream also located within the larger Flat Creek Watershed, drains a smaller area with a similar land use composition. Five “Extensive” sites (E1-E5) were then placed throughout the watershed, to determine any

cumulative, downstream water quality changes from harvesting in areas upstream. These sites were used to monitor both downstream effects of the harvest sites and stream characteristics over the entire watershed. Sites were chosen based on ease of access, such as intersection of a major road, to allow for timely collection of data at all sites. A final site at the watershed outlet (E6), where Flat Creek joins Castor Creek, was unable to be monitored due to an inability to obtain permission to access the land along the stream at this point. Two other sites, also considered extensive sites, were added in June 2006 in cooperation with the National Council for Air and Stream Improvement (N1/N2) to monitor upstream and downstream conditions of a third harvest site on Turkey Creek.

Table 3.1. Descriptions of stream monitoring locations (sites) where stream discharge was measured, and water samples were collected.

Sites[1]	Latitude	Longitude	Elevation (m)	Mean Width[2] (m)	Mean Depth[2] (m)	Drainage Area (km^2)	Stream Order[3]
I1	32º 04' 51"	92º 27' 38"	54.4	1.66	0.28	3.0	1
I2	32º 04' 50"	92º 25' 34"	50.9	3.63	1.16	3.6	1
I3	32º 03' 35"	92º 23' 35"	54.1	3.94	0.66	12.4	1
I4	32º 00' 56"	92º 21' 58"	50.8	5.64	0.75	14.3	1
I5	32º 00' 30"	92º 20' 12"	48.3	6.89	1.20	17.8	1
I6	32º 08' 21"	92º 27' 36"	47.4	5.70	1.09	18.3	1
E1	32º 08' 06"	92º 27' 36"	38.6	9.55	1.68	109.6	2
E2	32º 08' 30"	92º 29' 01"	38.9	3.91	0.37	45.1	2
E3	32º 03' 35"	92º 23' 35"	37.2	2.98	0.81	6.1	1
E4	32º 07' 26"	92º 27' 59"	34.2	10.64	1.28	285.6	3
E5	32º 07' 14"	92º 27' 46"	34.9	4.56	0.79	23.0	1
N1	32º 06' 36"	92º 27' 19"	43.8	3.26	0.56	33.8	2
N2	32º 06' 22"	92º 27' 14"	42.6	4.36	0.53	34.2	2

[1]I=Intensive Sites, E=Extensive Sites, N=NCASI Sites
[2]Mean Stream Width & Depth are determined from area of water in the stream channel from monthly baseflow sampling
[3]Stream Order as defined by Strahler (1952)

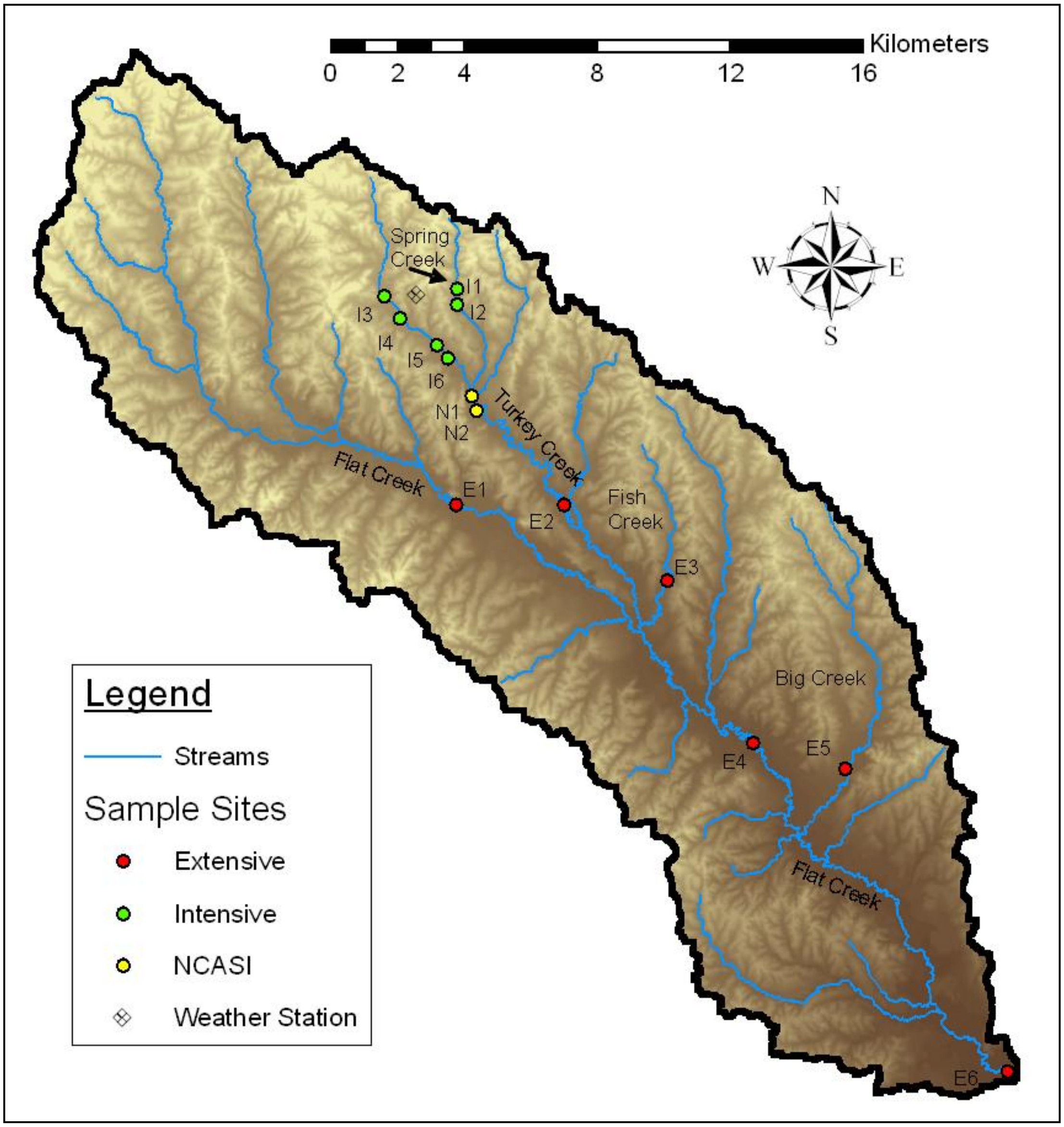


Figure 3.5. A map of the 369 km^2 Flat Creek Watershed showing sample sites, weather station, and stream locations. Site E4 is used as the watershed outlet, as access to the actual watershed outlet at site E6 was unavailable.

Intensive site sampling consisted of both monthly grab samples (1000 mL unfiltered, 500 mL filtered) to characterize stream baseflow sediment conditions. Composite storm event samples, as suggested by Harmel and others (2003), were also collected to determine direct runoff effects on stream sediments. Changes in Six ISCO 6712 automatic storm samplers (Teledyne Isco, Inc., Lincoln, NE) were installed above

and below the location of each harvest site. The ISCOs were programmed to start sampling at a 0.5 ft rise in stream level, collect 400 mL samples hourly for a period of 20 hours (20 x 400mL = 8 L composite sample), and then reduced to 1000 mL unfiltered and 500 mL filtered samples. Effects of harvesting on streams are most apparent during runoff from storm events, necessitating stormflow samples for comprehensive water quality analysis. Baseflow and stormflow 500 mL samples were filtered with a 47µm glass fiber filter (GF/F Whatman International Ltd., Maidstone, England). The 500 mL and 1000 mL samples were analyzed for Total Dissolved Solids (TDS) and Total Solids (TS), respectively, by the Louisiana State University AgCenter Chemistry Laboratory (Baton Rouge, LA). Samples were processed in accordance with USEPA procedures, with a holding time of 7 days and storage at 4^{o}C. The test for suspended solid concentration had a detection limit of 5.0 mg/L, samples less than this level were estimated at 2.5 mg/L. Lastly, soil samples were collected within 150 m of the stream at depths of 0-10 cm and 10-20 cm, then analyzed for levels of Ca^{+2}, Mg^{+2}, K^{+}, and Na^{+} for soil exchangeable cation characterization. A total of six soil samples were obtained along Spring Creek, in between sites I1 and I2, with 20 samples collected along Turkey Creek, between sites I3 and N2.

Additionally, the ISCO samplers record stream level in continuous 15 minute intervals using a vented pressure transducer. Level data was downloaded from the ISCOs at each monthly sample and after each storm event. These recorded stream levels were converted to discharge using an equation relating stage and discharge (described below) developed for each sample location from discharge measurements recorded at different

stages using an Acoustic Doppler Velocimeter (FlowTracker: SonTek/YSI, Inc., San Diego, CA).

Extensive site sampling consisted of monthly baseflow samples. Stream stages were initially recorded using stage gages installed on bridge support columns at each site, where monthly readings were related to intensive site level records to determine daily level. HOBO Water Level Loggers (U20-001-01) were later installed in January 2007 at all extensive sites except E3 (Spring Creek) to improve discharge estimates. Siting wells were constructed using 3.8 cm PVC pipe and attached to bridge pylons near the originally installed stage gages. A HOBO atmospheric pressure logger (HPA-0015) was also placed inside the ISCO at I4 to correct the water level logger pressure readings. Development of stage-discharge relationship is the same as the intensive sites.

Site E1 is placed on Flat Creek at Hwy 126, above any influence from the harvest sites. Site E2 is the Turkey Creek outlet at Hwy 126, into which flows all harvest site outputs. Site E3 measures Spring Creek at Delany Rd. and is another headwater area flowing into Turkey Creek. Site E4 is the lowest sampling site on Flat Creek located on Hwy 127, and is considered the watershed outlet for this study as the true outlet located at site E6 was not able to be monitored. Site E5 is on Big Creek, a 2nd order stream which crosses at Hwy 127.

Extensive and intensive site sampling was performed for a 17-month period, from December 2005 through April 2007. Additionally, YSI 6920 V2 (SonTek/YSI, Inc., San Diego, CA) water quality monitoring sondes were temporarily installed every month on Turkey Creek starting in June 2006. The sondes were deployed for a minimum of 10 days/month, recording stream level and conductance values at 15-minute intervals.

Weather data recorded from a 3 m high HOBO weather station (4 Channel MicroStation, #H21-002, Onset Computer Corp., Bourne, MA) set in a centrally located forest clearing (32º08'15" N, 92º28'22") is entered into the model. The weather station used HOBO sensors that recorded precipitation using an automatic tipping bucket rain gage (S-RGB-M002), solar radiation using a photosynthetic light sensor (S-LIA-M003), temperature in a solar radiation shield (S-THB-M002), and wind speed using a three-cup anemometer (S-WSA-M003).

3.3 Development of Stage-Discharge and Sediment Rating Curves

A stage-discharge rating curve was developed for each stream sample site using stream level and velocity measurements (Figure 3.6). The curve was fitted through a natural log transformation as given below:

$$\ln(Q(t)) = b_0 + b_1 \ln(L(t)) + \varepsilon(t)$$

where Q represents discharge (m^3/s), and L(t) is stream level (m).

The stage gages and water level loggers installed at the extensive sites were used to similarly develop a discharge rating curve for each sample location. Relationships were initially determined between the extensive level stage-gage records and other intensive monitoring locations where daily level data was available for the study period. The water level loggers installed in January 2007 were used to relate discharges between all other extensive sites and an associated intensive site, where daily discharge information was available, to determine the extensive site daily discharges

previous to the logger installation. Discharge at site E1 did not show a good relationship with any intensive site and subsequently could not be calculated. This may have been due to the spatial variation of precipitation inputs or differences in individual site characteristics.

Figure 3.6. Methods used for determining stage-discharge relationships. Flow measurements for discharge determination (left), and inserting the water level logger in the stilling well on a bridge pylon (right). The stage gage is also visible on the adjacent pylon in the background.

A log-linear regression model was developed to estimate TSS and TDS loadings at all sites:

$$\ln(S_i(t)) = b_0 + b_1 \ln(Q_{day}(t)) + \varepsilon(t)$$

where Q_{day} represents daily discharge (m^3), S(t) daily loading (kg), *i* the type of solid, and ε(t) is an error term assumed to be normally distributed. The regression was performed using SAS Statistical Software (SAS Institute Inc., 1996). The fitted parameters used to estimate discharge and solids loadings are summarized in Table 3.2. Stage-discharge

relationships for I5 & I6, impacted heavily by beaver and debris dams, were unsuccessful and resulted in an inability to determine TSS and TDS loading relationships.

Table 3.2. Discharge, Total Suspended Solid (TSS) and Total Dissolved Solid (TDS) r-squares from log-linear regression. Discharge (m^3/s) is related to stream depth (m) where TSS loading (kg) & TDS loading (kg) is related to discharge.

Sample Site		b_0	b_1	r-square
I1	Discharge	-1.60	1.98	0.87
	TSS	-6.57	1.33	0.78
	TDS	-2.80	1.06	0.99
I2	Discharge	-1.60	1.98	0.87
	TSS	-7.27	1.41	0.83
	TDS	-2.26	0.99	0.98
I3	Discharge	-1.99	10.15	0.82
	TSS	-8.03	1.50	0.91
	TDS	-1.53	0.92	0.96
I4	Discharge	-1.38	3.07	0.73
	TSS	-6.20	1.26	0.87
	TDS	-1.81	0.95	0.98
I5	Discharge	-3.54	1.07	0.21
	TSS	NR[1]	NR[1]	NR[1]
	TDS	NR[1]	NR[1]	NR[1]
I6	Discharge	-4.49	-4.13	0.10
	TSS	NR[1]	NR[1]	NR[1]
	TDS	NR[1]	NR[1]	NR[1]
E1	Discharge	-5.62	8.86	0.96
	TSS	-4.96	1.05	0.82
	TDS	-1.81	0.95	0.97
E2[2]	$Discharge_a$	0.80	2.54	0.85
	$Discharge_b$	0.37	3.98	0.98
	TSS	-4.02	0.91	0.85
	TDS	-2.67	1.03	0.98
E3	Discharge	-1.33	5.67	0.86
	TSS	-4.83	1.07	0.74
	TDS	-1.54	0.91	0.95
E4	Discharge	-2.48	2.26	0.81
	TSS	-6.55	1.17	0.88
	TDS	-1.71	0.96	0.99
E5	Discharge	38.47	-15.95	0.84
	TSS	-6.28	1.25	0.92
	TDS	-1.86	0.96	0.99

[1]No Relationship - unable to determine due to poor stage-discharge rating curve
[2]October 16 storm caused change in relationship, a/b is before/after

3.4 Hydrologic Modeling

To help determine effects of forest harvesting at a watershed scale, the Soil and Water Assessment Tool (SWAT) was employed to model the hydrologic effects of

harvesting on streams. SWAT has been proven successful in modeling hydrologic response in agricultural areas as well as in land use change studies. In this study, SWAT is newly applied to a low-gradient area dominated by forestry, to model the effects of clearcutting forest patches.

To model hydrology in SWAT, three GIS layers containing information on elevation, soil, and land use are required. The elevation layer is a 30 square meter Digital Elevation Model (DEM) obtained from the USGS Seamless Data Distribution web site (http://seamless.usgs.gov/), used by SWAT to determine land and stream channel slopes. The Natural Resource Conservation Service (NRCS) Soil Survey Geographic (STATSGO) Database is used for the soil GIS layer (Soil Survey Staff, 2006). The land use layer was mapped by analyzing and classifying a LandSat image from 16 May 2006, in combination with data provided by private forestry companies.

Climatic parameters including rainfall, temperature, humidity, solar radiation and wind speed are entered into the SWAT Model. The Flat Creek Watershed boundary was determined using the DEM and BASINS automatic delineation tool. Drainage area (Table 3.1) for all sites (sub-basins) was also determined using the automatic delineation method. Evapotranspiration was calculated using the weather station parameters entered into the Penman-Monteith equation (Monteith 1965), which has been previously determined reliable for this type of watershed (Harder *et al.* 2007). The SWAT model was run from December 2005 to April 2007 for comparison with available observed data.

SWAT was trained using three years of precipitation data, November 2002-2005, from the closest USGS gage station, on the Dugdemona River at Joyce, LA (USGS Gage # 07372050). Calibration of the model is performed by comparing observed and

simulated streamflow at the sampling sites. Model calibration was performed using guidance from the SWAT user manual (Neitsch *et al.* 2002) and a previous work on parameter sensitivity in Louisiana coastal watersheds (Wu 2005; Wu and Xu 2006). The entire 17-month study period was used for calibration due to the short time period of observed data available for comparison.

Table 3.3. Parameters adjusted in the Soil and Water Assessment Tool (SWAT) during model calibration. Ranges are recommended, and default values given are from the initial model run, before calibration.

Module	Parameter[1]	Range	Default Values
Hydrologic Response Unit (.hru)	CANMX	0-100	0
	ESCO	0-1	0
	OV_N	0.01-30	0.01-0.15
Soil (.sol)	SOL_AWC	0-1	0-0.23
Groundwater (.gw)	GW_DELAY (days)	0-500	31
	GWQMN (mm)	0-5000	0
	GW_REVAP	0.02-0.2	0.02
	ALPHA_BF (days)	0-1	0.048
	RCHRG_DP	0-1	0.05
	SHALLST (mm)	0-1000	0.5
	REVAPMN (mm)	0-500	1
Land Management (.mgt)	CN2	35-98	55-92
Main Channel Routing (.rte)	CH_N2	0.01-0.3	0.014

[1]Parameter descriptions

CANMX:	Maximum Canopy Storage
ESCO:	Soil Evaporation Compensation Factor
OV_N:	Manning's "n" Value for Overland Flow
SOL_AWC:	Available Water Capacity of the Soil Layer
GW_DELAY:	Groundwater Delay Time
GWQMN:	Threshold Depth of Water in the Shallow Aquifer Required for Return Flow
GW_REVAP:	Groundwater Revaporization Coefficient
ALPHA_BF:	Baseflow Alpha Factor
RCHRG_DP:	Deep Aquifer Percolation Fraction
SHALLST:	Initial Depth of Water in the Shallow Aquifer
REVAPMN:	Threshold Depth of Water in the Shallow Aquifer for Revaporization to Occur
CN2:	Initial SCS Runoff Curve Number for Moisture Condition II
CH_N2:	Manning's "n" Value for the Main Channel

CHAPTER 4. RESULTS

4.1 Hydrology

4.1.1 Seasonal Conditions

Precipitation during the study period from December 2005 to April 2007 was lower than the long-term average observed from 1971-2000 (NCDC 2002). Only three months (Feb, Oct, Dec 2006) showed higher precipitation than the long-term average (Figure 4.1). Precipitation in March-September 2006 was low, representing 54% of the long-term average amount for the same period. The largest storm event occurred on Oct 15-16 where 185 mm of rain fell, 11% of the entire 17-month total.

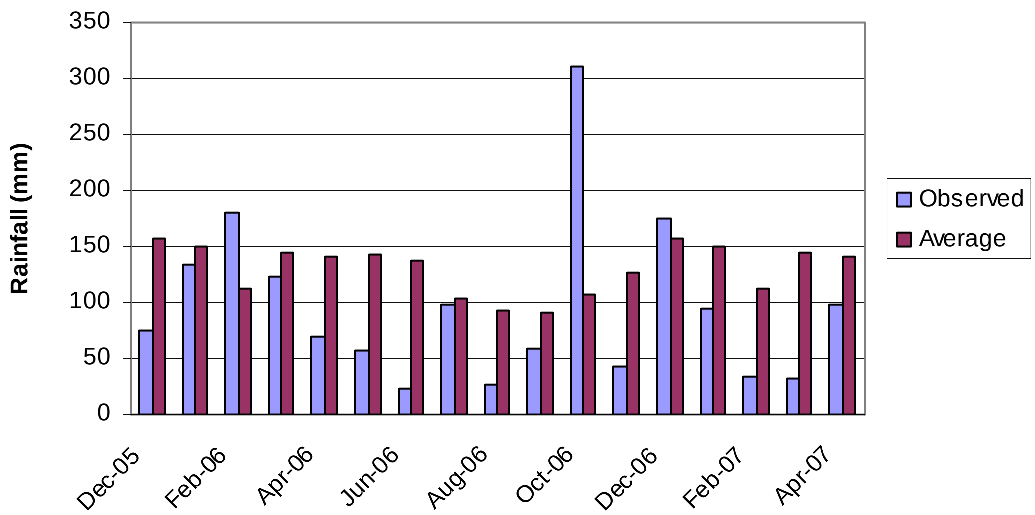


Figure 4.1. Monthly observed and average (1971-2001) precipitation for the 17-month study.

Streamflow during the study period was similarly variable. Discharges generally peaked in February 2006 and December 2006/January 2007 due to a combination of high precipitation and wet antecedent conditions during those months (Figure 4.2). All sites experienced intermittent, no flow conditions in the late summer months of 2006 due to

low precipitation. The large storm in October 2006 came after this dry period and returned all streams to a connected, actively flowing status. Discharge is most likely underestimated for this month as streams extensively overflowed their banks, flooding the riparian zone and were beyond the extents of the developed stage-discharge relationships. Although bank overflow occurred several times during the course of the study, it was not as extreme or long-lasting.

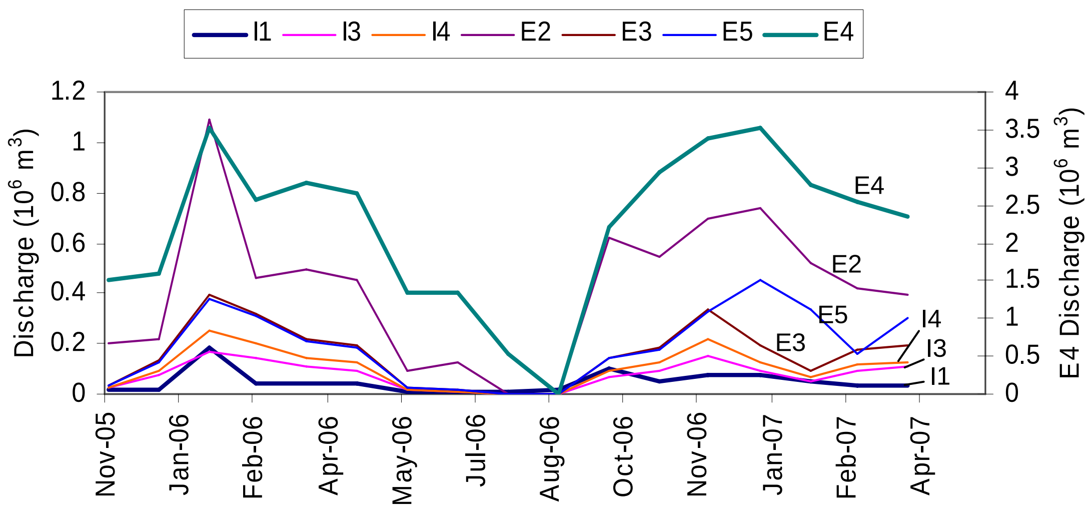


Figure 4.2. Total monthly discharge for all study sites where flow could be determined. E4 discharge is on the right y-axis due to higher magnitude of streamflow.

Variation of both precipitation and streamflow was high over the 17 months (Figure 4.3). Comparing the Coefficient of Variation (CV) for both input and outputs using depth (mm), CV for precipitation is 77% with streamflow ranging from 46% to 91%. Site E4, with the largest drainage area (Table 3.1), and site I1, with the smallest drainage area, had the lowest and highest CV, respectively. All other stream sites were within 8% of the precipitation variability. Overall, variation decreased with increasing drainage area (Figure 4.3) in the Flat Creek Watershed.

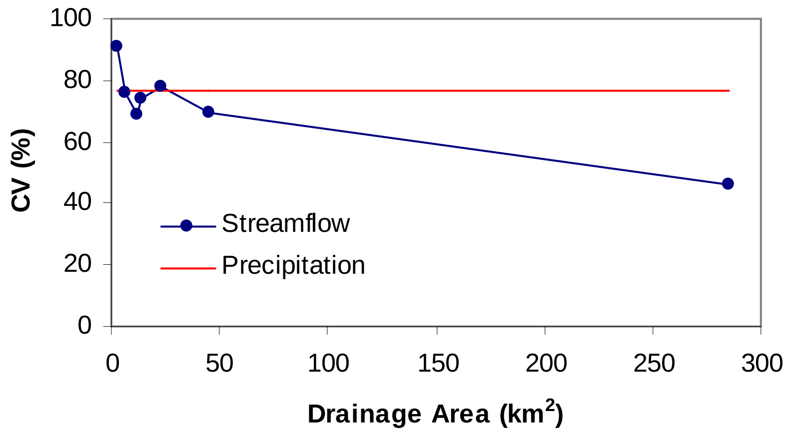


Figure 4.3. Coefficient of Variation (CV) for monthly streamflow (mm) generally decreases with increasing drainage area. Streams draining smaller areas tend to respond more quickly to variations in precipitation than streams draining larger areas. When compared with monthly precipitation (mm) CV, streamflow in several smaller streams is more variable than precipitation and less variable in larger streams.

Figure 4.4. Streamflow variability of Turkey Creek between dry and wet seasons, downstream of site N1.

Runoff coefficients, or percent of precipitation converted to streamflow, were compared for the headwater site on Spring Creek (I1) with the smallest drainage area, and the effective watershed outlet of Flat Creek (E4). At site I1, 16.8% of the precipitation left the drainage area as streamflow, ranging from 3.7% in July 2006 to 50.2% in February 2007, with 8.1% of precipitation flowing past E4, ranging from 0% (no flow) in

September 2006 to 29.2% in February 2007. While these levels are generally smaller than reported in the literature (Bosch 2006; Chescheir *et al.* 2003; Sun *et al.* 2000), the combination of lower than average precipitation and beaver/debris dams likely decreased runoff levels. Site I3 showed the lowest runoff percentage at 6.4%, and E3 had the highest at 26.7% (Figure 4.5). I3 and E3 are both 1st order streams with small drainage areas, so it is interesting that they have both the highest and lowest runoff percentages. Runoff variability between sites is affected by the spatial distribution of rainfall and individual catchment characteristics such as drainage area, slope, soil type, and land use among others. E3 is located much lower in the watershed, for instance, closer to sites E5 and E4 (watershed outlet). Precipitation not leaving through streamflow was assumed to be lost to evapotranspiration, as the slow permeable soils prevent deep groundwater recharge from occurring.

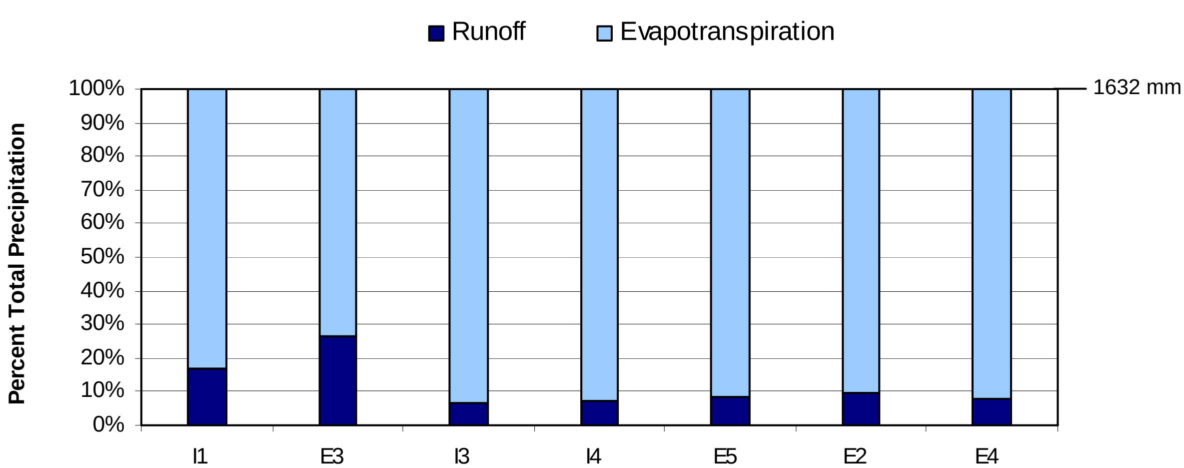


Figure 4.5. Percent of total precipitation over entire study period (1632 mm) converted to runoff at each site. Runoff is the total discharge measured at each stream site, divided over the drainage area. Remaining precipitation is assumed to be lost to evapotranspiration due to negligible groundwater recharge.

Although the headwater I1 site had the most continuous flow, antecedent moisture conditions also appear to have affected it much more than any other site. February and

December 2006 had very similar levels of rainfall, with 180 mm and 175 mm, respectively. Precipitation in each of the previous months, however, were very different with a wetter 134 mm in January 2006 and a drier 43 mm in November 2006. Wet antecedent conditions (Feb 06) resulted in 34.3% of precipitation converting to streamflow at site I1, reducing to 14.2% in dry antecedent conditions (Dec 06). Conversely, runoff response at site E4 was very similar in both months, with 6.9% in wet and 6.8% in dry antecedent conditions, confirming the reduction of streamflow variability in the larger drainage area (Figure 4.3). Most sites, except for E2, had responses similar to E4 (Table 4.1). The lack of extensive runoff variation due to different antecedent conditions may be due to the large amount of precipitation in October 2006, sustaining soil moisture and streamflow through the dry November. Located higher in the watershed, available soil water and the local water table may have been reduced at a quicker rate than positions lower in the watershed, which may take longer than one month to be strongly affected by dry weather. Use of one weather station to measure precipitation also assumes uniform precipitation, and may result in errors from unknown spatial variation.

Table 4.1. Amount of precipitation converted into runoff with wet and dry antecedent conditions, in order of increasing drainage area. Use of one weather station to measure precipitation assumes uniform precipitation, and may result in errors from unknown spatial variation.

Site	**Runoff (Wet Antecedent Conditions, Feb 06)**	**Runoff (Dry Antecedent Conditions, Dec 06)**	**Change**
I1	34.3%	14.2%	-20.1%
E3	35.6%	31.7%	-3.9%
I3	7.5%	6.9%	-0.6%
I4	9.7%	8.7%	-1.0%
E5	6.9%	6.8%	-0.1%
E2	13.5%	8.8%	-4.7%
E4	6.9%	6.8%	-0.1%

Discharge levels between the sites were also variable, and not necessarily dependent upon position in the stream network. Flow Duration Curves (FDCs), plots of discharge against the probability of exceeding that discharge, provide a method of visually analyzing and comparing streamflow (Vogel and Fennessey 1995). The FDCs for streams in the Flat Creek Watershed show that E2, the first extensive site on Turkey Creek into which all intensive sites flow, actually had the highest period of no-flow activity of all sites monitored (Figure 4.6). Although an extensive site located lower in the watershed, E2 is actually in a relatively high position upon the landscape, resulting in the lengthy time of no-flow.

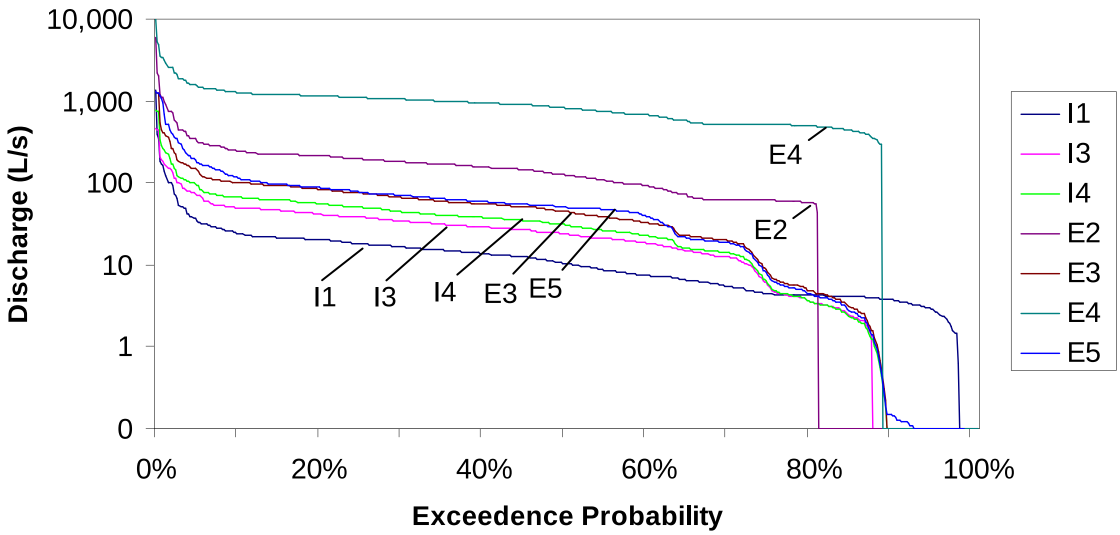


Figure 4.6. Flow Duration Curves (FDCs) for all sites analyzed. FDCs provide a way to compare sample sites using mean daily discharge (L/s), showing here that site I1 had the most continuous flow and site E2 had the least continuous flow.

Conversely, the headwater site with the smallest drainage area, I1, had the most continuous flow. All other streams remained at intermittent, no flow conditions for approximately 10% of the study period (Figure 4.6). Spring Creek at I1 was also the only site to have a value other than zero for the most common level of daily streamflow (Table

4.2). Both I1 and E2, the most and least continuous flowing sites, had the highest levels of skewness for daily discharge among all stream sites. Higher skewness values indicate higher streamflow variability and extremes. In these lowland stream systems, with extremely low slopes, geomorphological properties of the stream reach may play an important role in determining surface discharge during dry periods. These results also influence the level of connectivity in the stream network. Although streams in the uppermost reaches of a watershed may be flowing, they are not necessarily flowing at all points located downstream in the watershed.

Table 4.2. Descriptive statistics of daily streamflow (L/s) for all sample sites.

Site	Min	Max	Mean	Median	Mode	Skewness
I1	0	1,358	18.4	10.4	4.2	18.5
E3	0	1,314	59.5	45.1	0.0	8.2
I3	0	455	29.3	23.5	0.0	6.4
I4	0	789	39.2	30.8	0.0	7.8
E5	0	1,309	71.2	50.1	0.0	6.3
E2	0	2,901	158.7	124.8	0.0	12.8
E4	0	9,904	843.8	818.4	0.0	5.5

4.1.2 Stormflow Hydrology

Stormflow from 17 precipitation events were sampled at the six intensive sites over the entire study period. A majority of those samples were collected in the winter months of 2006-07 due to the time required to calibrate the ISCO automatic samplers, a dry 2005-06 winter, and a very dry 2006 summer. All samplers did not trigger for each storm event due to variations in individual stream sample site responses. In fact, only one event resulted in a full six successful storm samples (Table 4.3). Storms were considered to be precipitation events that raised stream depths by 0.5 ft over 24 hours. Unsuccessful samples were also caused by equipment malfunction or laboratory testing problems, and were removed from analysis.

Table 4.3. Dates of sampled storms with "x" denoting a storm sample at the respective site. Missing storm samples were due to variation in individual site response, equipment malfunctions, or laboratory testing problems.

Date	I1	I2	I3	I4	I5	I6
02-Feb-06		x				
22-Feb-06	x			x		
25-Feb-06		x	x	x		
09-Mar-06	x		x			
20-Mar-06		x				
17-Oct-06	x	x	x	x	x	
19-Oct-06				x	x	
26-Oct-06	x	x	x	x	x	
13-Dec-06		x		x	x	x
22-Dec-06		x	x	x		x
27-Dec-06					x	
31-Dec-06		x	x	x	x	x
05-Jan-07		x	x	x	x	x
16-Jan-07	x	x	x	x	x	x
22-Jan-07	x			x	x	x
13-Feb-07	x			x		x
02-Apr-07			x			
14-Apr-07	x		x	x		
26-Apr-07			x	x	x	

Storm response to precipitation in these headwater streams is relatively quick, due to the small drainage areas. A 02 Feb 2006 storm of 34.0 mm precipitation resulted in a time to peak flow ranging from 3.5 hours to 11.75 hours, increasing with amount of area drained (Table 4.4). Return to baseflow was calculated using the equation $D=A^{0.2}$, where D is the time in days and A is the drainage area in square miles (Linsley *et al.* 1975). Stream position in the watershed may considerably affect the time of travel, or time it takes for the water to reach the stream from where it fell as precipitation. Using the upstream/downstream site pairs of I1/I2 on Spring Creek, with I3/I4 and I5/I6 on Turkey Creek drainage area and time to peak was compared. Drainage areas increased by 0.6 km^2 from site I1 to site I2, 1.9 km^2 from site I3 to site I4, and 0.5 km^2 from site I5 to site I6, while time to peak flow increased by 0.75 hr, 0.25 hr, and 2 hrs, respectively. The

smallest drainage area increase of 0.5 km^2 from site I5 to site I6, had the largest increase in the time to peak of 2 hrs. However, sites I5 and I6 occupy the lowest position among all the intensive sites and are heavily affected by beaver and debris dams.

Table 4.4. Storm hydrograph characteristics for all intensive sites in response to a 34.0 mm precipitation event, occurring on 02 Feb 2006.

Site	Drainage Area (km^2)	Time to Peak (Hours)	Return to Baseflow (Hours)	Total Stormflow Period (Hours)
I1	3.0	3.50	24.75	28.25
I2	3.6	4.25	25.75	30.00
I3	12.4	7.00	32.75	39.75
I4	14.3	7.25	33.75	41.00
I5	17.8	9.75	35.25	45.00
I6	18.3	11.75	35.50	47.25

Difficulties in calculating discharge using stage levels, due to beaver and debris dams, equipment malfunctions, and individual site characteristics, resulted in two primary sites being used for comprehensive storm discharge and loading analysis, I1 and I4. Baseflow contribution to stormflow was higher at site I4 than site I1 (Figure 4.7), which may be due to site I4 having a larger drainage area and being located lower on the landscape. Sites lower on the landscape have water tables closer to the land surface, influencing stormflow and affecting concentration of both suspended and dissolved solids, discussed later.

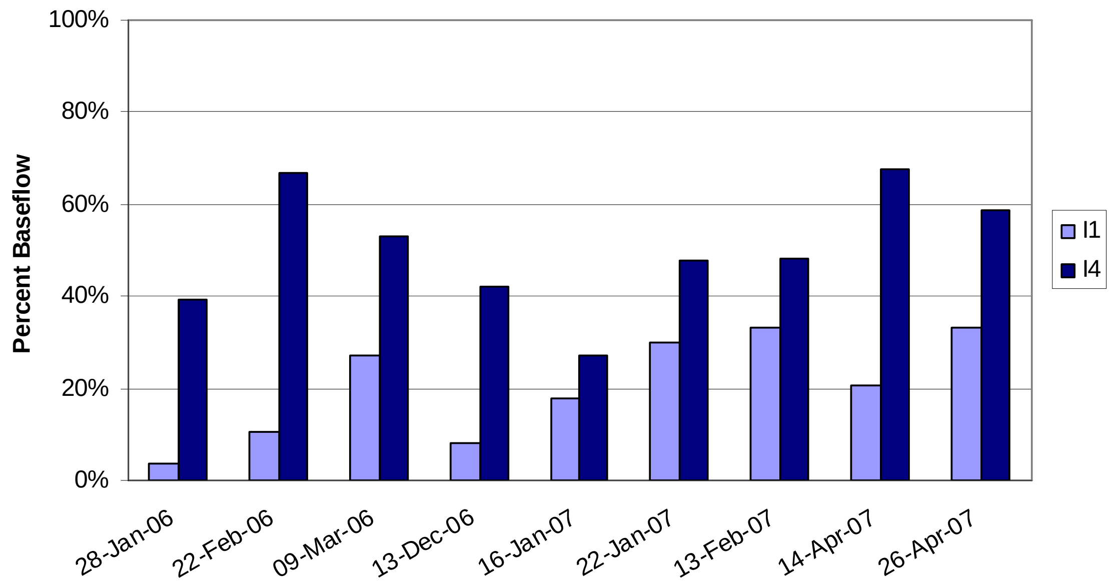


Figure 4.7. Percentage of baseflow, or groundwater, contributing to stormflow at sites I1 and I4. Site I4 shows higher proportions of baseflow contributing to stormflow than at site I1.

Responses to storms were variable and based upon the distribution of precipitation, drainage area, antecedent conditions, and individual stream/site characteristics. A 26.7 mm precipitation event on 25 Apr 2007 shows the variability in stream response to storm events at sample locations. The storm produced an expected stream response at all sites except I2, which had a barely discernable rise and is located directly downstream of I1 (Figure 4.8). Lack of stream response at various sites was common throughout the study period for multiple reasons including in-stream dams, inundation of backwater and riparian areas, and deep sites that generally contained large volumes of water with low velocities.

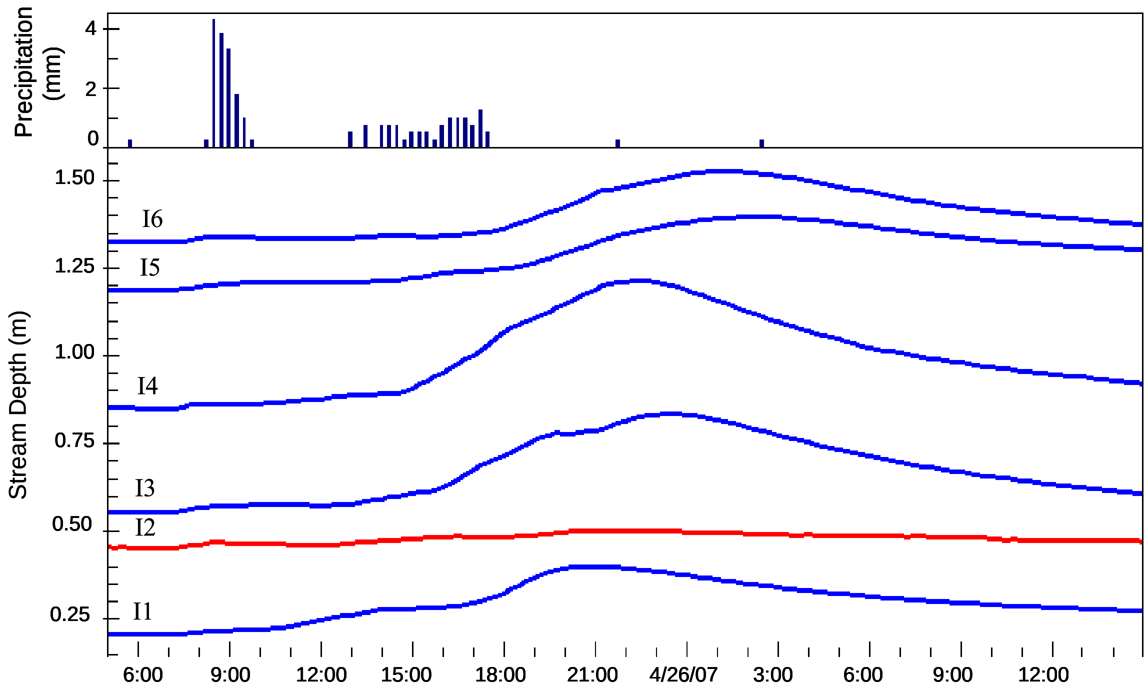


Figure 4.8. Precipitation event and associated stream response for all intensive sites on 25-26 Apr 2007. Stream depth instead of discharge was used in order to compare all sites, as discharge was unable to be determined at sites I2, I5, and I6. The lack of response at site I2, shown in red, shows the potential for variation in storm responses between stream sample locations.

Stormflow recession equations were developed at four sites to look at the effects of scale and drainage area characteristics on stormflow. Parameters were derived for one linear and two exponential recession equations from multiple storm events at each site. Recession equations can be used to compare stream hydrograph responses to storm events across different scales and drainage basins. It is expected that headwater streams will have a quick response time to precipitation, with a lower recession constant corresponding to a rapid decline after peak flow. Streams with a slower, more gradual, response time would have a higher constant representing a lesser change in flow between time steps.

The correlation recession equation (Langbein 1938 *in* Vogel and Kroll 1996) plots current discharge against discharge in the previous time step, creating a line with the slope being the recession constant (Eq 4.1). Two variations of the same exponential equation (Eq 4.2, 4.3) are also used, where the plot of time against the natural log of discharge on a semi-logarithmic graph yields a straight line with the slope ln(k) (Tallaksen 1995).

$$Q_t=Q_{t-1}k_1 \tag{4.1}$$

$$Q_t=Q_0k_2^{t} \tag{4.2}$$

$$Q_t=Q_0e^{(-t/C)} \tag{4.3}$$

where Q_t is the discharge at time "t", Q_{t-1} is the discharge in the previous time step, Q_0 is the discharge when t=0, and C and k are constants. While k is a dimensionless constant, C is dependent on time and the half-flow period (Martin 1973 *in* Tallaksen 1995).

Recession constants increased with increasing drainage area (Table 4.5, Figure 4.9), indicating the slower response of the downstream sites. The linear equation had the highest coefficient of determination between predicted and observed streamflow recessions, with the exponential equations showing lower coefficient of determinations. While these parameter constants are based upon a limited number of storm events, they give a relative idea of the change in basin response with size.

Table 4.5. Stormflow recession constants for sites with increasing drainage areas. Coefficients of determination (r^2) are calculated between predicted recessions using the individual equation, and observed streamflow recessions.

Site	Eqn 4.1 k_1	r^2	Eqn 4.2 k_2	r^2	Eqn 4.3 C	r^2	Drainage Area (km^2)	Number of Storms
I1	0.8614	0.9892	0.8270	0.8925	6.12	0.8934	3.0	9
I4	0.9153	0.9949	0.8832	0.9219	9.90	0.9210	14.3	7
E2	0.9551	0.9983	0.9277	0.9339	18.61	0.9073	45.1	6
E4	0.9780	0.9996	0.9651	0.9278	40.38	0.8875	285.6	5

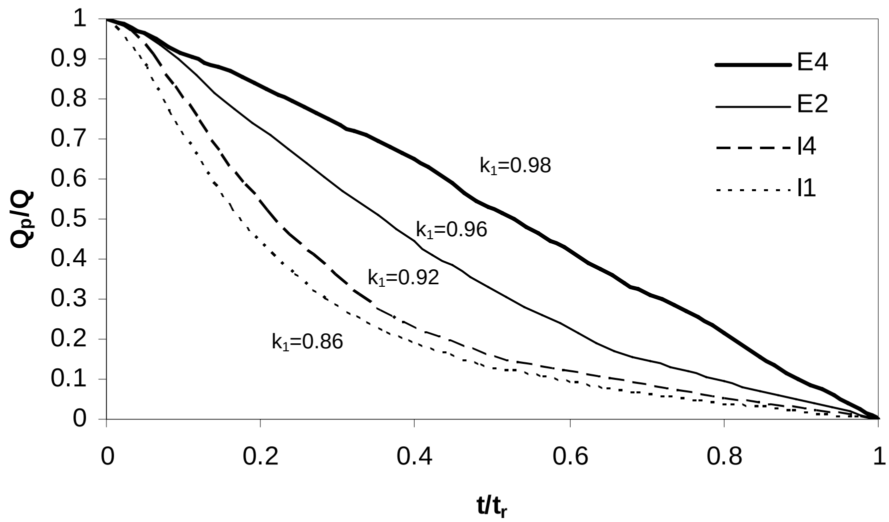


Figure 4.9. Comparison of stormflow recession curves of sites with different drainage areas. Discharge and time were normalized using peak discharge (Q_p) and total time of recession (t_r). Details of the recession constant (k_1) are in table 4.5.

Using the exponential recession constant C, the half-flow period, or the time it takes for the streamflow to decrease by half, can be calculated using the following equation:

$$t_{0.5} = -C \ln(0.5)$$

In the Flat Creek Watershed, as area increased from 3.0 km^2 to 285.6 km^2 at the four sample sites, the half-flow period increased from 4.2 hrs to 28.0 hrs. Stream half-flows initially showed a sharp increase with drainage area, slowing with greater basin size (Figure 4.10).

Lag time (T_L), or the time between the centroid of the excess precipitation and peak flow, was calculated for three storm events at four sites with increasing drainage area. Calculated storm discharge showed very little direct runoff at all four sites (< 5mm), so centroids of the entire hyetographs were used. Expanding the basin from 3.0 km^2 to 285.6 km^2 increased average lag time from 2.6 hrs to 67.2 hrs. Plotted against

drainage area, T_L shows a curve very similar to the half-flow period (Figure 4.10). This similarity is expected due to the general uniformity of the rising and falling hydrograph limbs. Storm events used to calculate recession constants and lag times all occurred during Jan-Apr 2007 due to data availability and to minimize differences due to seasonality that can occur in master recession curves, as noted by Sujono (2004).

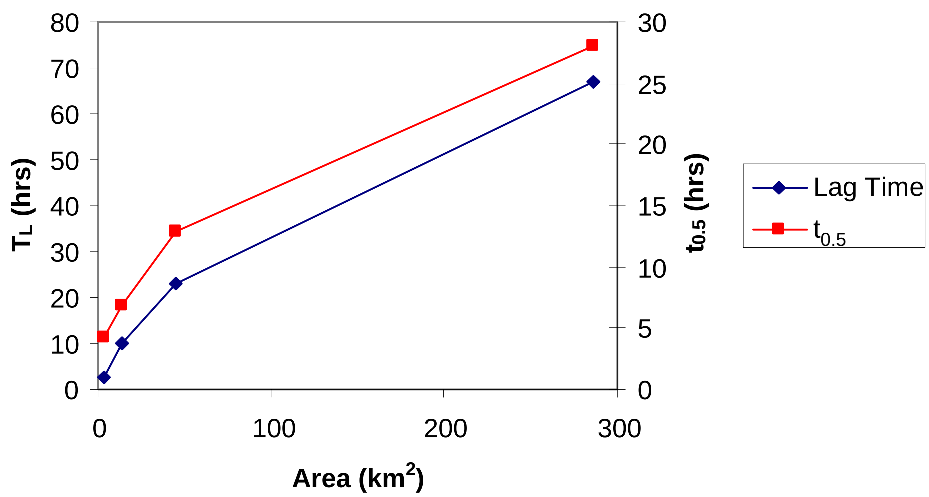


Figure 4.10. Storm hydrograph characteristics of Lag Time (T_L) and half-flow period ($t_{0.5}$) increase with drainage area.

4.2 Suspended Solids

4.2.1 Baseflow Total Suspended Solids (TSS)

Total Suspended Solid (TSS) loading for all streams showed a high coefficient of determination with streamflow (Table 3.2), although lower than Total Dissolved Solids (TDS) due to larger impacts from antecedent moisture conditions and individual rainfall characteristics such as intensity and duration. TSS concentrations generally showed expected responses to streamflow conditions. Highest levels were observed following initial increases of streamflow after long dry periods, as in December 2005 and

November 2006, and particularly in streams draining the largest areas (Table 4.6). Generally, higher values were seen in the wet winter months, with lower values in the dry summer period. Average monthly values across all sites ranged from 5.7 mg/L in July 2006 to 38 mg/L in December 2005.

Table 4.6. Stream Total Suspended Solid (TSS) concentrations determined from monthly baseflow water sampling over the study period. Dashed (-) values represent no flow during monthly sampling.

	Total Suspended Solids (mg/L)						
Sites	**I1**	**E3**	**I3**	**I4**	**E5**	**E2**	**E4**
Dec-05	12.0	19.0	9.0	15.0	37.0	70.0	105.0
Jan-06	2.5	2.5	12.1	16.1	12.1	14.1	10.1
Feb-06	8.1	25.5	16.2	11.2	19.1	11.1	21.2
Mar-06	9.2	14.3	9.2	5.1	9.2	5.1	2.5
Apr-06	25.5	22.9	23.5	28.3	25.5	20.1	20.0
May-06	8.1	9.1	5.2	2.5	10.2	19.2	2.5
Jun-06	14.4	14.2	13.3	20.5	2.5	-	19.3
Jul-06	6.2	2.5	2.5	9.1	5.1	5.0	9.3
Aug-06	6.1	34.1	-	9.0	2.5	-	2.5
Sep-06	-	-	-	-	6.1	-	-
Oct-06	19.2	-	-	-	-	-	-
Nov-06	25.9	19.0	26.9	26.1	28.3	43.6	39.8
Dec-06	2.5	25.9	23.1	24.3	25.5	19.4	26.7
Jan-07	8.1	14.1	14.1	13.1	23.3	6.2	19.6
Feb-07	17.4	17.2	10.1	10.2	15.2	7.1	6.1
Mar-07	25.2	28.6	31.6	18.3	28.2	18.3	30.6
Apr-07	15.2	17.0	19.6	15.1	19.3	22.2	34.4
Mean	**12.8**	**17.7**	**15.5**	**14.9**	**16.8**	**20.1**	**23.3**
±Std. Dev.	*±7.9*	*±8.9*	*±8.5*	*±7.5*	*±10.5*	*±18.2*	*±25.6*

No clear spatial variation existed in suspended solid concentration, although maximum values were highest in the streams with the largest drainage areas - E2 and E4 (Figure 4.12). Major differences in monthly sediment loading were mostly due to stream discharge fluctuations and not variation in TSS concentration (Figure 4.13). This effect can be seen when comparing monthly concentration and discharge, as opposed to monthly loading and discharge.

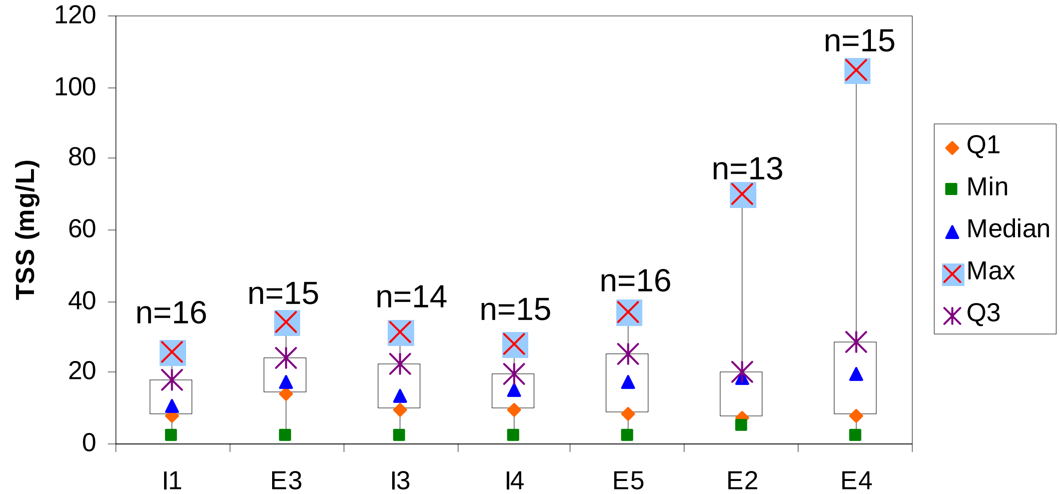


Figure 4.12. Box and whisker plots of Total Suspended Solid (TSS) concentrations for all sites. Boxes show values in the middle 50%, bounded by the first and third quartiles (Q1 & Q3), and sites are arranged from lowest to highest drainage area. Variations in sample numbers (n) are due to dry periods where no surface flow existed at the site and samples were not collected.

Looking at the TSS loading over the study period (Figure 4.14), the level of streamflow shows a greater influence on loading than variations in concentration. Flow conditions, influenced by characteristics such as antecedent moisture conditions and rainfall intensity/duration, would then have a lesser effect on TSS loading. Seasonal patterns of loading rates closely follow discharge, with high levels in the wet winter months and low levels in the drier summer. Site E5 appears to have higher rates of loading than all other sites except E4 in the winter.

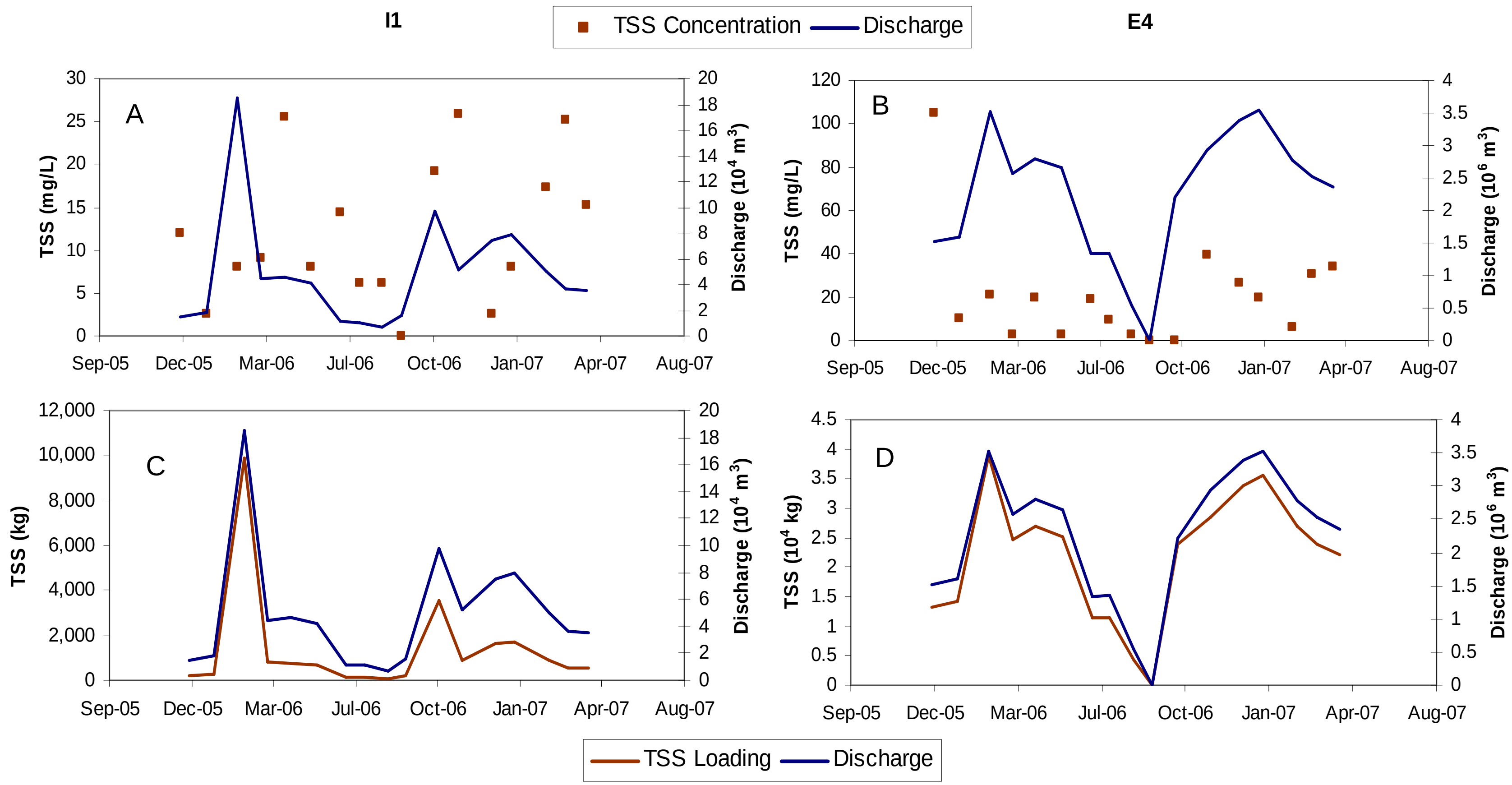


Figure 4.13. Comparisons of monthly discharge with monthly Total Suspended Solid (TSS) concentrations (A&B) and loadings (C&D) for sites I1 and E4, the smallest and largest drainage areas, over the 17-month study period.

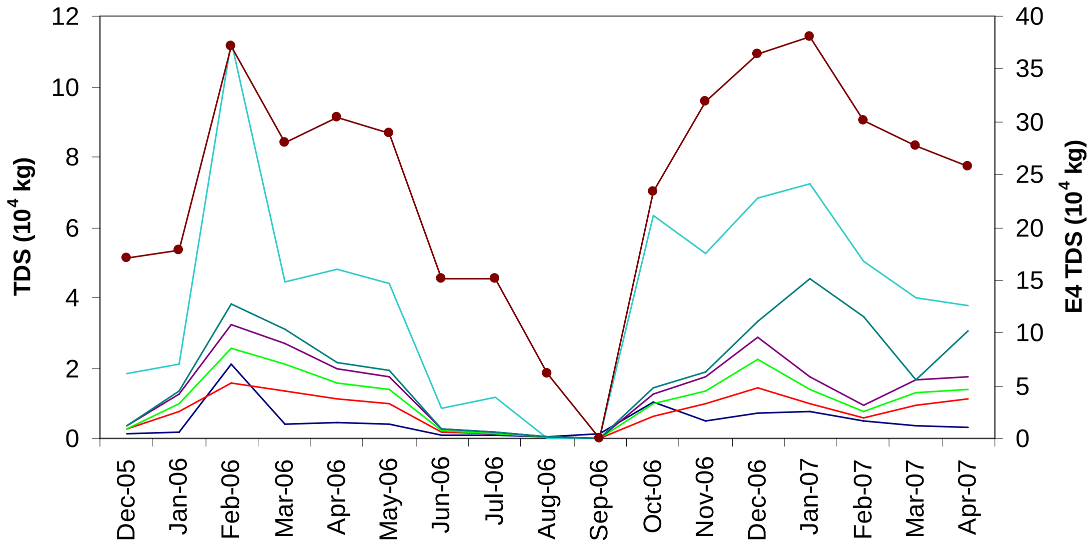


Figure 4.14. Monthly Total Suspended Solid (TSS) loading for all sites. Site E4 values are listed on the right y-axis, with all other site values located on the left y-axis. Zero values occur at no flow periods during monthly sampling.

Mean monthly sediment flux from the effective watershed outlet at site E4 was 0.8 kg ha^{-1}, increasing to 4.5 kg ha^{-1} at site I1. Site E2, the lowest monitoring location on Turkey Creek before draining into Flat Creek, had the lowest flux at 0.7 kg ha^{-1} month^{-1} (Figure 4.15). The higher discharge of Flat Creek at site E4 also carries a higher sediment flux than the input from Turkey Creek, even though it drains a larger area. Although these average fluxes cover two wet seasons and one dry season in the 17 months analyzed, precipitation was also 26% below normal for the study period, so fluxes may not be far from mean monthly value from one year with normal precipitation.

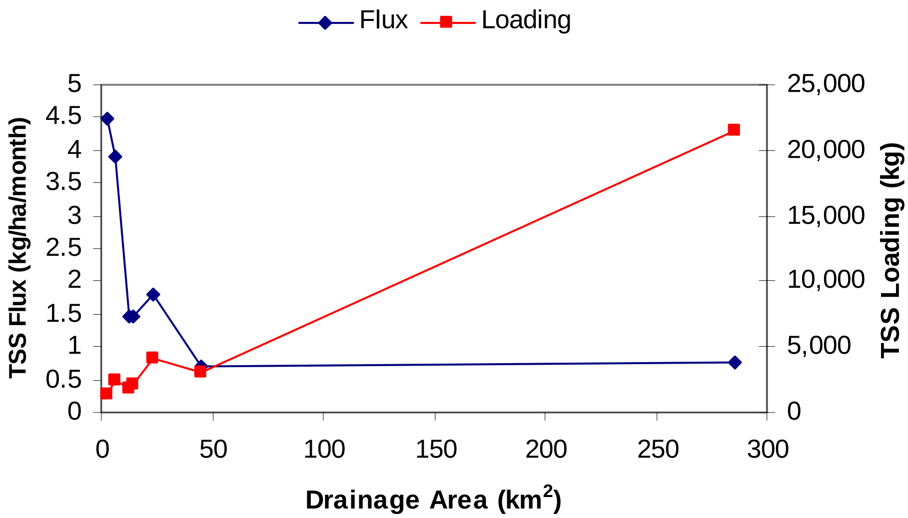


Figure 4.15. Average monthly Total Suspended Solid (TSS) loading and flux over the 17-month study. TSS loading increases and TSS flux decreases with increasing drainage area.

4.2.2 Stormflow TSS

Storm sample TSS concentrations across all sites ranged from <5.0 mg/L (I4, I5) to 109 mg/L (I1) (Figure 4.16). TSS concentrations below the 5.0 mg/L level were not able to be determined by the testing laboratory and were estimated at 2.5 mg/L. Once again, sites I5 and I6 were affected by debris and beaver dams, likely resulting in an even greater reduction in sediments, as evidenced by the large amount of sediment deposition found in and behind the beaver dam structures. Notably, site I6 had the fewest number of storm event samples (n=7), with the lowest range of storm suspended solids of all the intensive sites.

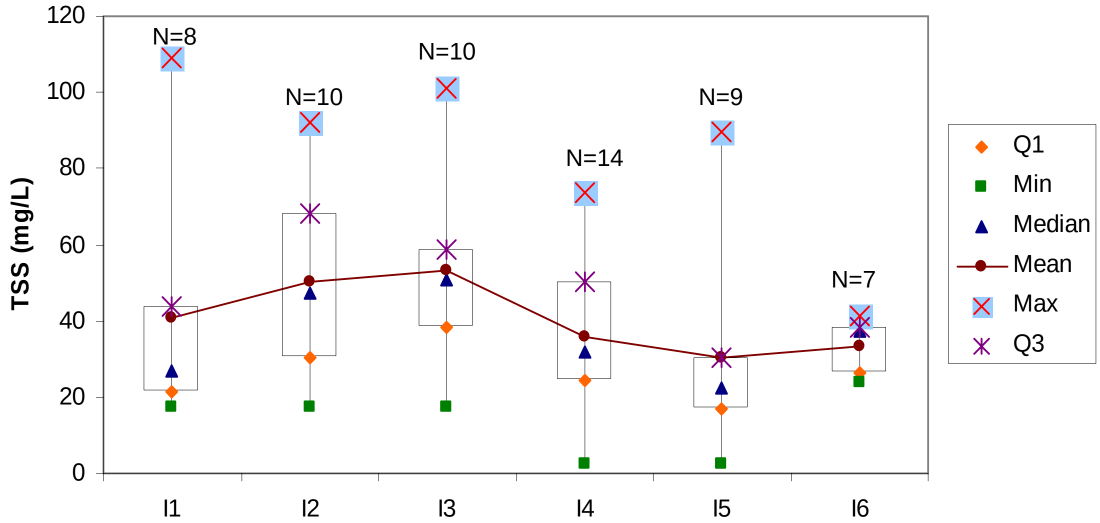


Figure 4.16. Box and whisker plots of Total Suspended Solid (TSS) concentrations for storm samples collected during the study period from intensive sites. Boxes show values in the middle 50%, bounded by first and third quartiles (Q1 & Q3), and sites are arranged from lowest to highest drainage area. Connected points show the trend of average TSS with increasing area. Variations in sample numbers (n) are due to variable stream responses not triggering all automatic samplers or equipment malfunction.

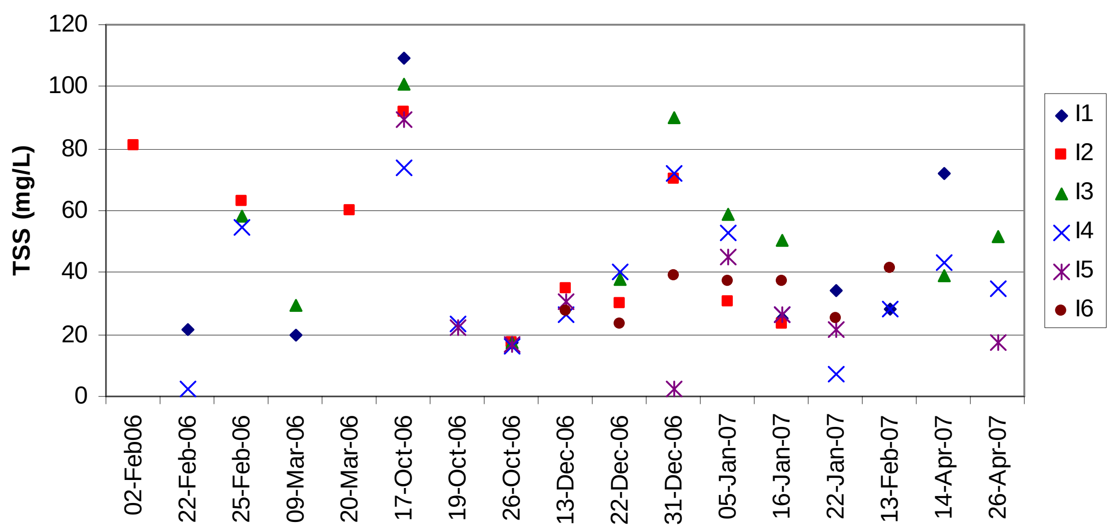


Figure 4.17. Seasonal variation in storm sample Total Suspended Solid (TSS) concentration levels.

The combination of a very dry summer and the largest storm event of the study period resulted in the highest overall TSS values on 17 October 2006 (Figure 4.17). Three

storm events from 31 December 2006 to 22 January 2007 show a reduction in TSS with every subsequent event, indicating the effects of antecedent moisture conditions and the amount of precipitation. This response is similar to the reduction in monthly baseflow concentrations occurring at the same time (Table 4.6).

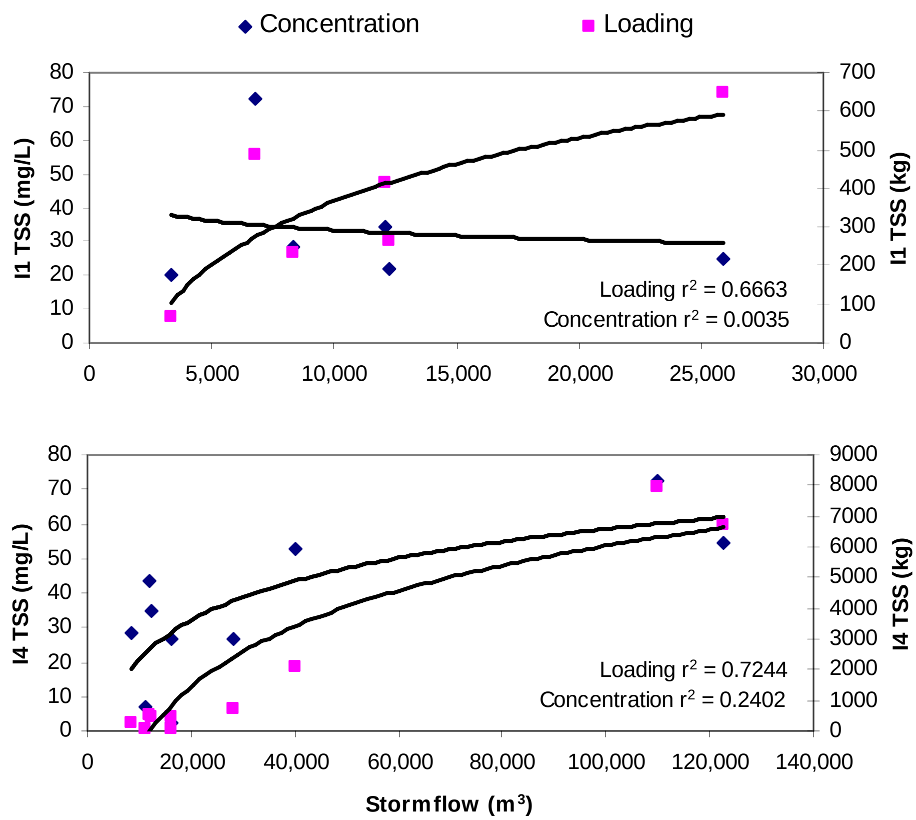


Figure 4.18. Relationships of streamflow to Total Suspended Solid (TSS) concentrations and loadings at I1 and I4. Data points are direct values, but regression r^2 values are for log-transformed data.

Storm event size shows more influence on TSS loading rates than concentrations (Figure 4.18). Site I4 also has a higher coefficient of determination than site I1 for both parameters. Site I1, with the smaller drainage area, shows a more consistent storm response as the Coefficient of Variation for loading and concentration are also smaller

than I4 (CV: I1, I4; Loading: 9.2, 14.9; Concentration: 15.3, 29.5). Beaver and debris dam effects at I5 and I6 are highlighted when comparing the relationships between storm characteristics and TSS. While storm event size and intensity has some influence on TSS concentrations at sites I1 - I4, concentrations at I5 and I6 are not affected by these parameters (Table 4.7). Larger sediment particles are forced to settle from the reduced stream velocities in the pools created behind the dams, along with the additional filtering of suspended sediments from the water passing through the impedance.

Table 4.7. Log transformed regression coefficients of determination between Precipitation (mm), Average Storm Intensity (mm/hr), and TSS (mg/L) for all intensive sites.

	r^2 Value	
Site	Precipitation & TSS	Average Intensity & TSS
I1	0.30	0.48
I2	0.29	0.46
I3	0.21	0.13
I4	0.31	0.35
I5	0.02	0.00
I6	0.01	0.00

4.3 Dissolved Solids

4.3.1 Baseflow Total Dissolved Solids (TDS)

Mean monthly TDS concentrations from all sites ranged from 79.8 mg/L to 148.3 mg/L in December 2006 and December 2005, respectively. TDS concentrations showed some seasonal differences (Table 4.8). Generally increasing values were observed as the streams returned from dry, no flow conditions, to the higher winter discharges as in November and December 2006. This could possibly be due to higher levels of the local water table, increasing the influence of groundwater on streamflow. However, as with

TSS, streamflow influence on loading remains larger than any fluctuations in concentration (Figure 4.18).

Table 4.8. Stream Total Dissolved Solid (TDS) concentrations determined from monthly water baseflow sampling. Dashed (-) values represent no flow during monthly sampling.

	Total Dissolved Solids (mg/L)						
Sites	**I1**	**E3**	**I3**	**I4**	**E5**	**E2**	**E4**
Dec-05	74.0	186.0	145.0	169.0	121.0	90.0	253.0
Jan-06	91.1	113.5	140.9	135.9	109.9	93.9	140.9
Feb-06	92.9	77.5	102.8	108.8	123.9	83.9	79.8
Mar-06	87.4	100.7	126.8	141.9	130.8	96.9	106.5
Apr-06	82.5	111.1	115.5	108.7	116.5	100.9	109.0
May-06	126.9	124.9	148.8	105.5	141.8	117.8	99.5
Jun-06	72.8	118.8	114.7	116.5	126.5	-	154.7
Jul-06	70.5	64.2	118.5	104.9	92.4	56.7	116.7
Aug-06	106.9	130.9	-	117.0	162.5	-	173.5
Sep-06	-	-	-	-	128.9	-	-
Oct-06	107.8	-	-	-	-	-	-
Nov-06	86.1	101.0	117.1	108.9	79.7	71.4	59.6
Dec-06	98.5	61.6	82.9	101.7	62.7	65.2	86.3
Jan-07	108.9	99.9	96.9	64.3	99.7	94.8	96.4
Feb-07	89.6	114.8	123.9	97.8	132.8	99.9	124.9
Mar-07	120.8	100.4	123.4	145.7	139.8	86.7	101.4
Apr-07	156.8	104	133.4	138.9	150.7	100.8	120.6
Mean	**98.3**	**107.3**	**120.8**	**117.7**	**120.0**	**89.2**	**121.5**
±*St. Dev.*	*±22.7*	*±29.7*	*±18.4*	*±25.1*	*±26.1*	*±16.6*	*±46.5*

Spatial variation of TDS concentrations, due to position in the watershed or stream network, did not exist (Figure 4.19). However, geomorphic characteristics may play a role in concentration of TDS in a stream. Stream sites I1 and E2, that were straight and narrow with high velocities and a high position on the landscape, had the lowest overall TDS concentrations. Other sites with wider and deeper streams, and slower velocities, were at times characterized as pools due to extremely low flow, but contained a relatively large volume of water (Table 4.9). Sites characterized as pools, may provide greater time for the stream water to interact with the adjacent soil and groundwater in the hyporheic (adjacent riparian) zone, increasing TDS levels. Sharp TDS peaks in July

2006 during extremely low flow conditions, and just before a majority of the streams became intermittent, suggest the same phenomena. Although site E4 also has higher velocity than most other sites, its wetted area was the largest and the site is located in an area of extensive backwaters, providing a similar interaction with soils as the pooled sites.

Table 4.9. A comparison of stream flow characteristics from monthly sampling performed on 21-22 Feb 2007, in order of increasing drainage area.

Site	Drainage Area (km^2)	Stream Profile Wetted Area (m^2)	Velocity (cm/s)	Flow (m^3/s)
I1	3.0	0.1	6.1	0.004
E3	6.1	1.9	1.0	0.02
I3	12.4	2.0	1.4	0.03
I4	14.3	3.0	1.1	0.03
E5	23.0	3.1	2.6	0.08
E2	45.1	1.2	14.5	0.17
E4	285.6	7.0	10.8	0.75

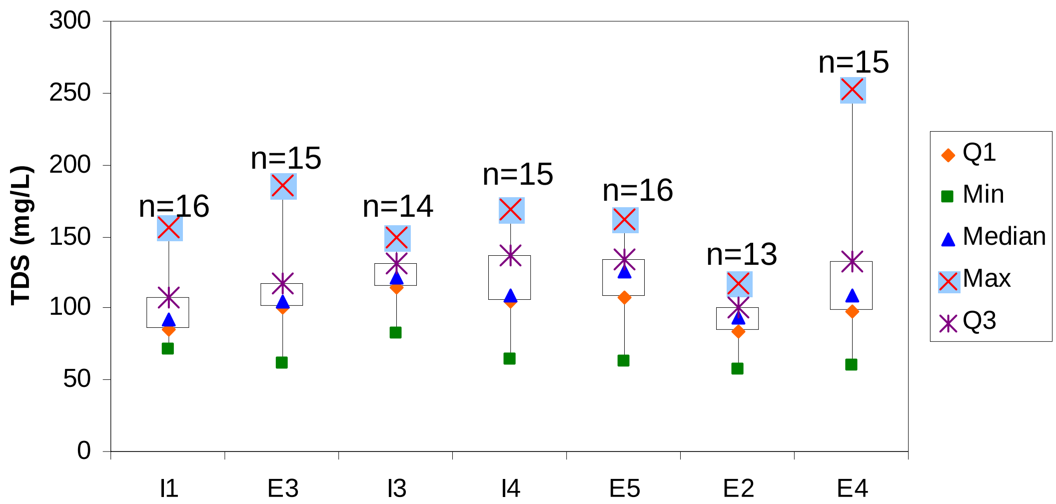


Figure 4.19. Box and whisker plots of monthly baseflow Total Dissolved Solid (TDS) concentrations for all sites during the study period. Boxes show values in the middle 50%, bounded by first and third quartiles (Q1 & Q3) and sites are arranged from lowest to highest drainage area. Variations in sample numbers (n) are due to dry periods where no surface flow existed at the site and no sample was collected.

Monthly average TDS loads for all sites ranged from 699 kg in September 2006, when only I1 and E5 were flowing, to 88,131 kg in February 2006 (Figure 4.20). Again, monthly TDS loading followed the pattern of streamflow, even more closely than TSS loading (Figure 4.21). Moisture conditions and rainfall characteristics may have a lesser effect on monthly TDS loading than even the small amount of influence they exert on TSS loads in this region. Stormflow interaction and mixing with groundwater is likely also common from the prevalent high water table level.

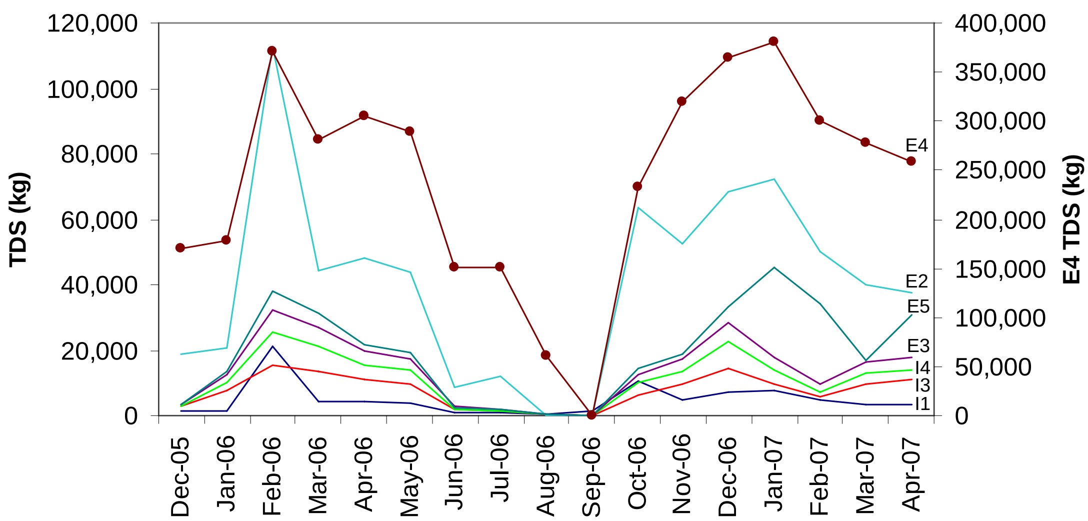


Figure 4.20. Monthly Total Dissolved Solid (TDS) loading for all sites. Site E4 values are listed on the right y-axis, with all other site values located on the left y-axis. Zero values represent no flow during monthly sampling.

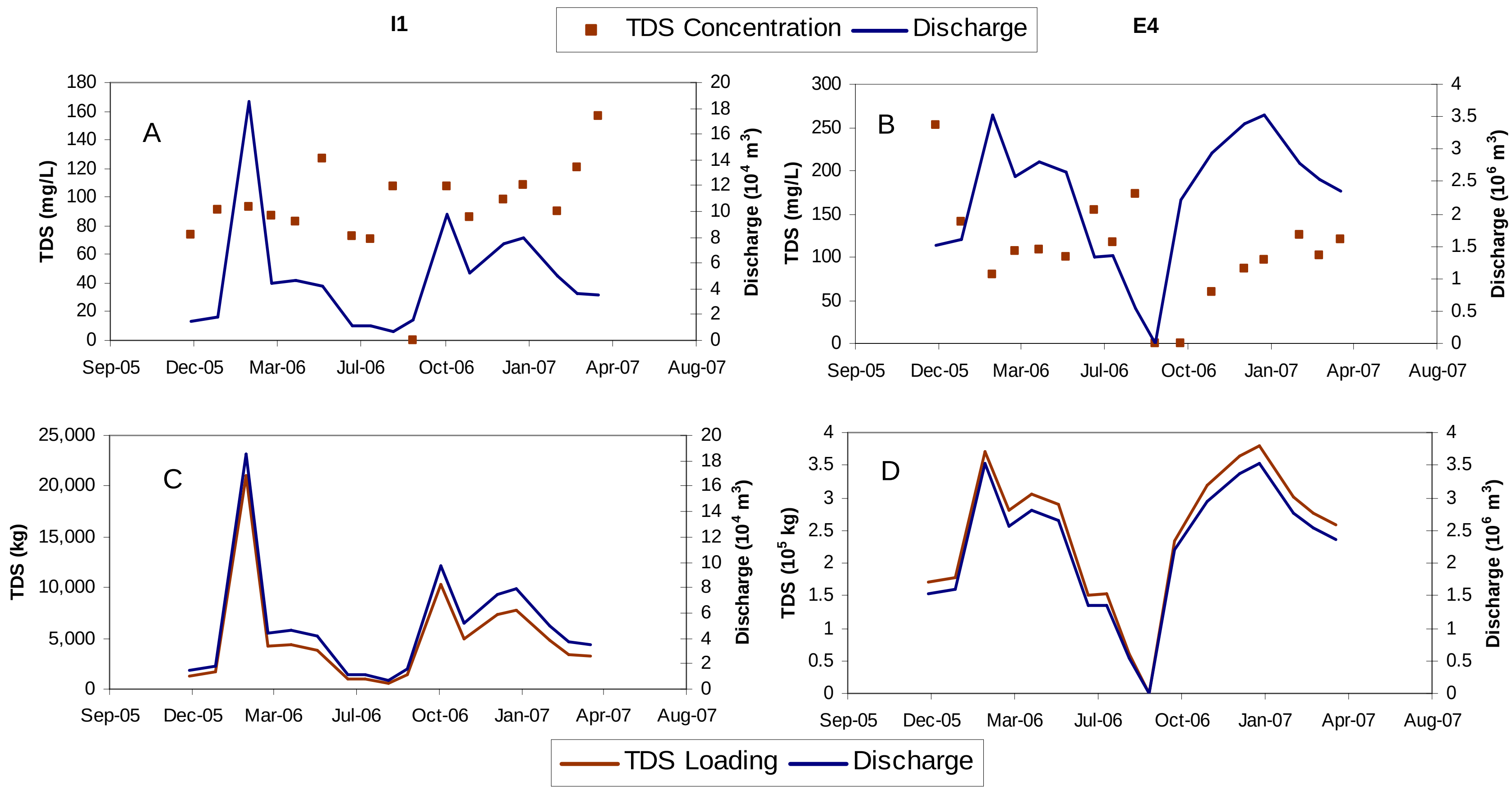


Figure 4.21. Comparisons of monthly discharge with monthly Total Dissolved Solid (TDS) concentrations (A&B) and loadings (C&D) for sites I1 and E4, the smallest and largest drainage areas, over the 17-month study period.

4.3.2 Storm TDS

Storm sample TDS concentrations across all sites ranged from 54.3 mg/L (I4) to 188.8 mg/L (I3) (Figure 4.22). Mean concentrations generally increased with increasing drainage area and may be due to having a lower position in the watershed and more influenced by baseflow levels with higher TDS. Although site I6 had the lowest mean dissolved solids with the greatest drainage area, it was heavily affected by beaver dams and sampled the least number of storms due to the created beaver pond. When sampling did occur, it was largely in the wet and cold winter months, shown below to have generally lower levels of storm TDS (Figure 4.23).

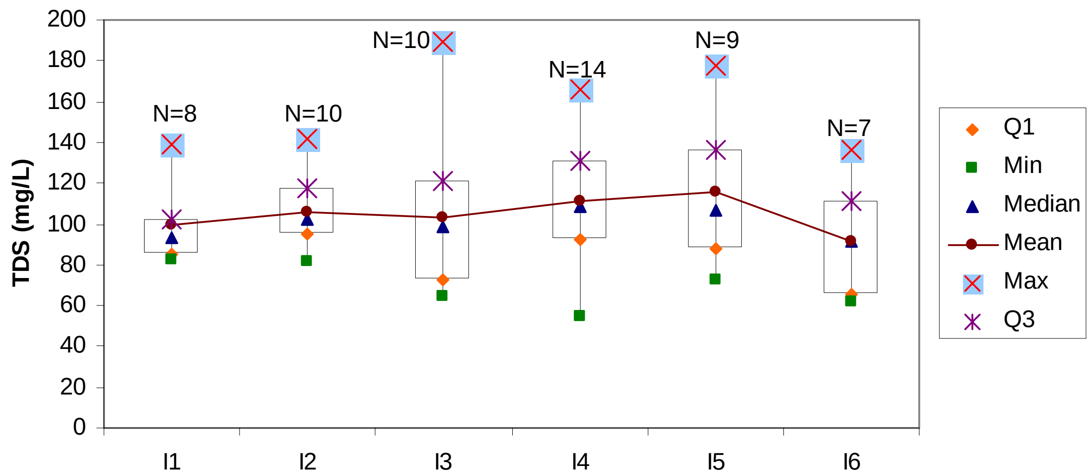


Figure 4.22. Box and whisker plots of storm Total Dissolved Solid (TDS) values for all sites. Boxes show values in the middle 50%, bounded by the first and third quartiles (Q1 & Q3), and sites are arranged from lowest to highest drainage area. Connected points show the trend of average TDS with increasing area. Variations in sample numbers (n) are due to variable stream responses not triggering all automatic samplers or equipment malfunction.

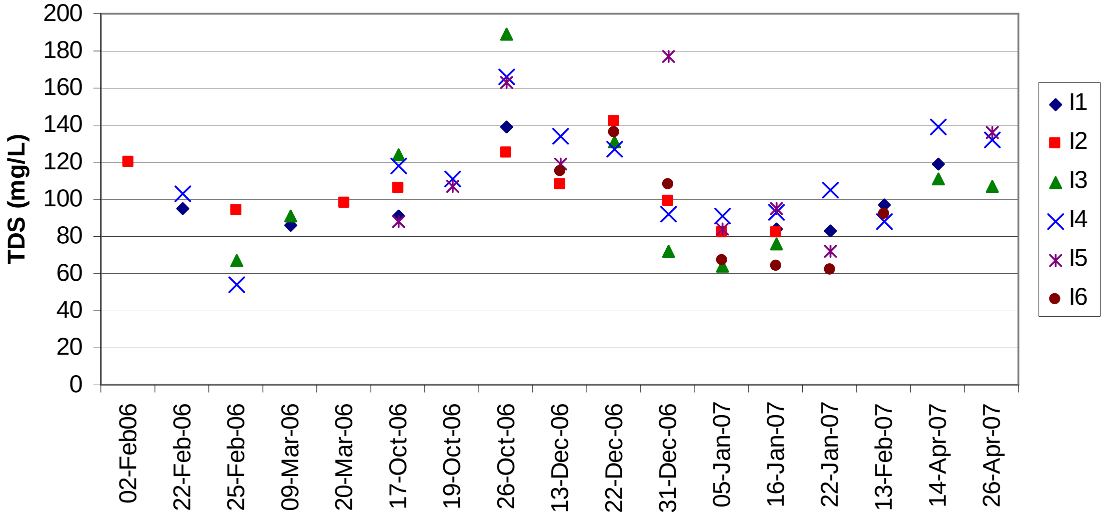


Figure 4.23. Seasonal variation in storm sample Total Dissolved Solid (TDS) concentration levels.

Although some seasonal variation in monthly baseflow TDS concentration exists, there is a much more distinct variation in storm samples over the study period (Figure 4.23). Using high frequency measurements at site N1, stream depth shows an effect on TDS levels (Figure 4.24). Diurnal temperature fluctuation causes a similar, though delayed, diurnal pattern in dissolved solids. Decreasing stream levels can cause an increase in dissolved solid concentrations, with less stream water available for dilution. Variations in stream depth, and therefore discharge, may be able to explain some of the seasonal variation in storm TDS values.

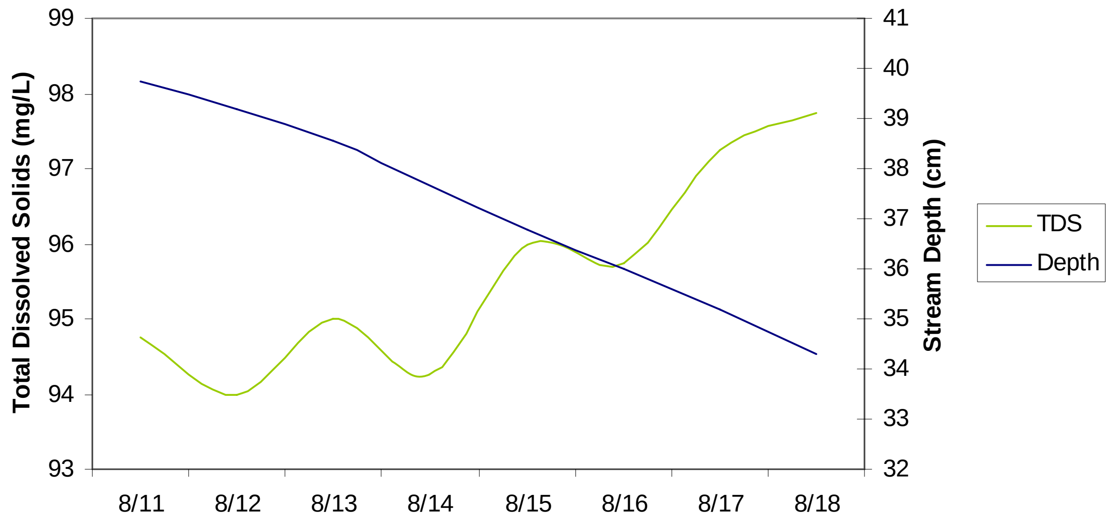


Figure 4.24. Daily stream depth and Total Dissolved Solid (TDS) Concentrations at site N1 on Turkey Creek in August 2006.

Concentration of storm TDS is additionally influenced by storm event size and frequency. Using available storm samples from site I4, which had the highest number of storms sampled, the two largest storms of 122,764 m^3 and 110,014 m^3 had two of the lowest TDS values of 54.3 mg/L and 91.8 mg/L, respectively. With these large storms the relative level of surface and interflow water sources is greatly increased and baseflow, having generally higher rates of TDS, has a much reduced impact (Table 4.10). Although amount of precipitation does not explain all the storm TDS concentration variation, regression of the log-transformed precipitation (mm) and TDS (mg/L) data shows a strong influence (r^2=0.47, d.f.=9, p=0.0276).

Table 4.10. Stormflow and storm sample Total Dissolved Solid (TDS) characteristics for site I4.

Date	Stormflow (m^3)	Percent Baseflow	TDS (mg/L)	TDS (kg)
31-Dec-06	110,014	7.0%	91.8	10,099
25-Feb-06	122,764	9.7%	54.3	6,666
05-Jan-07	40,074	16.4%	91.3	3,659
16-Jan-07	28,211	25.5%	93.5	2,638
13-Dec-06	16,147	42.2%	134.5	2,172
22-Jan-07	11,325	47.9%	104.9	1,188
13-Feb-07	8,456	48.1%	87.7	742
26-Apr-07	12,195	58.5%	132.0	1,610
22-Feb-06	16,383	66.8%	103.5	1,696
14-Apr-07	11,932	67.5%	138.6	1,654

Additionally, storm frequency also contributes to the variation in storm TDS concentrations. After the large storm on 31 December 2006, the following two smaller storms had a similarly low TDS value. The high TDS value of 134.5 mg/L from the storm on 13 December 2006 came after a dry period of greater than one month. However, frequency and size alone do not explain concentrations such as the extremely low TDS value of 54.3 mg/L on 25 February 2006, or the second lowest value of 87.7 mg/L on 13 February 2007 that occurred during the smallest storm event. Overall, the larger storms resulted in higher levels of TDS loading due to the large volumes of water, even with the generally lower TDS concentrations.

4.4 Hydrologic Modeling

4.4.1 Streamflow Initial Simulation and Calibration

The SWAT model was used to simulate streamflow over the study period, December 2005 through April 2007. Initial simulation and iterative calibrations were compared with observed streamflow values at selected sites throughout the watershed. Flat Creek was divided into 8 sub-basins, one sub-basin for each study site where

streamflow could be determined, along with the final watershed outlet before the confluence with Castor Creek (Figure 4.25, Table 4.11).

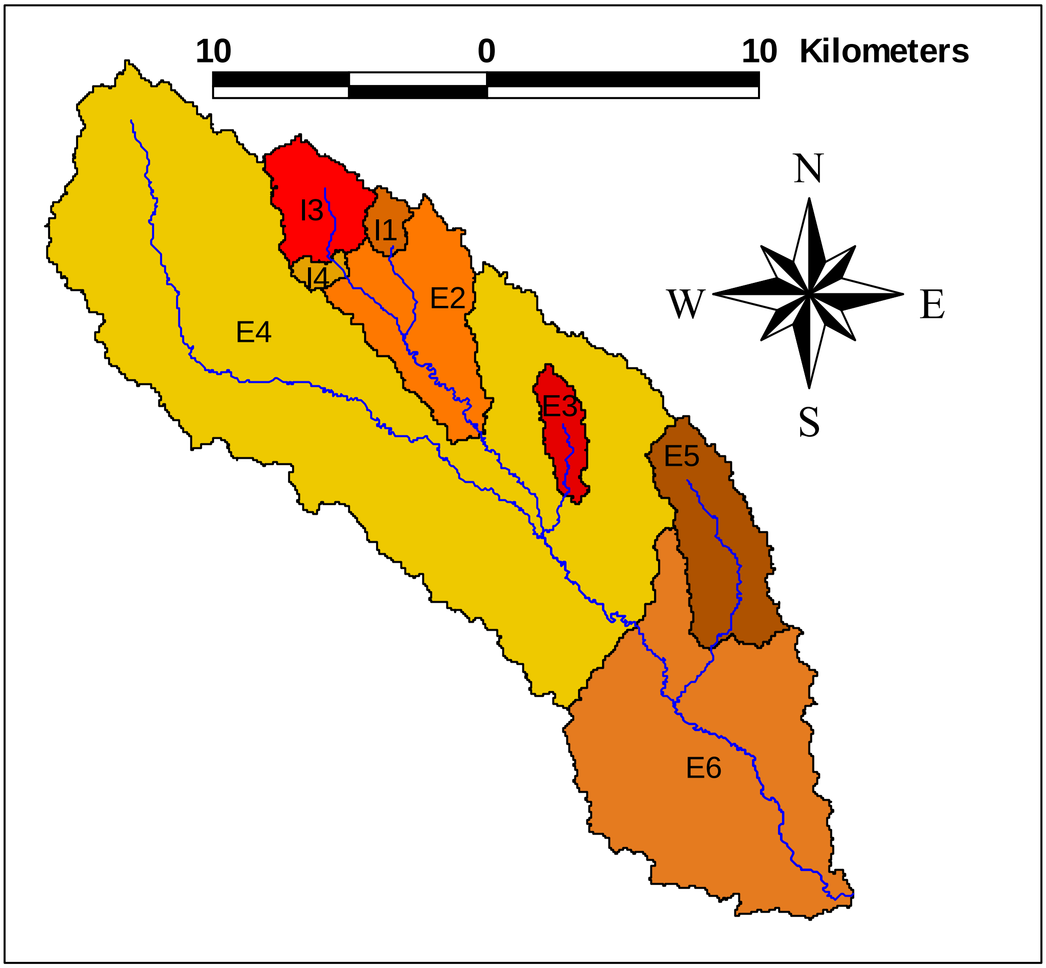


Figure 4.25. Subwatersheds used for the Soil and Water Assessment Tool simulation based upon sites where discharge was measured, to compare observed and simulated streamflows.

Table 4.11. Soil and Water Assessment Tool characteristics for each subwatershed.

Site	Sub-watershed	Area (km^2)	Elev (m)	CH_L2[1] (km)	CH_S2[2] (%)	CH_D[3] (m)	CH_W2[4] (m)	SLOPE[5] (%)
E2	1	27.7	52	11.5	0.2	0.60	12.7	4.0
E3	2	6.1	50	3.3	0.3	0.27	3.8	4.7
E4	3	211.5	41	38.0	0.1	1.21	36.5	4.1
E5	4	23.0	45	8.8	0.2	0.56	8.5	3.6
I1	5	3.0	65	0.4	0.5	0.20	2.5	5.4
I3	6	12.4	72	3.1	0.2	0.36	5.8	5.5
I4	7	1.9	54	0.9	0.8	0.38	6.4	4.3
Outlet	8	83.8	30	18.2	0.1	1.38	44.8	3.1

[1]Main Channel Length
[2]Main Channel Slope
[3]Average Main Channel Depth
[4]Average Main Channel Width
[5]Average Sub-basin slope

A 20% land use and 10% soil threshold, or area percentage of each sub-basin, is recommended in the SWAT User Manual when determining the Hydrologic Response Units (HRUs). HRUs are unique combinations of land use and soil types. Ideally, the threshold reduces the number of HRUs, simplifies the model, and decreases processing time. However, as this study was implemented to determine site harvesting effects on streamflow, harvested areas are not large enough to meet any such thresholds and would be eliminated (Table 4.12). Therefore, the model was run with and without thresholds. With the recommended thresholds in place, only 21 HRUs were created, increasing to 79 HRUs without any thresholds, due to the increased number of land use and soil combinations. The differences in the simulation with these two threshold methods are also compared.

Table 4.12. Land Use and Soil Distribution

Land Use	SWAT Class	Area (km^2)	% Total
Forest-Evergreen	FRSE	189.5	51.3
Forest-Deciduous	FRSD	121.3	32.8
Harvested, 1-3yrs	RNGB[1]	26.0	7.0
Harvested, <1yr	AGRL[2]	18.2	4.9
Pasture	PAST	14.0	3.8
Water	WATR	0.4	0.1
Soil Type	MUID[3]		
Sacul	LA148	289.8	78.5
Guyton	LA114	60.1	16.3
Frizzell	LA146	6.5	1.8
Briley	LA336	4.8	1.3
Frizzell	LA333	4.8	1.3
Guyton	LA294	3.3	0.9

[1]SWAT Class Range-Brush was used to represent 1-3 year harvests,
[2]SWAT Class Agricultural Land-Generic (with no crop, growing season) was used to represent <1 year harvested areas.
[2]Mapping Unit ID

SWAT was run without any calibration, using the inputs of climate, elevation, land use and soils data described in the methods. This initial streamflow simulation run overestimated peak storm flows, especially during large events, and consistently

underestimated baseflow conditions in the wet season. Calibration was then performed on multiple parameters guided by previous work in a similar area from Wu and Xu (2006) and recommendations in the SWAT User Manuel (Neitsch *et al.* 2002). Parameters tested for calibration in the Hydrologic Response Unit module (.hru) were CANMX, ESCO, and OV_N; in the Soils module (.sol) was SOL_AWC; in the Groundwater module (.gw) were GW_DELAY, GWQMN, GW_REVAP, ALPHA_BF, RCHRG_DP, SHALLST, REVAPMN; in the Land Management module (.mgt) was CN2; and in the Main Channel Routing module (.rte) was CH_N2.

CANMX, the maximum canopy storage, was adjusted from 0.0 mm up to 10.0 mm for forested areas, with no effect on streamflow. ESCO, the soil evaporation coefficient, was determined to be optimal at 0.950. However, SWAT already accurately represented this parameter, as again there was no improvement in streamflow simulation. OV_N, Manning's roughness coefficient "n" for overland flow, was increased by 0.30 and returned a slight improvement on stormflow. Hydrograph storm peaks were reduced, with a longer sustaining falling limb. The single parameter adjusted in the soils module was the available water content of the soil, SOL_AWC. Increasing this parameter led to increased baseflow and storm peaks, decreasing led to lower baseflow and storm peaks, without statistical improvement either way.

Further calibration of stormflow simulation could not be performed without first addressing the errors in baseflow. Baseflow is accurately portrayed during the dry summer season, but fails to rise with increases in storm event frequency in the transition to the wet season. The SWAT User Manuel suggests: decreasing GWQMN, the shallow aquifer depth at which baseflow occurs; decreasing GW_REVAP, the revaporization

coefficient where water moves from the water table into the vadose zone by capillary force; and increasing REVAPMN, the shallow aquifer depth at which revaporization starts. However, these variables are already at their respective maximum and minimum values, cannot be adjusted outside their given range, and may not accurately represent the watershed conditions even if it were possible.

Increasing GW_DELAY, the time it takes for the local groundwater table to recharge deep aquifers, from 31 days to 500 days (maximum value), improved model performance the most. Although this had the effect of increasing baseflow, it continues to be underestimated and without further means of adjustment. ALPHA_BF, the baseflow alpha factor for recession constant, was modified by both increasing and decreasing, without simulation improvement. This may be due to the groundwater delay already set at the maximum value, negating the baseflow recession constant. SHALLST, the initial depth of water in the shallow aquifer, was increased to the maximum (1000 mm) without effect on streamflow. One parameter, initial groundwater height (GWHT), was not active in this version of SWAT and may be critical for accurate baseflow simulation in this type of region.

In the land management module, the SCS Curve Number was reduced by 4.0 at the watershed outlet. This change also reduced storm peaks and sustained higher flow, similar to the change with the overland value of Manning's "n", OV_N. No change was necessary for the headwater stream. Out of the 13 parameters used for calibration, only two were modified (GW_DELAY, OV_N) for I1, and three (GW_DELAY, OV_N, CN2) were modified for E4. Most other parameters showed little sensitivity to adjustment, and

high sensitivity parameters such as ESCO and SOL_AWC, did not result in simulation improvement after adjustment.

4.4.2 Simulation Accuracy

Using the site with the smallest drainage area (I1, 3 km^2, Figure 4.26) and effective watershed outlet (E4, 286 km^2, Figure 4.27), streamflow simulation with SWAT was examined. Statistics of Mean Absolute Error (MAE), Nash-Sutcliffe Efficiency (NS_e) (Nash and Sutcliffe 1970), and Relative Error (RE) were used to compare simulated and observed streamflows (Table 4.13).

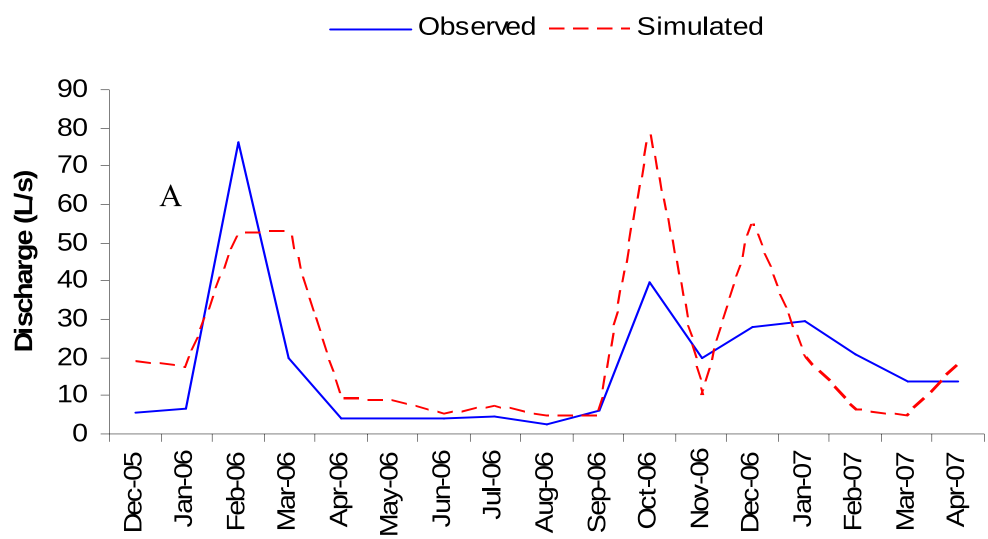
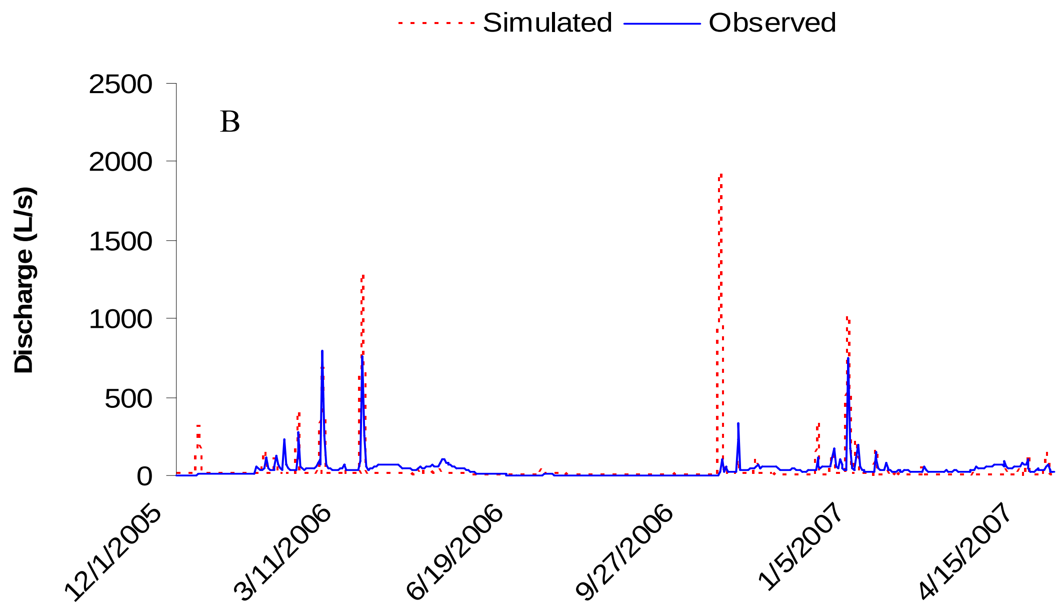


Figure 4.26. Monthly (A) and daily (B) streamflow simulation results, compared to observed streamflow at site I1, the site with the smallest drainage area.

(Figure continued)



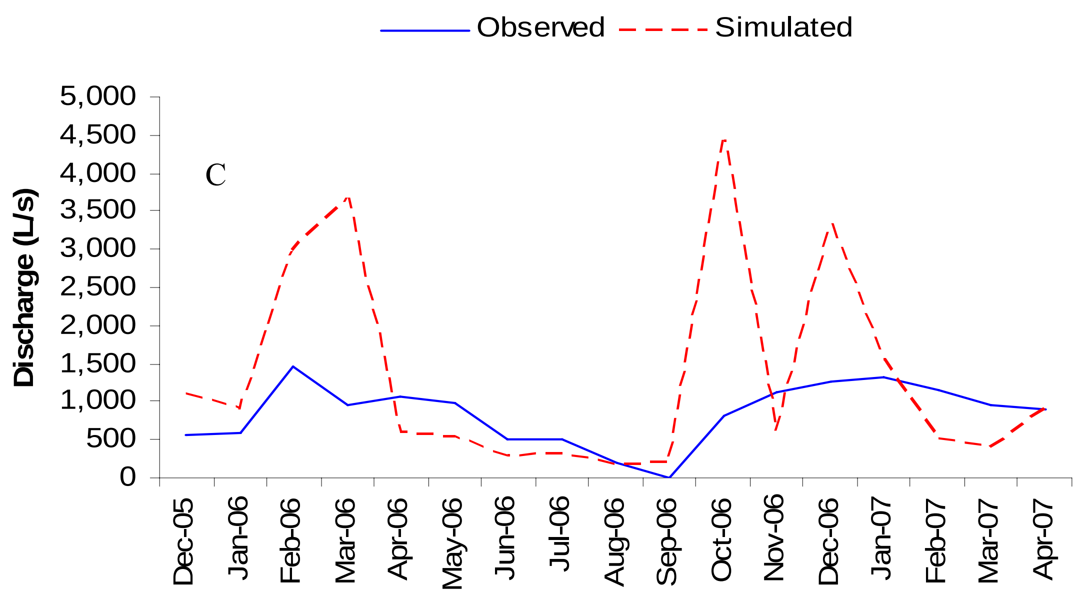
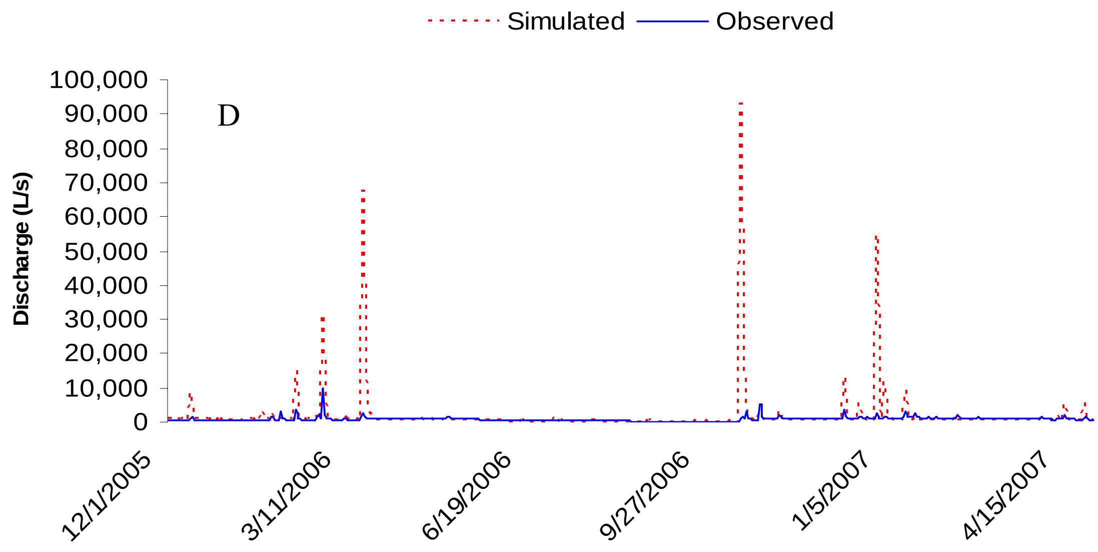


Figure 4.27. Monthly (C) and daily (D) streamflow simulation results, compared to observed streamflow at site E4, the Flat Creek Watershed outlet.

(Figure continued)



While it was possible to obtain an increase in peak flow accuracy by greatly increasing Manning's "n" and decreasing the SCS Curve Number, this produced hydrographs unrepresentative of these headwater streams and did not greatly reduce the total amount of storm flow. In months where baseflow dominated stream output, SWAT underestimated monthly flow levels. Months of storm dominated streamflow resulted in overestimations of monthly flow.

Simulation results, both with and without the land use and soil threshold, showed a poor accuracy when compared to observed results (Table 4.13). While the land use and soil threshold had little effect on the uppermost basin (I1), it greatly affected simulation results at the watershed outlet (E4).

Table 4.13. Statistical comparison of monthly simulated and observed results for I1 and E4, using the Nash-Sutcliffe efficiency (NS_e), Mean Absolute Error (MAE), and Relative Error (RE).

Site	Statistic	No Calibration (No Threshold)	Calibrated (No Threshold)	No Calibration (Threshold)	Calibrated (Threshold)
I1	NS_e	-0.25	-0.06	-0.26	-0.07
	MAE (L/s)	26.8	25.1	26.9	25.2
	RE (%)	55.2	44.5	55.3	44.7
E4	NS_e	-13.86	-10.43	-9.03	-5.72
	MAE (L/s)	958.1	841.5	850.2	677.0
	RE (%)	36.6	56.2	4.1	9.0

Relative error actually increased from the pre-calibrated simulation to the calibration at E4. Baseflow was increased with relatively little reduction in storm flow and since RE uses averages, the over-estimated stormflows were not offset as much by the under-estimated baseflows. Limits of the developed stage-discharge rating curves are also likely causing large discharge calculation errors and underestimation during the highest stormflow.

CHAPTER 5. DISCUSSION

5.1 Hydrologic Responses in the Flat Creek Headwaters

Headwater streamflow in this lowland watershed has high seasonal variability, ranging from intermittent/no flow periods in the late summer, to overbank flooding in response to large storm events (Figure 5.2). Even with the typical quick response to storm events, peak discharges and total runoff percentages are reduced at all stream sites in the Flat Creek Watershed. Streamflow response may be explained by several physical characteristics of the drainage basin. Flat Creek has extremely low slopes, particularly along floodplains and stream channels, reducing the level of direct overland runoff from the landscape. Soils in depressions and along the floodplain have low permeability, resulting in a seasonally elevated water table existing just below the surface or ponded above the ground (NRCS 1997). These soils increase the hydrologic storage capacity of the watershed, reducing initial runoff from storms, followed by a release of water to the stream during dry periods. Water stored in the soil profile is also more likely to be lost through evapotranspiration before reaching the stream. Lastly, beaver activity in the area, along with natural stream debris, create dams in the stream channel which result in ponding and compounds the effects on streamflow caused by the low slopes and poorly drained soils.

Beaver dams have been found to affect the hydrologic response of streams and adjacent areas in both wet and dry seasons. Dams increase the size and duration of inundation from stream flooding in wet seasons, and slow water table decline during the dry summer months in downstream areas (Westbrook *et al*. 2006). In this study, much of

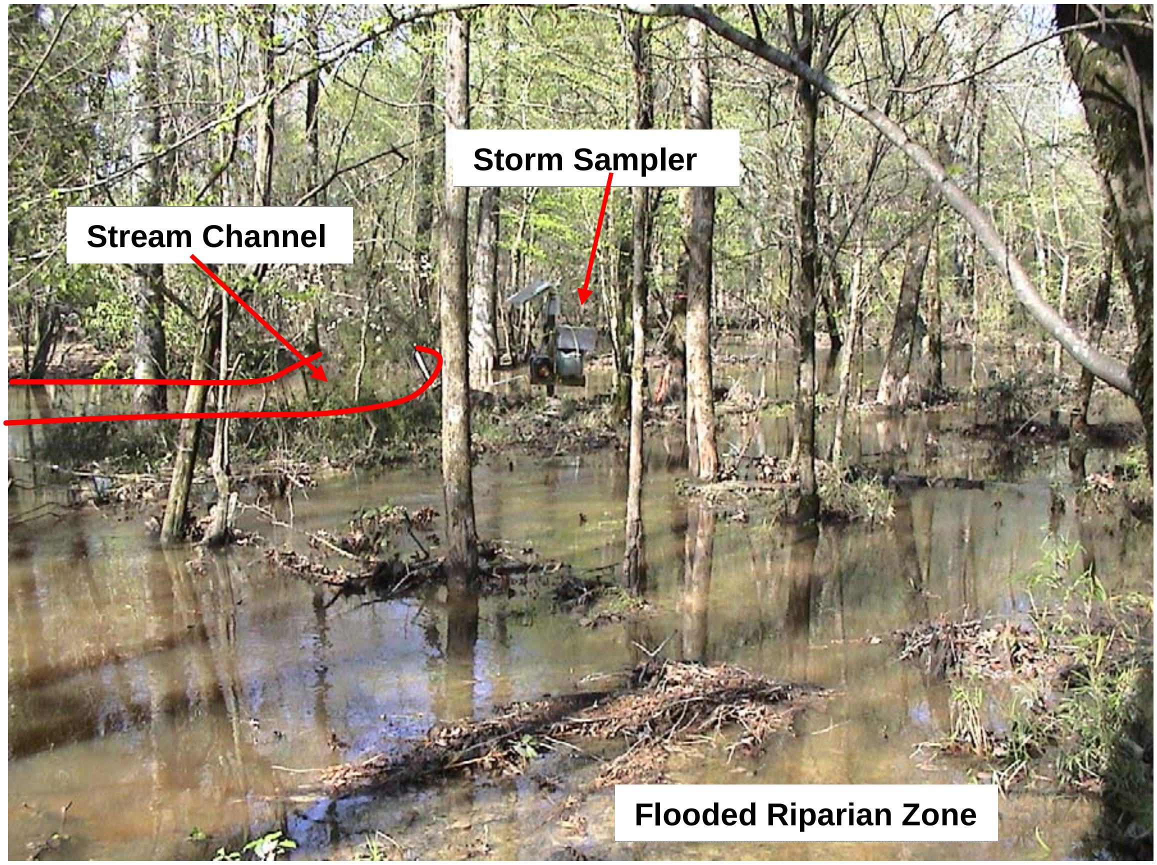


Figure 5.1. Riparian flooding at site I6 along Turkey Creek.

the variable hydrologic response between sites in the stream network could also be explained by beaver and debris dam effects. Site I1, located in a deep and narrow headwater channel, had the most continuous flow of all sites. Site E2, also in a narrow channel further down in the watershed, drains a much larger area and had the least continuous flow. I1 appears to be unaffected by dams, allowing flow from precipitation to run freely along the channel. However, when that flow enters a part of the channel blocked by a dam, velocity decreases, storage capacity of the channel increases, and flow continuity beyond the series of dams is greatly reduced or eliminated, especially during dry periods. One or more of these dams (Figure 5.2) along the stream network could be

causing increased intermittency during these dry periods, and require larger precipitation events to reconnect surface flow.

Figure 5.2. Beaver Dam located downstream of site I6 on Turkey Creek.

Antecedent moisture conditions appeared to have a strong effect on the uppermost headwater stream, while having much less of an influence on the watershed outlet. Much of this stream response may be due to the differences in land use, particularly with 25% of the I1 sub-watershed recently harvested. Additionally, it is likely that less precipitation is required to saturate the small headwater drainage than the entire watershed, in order to return an intermittent stream to a flowing status.

Runoff coefficients were generally low throughout the watershed, partially due to the lower than normal precipitation throughout the study period. The low slopes and elevated water table were also factors in increased storage time throughout the watershed. Ponding within the stream channel from the beaver dams and riparian ponding from the low permeable soils and elevated water table results in large portions of the watershed often acting as a wetland, similar to what McNamara and others (1998) found in the flat

coastal regions of Alaska during the summer. While the highest stormflow was probably underestimated due to the limitations of our developed stage-discharge curve ratings, the level of runoff is within a reasonable range of values reported in the literature, particularly in low precipitation conditions. Runoff calculated from Beasley and Granillo's (1988) report of water yield in catchments averaging 3.1 ha on a similar Arkansas watershed ranged from 0.01 to 0.20, lower than our range of 0.06 to 0.27.

Stormflow response of streams was variable throughout the watershed. Sites where discharge could be determined were used to show the increase of hydrograph parameters, such as lag time and recession constants, with increases in drainage basin area. Howard (2006) found basin size and relief to be the most important characteristics in predicting hydrograph time to peak and peak discharge. Land slope in the Flat Creek Watershed decreases with increasing drainage area, moving from 5.5% at the headwater (I1) down to 4.2% at the lowest site (E4), contributing to the longer response period of streams draining larger basins.

5.2 Sediment Transport in the Flat Creek Headwaters

Although Wolock and others (1997) found the sum of base cations (dissolved solids) increased with basin size, due to greater subsurface contact, this was shown not to be the case in the Flat Creek Watershed. Geomorphological properties such as width, depth, and flow velocity may have greater impacts than drainage area on levels of stream TDS. Sites with lower velocities and higher wetted areas may be interacting with the hyporheic zone more than sites with higher velocities and lower wetted areas. This interaction with the adjacent soil and water may be causing an increase in TDS concentrations. Malcolm and others (2003) determined a conductivity gradient

increasing from stream water through the hyporheic zone to groundwater, reflecting increasing residence times. However, hydrochemistry values were also highly variable within as little as ten meters and dependent upon position in the stream reach studied. Butturini and others (2002) also comment on the high levels of conductivity at locations adjacent to the stream channel, including the hyporheic and riparian zones.

Samples taken from pooled water in intermittent streams are inconclusive in supporting this reasoning. During October monthly sampling, the driest point before streamflow returned about a week later, samples were obtained from pools of water along the E2, E3, E4, I3, and I4 stream channels. Adding these dry stream measurements had the following results: I3 and E2 have TDS levels within the 1st quartile, I4 and E4 have TDS values within the 4th quartile, and the E3 TDS value is within the 3rd quartile (Figure 5.3). Sun and others (1998) also propose that the level of the shallow ground water table largely controls surface runoff to streams, indicating that it would have additional influence on stream TDS values.

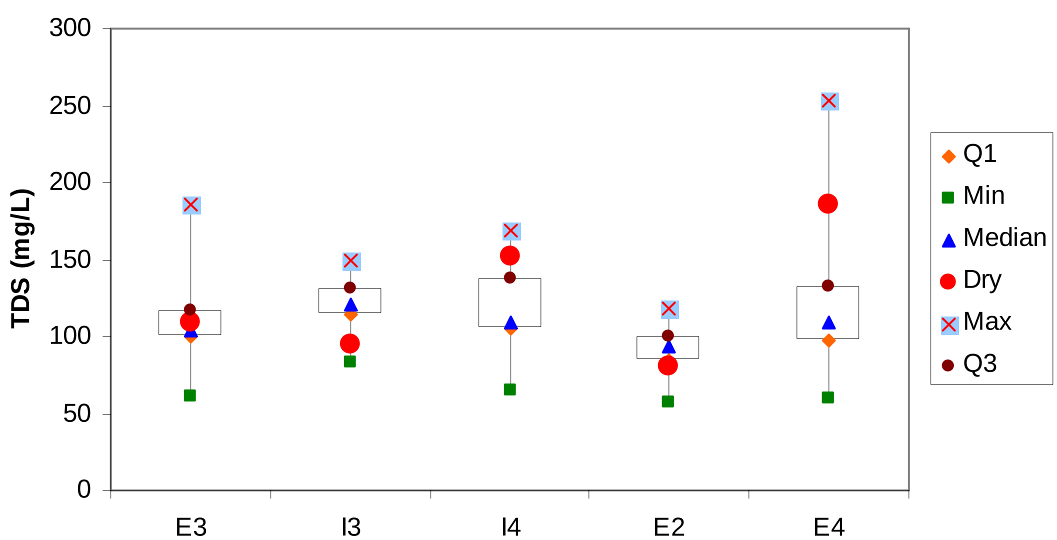


Figure 5.3. Box and whisker chart, modified from Figure 4.19 to include a Total Dissolved Solid (TDS) concentration from samples collected in pools of water on intermittent streams.

A higher groundwater table may cause higher storm runoff due to lower infiltration capacity of the soils. Lower water tables may reduce storm runoff, but more of the streamflow may come from interflow through the soil, interacting with the soil matrix and increasing the amount of dissolved solids in the runoff water. To more fully assess the effect of the variable water table on TDS concentrations, knowing the source of the storm runoff would also be necessary. Proportions of flow contributed by overland, interflow, and groundwater would be expected to result in higher dissolved solid concentrations with higher levels of each subsequent source.

Not only is the flowpath of the water important, but also the amount of stormflow from event (new) water and pre-event (old) water. Pre-event water would be expected to contribute higher dissolved solids than event water due to increased residence times. While multiple studies have explored flowpaths and sources to forested headwater streams (McGlynn *et al.* 2004; Brown *et al.* 1999; Elsenbeer *et al.* 1995; Pearce *et al.* 1986; Hewlett and Hibbert 1967) and found them to be variable due to individual site characteristics, seasonality, and catchment size, none have the unique combination of sub-tropical climate, low slopes, and elevated water table present in the Flat Creek Watershed.

Adding sites I2, I5, and I6 to the analysis of TSS and TDS concentrations may yield some additional insights into the characteristics of these streams (Figures 5.4, 5.5). The sites were not analyzed with the others due to impacts from dams that made it impossible to accurately calculate discharge using stage-discharge relationships, and therefore loading rates. These sites are generally characterized as the deepest, most pooled sites of all sample locations. Effects of the dams can be seen immediately, with

these sites never reaching dry conditions, so concentration values exist for all 17 months which no other locations have. However, although the streams were not necessarily intermittent or dry at these locations, effective flow was often negligible.

Comparing TDS values from these three sites, it would appear that these stream reaches are more stable. As deep, pooled sites with little flow and constant water throughout the year, less variation in TDS levels exist. Concentrations do appear to generally follow the trends of other sample sites, steady values in early 2006, and a slow rise as streams return to flow in late 2006/early 2007. Higher TDS concentrations would be expected for these sites, with a higher residence time and more interaction with the hyporheic zone. However, the characteristics of these sites may be close to the sites classified as pools.

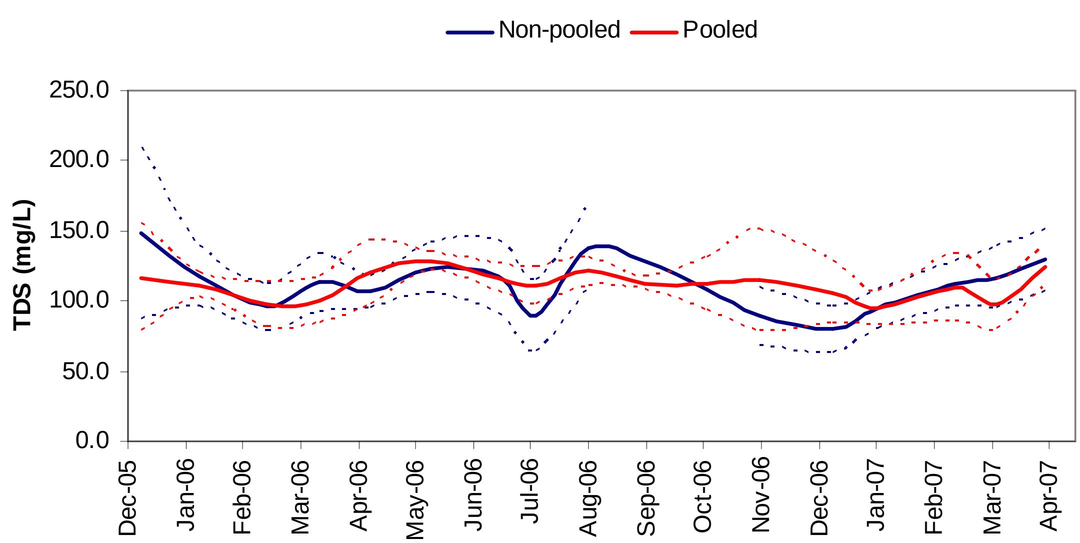


Figure 5.4. Monthly average Total Dissolved Solids (TDS) concentrations from previously analyzed non-pooled sites and pooled (I2, I5, I6) sites, with standard deviations marked by dashed lines. No standard deviations exist for two months (Sep, Oct 2006) of the non-pooled sites, as only one site was flowing.

Although TDS values give an indication of stream system stability, TSS concentrations show a different situation. Suspended solids follow the general trend through much of the year, but spikes in TSS occur for the pooled sites in both April and June. Multiple explanations for these spikes could exist. Beaver activity, such as dam building/repairing or removal of trees from the riparian zone may cause a temporary increase in suspended solids. Dam overtopping or failure would also affect solids at these sites.

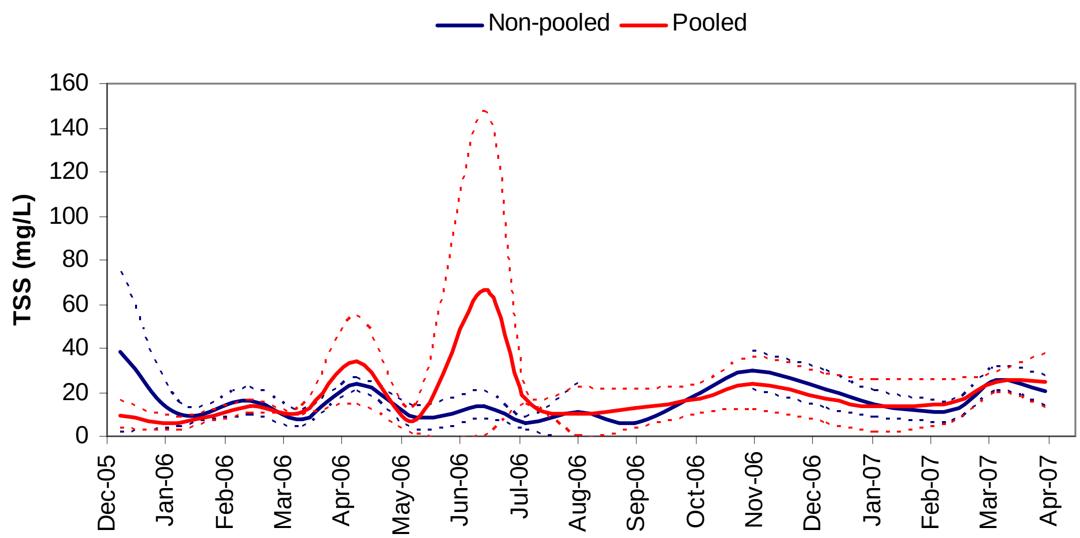


Figure 5.5. Monthly average Total Suspended Solids (TSS) concentrations of previously analyzed non-pooled and pooled (I2, I5, I6) sites, with standard deviations marked by dashed lines. No standard deviations exist for two months (Sep, Oct 2006) of the non-pooled sites, as only one site was flowing.

Sampling method may also influence these readings. Automatic ISCO samplers were used to collect the water. Suction lines for water sampling were placed near the stream bottom, to be able to sample even in the lowest flow conditions. Sediment deposition from reduced water velocities may have occurred along the stream reach, including around the suction line. Although the lines are rinsed and purged three times

before sampling, this may have stirred up deposited sediment - particularly fine sediments - which were then included in the water samples. The same situation may not have arisen at I2 as it appeared to be constantly deep with very low flows. I2 was not heavily affected by dams, just a very deep low-flow site that would be similar to sites influenced by dams (I5, I6).

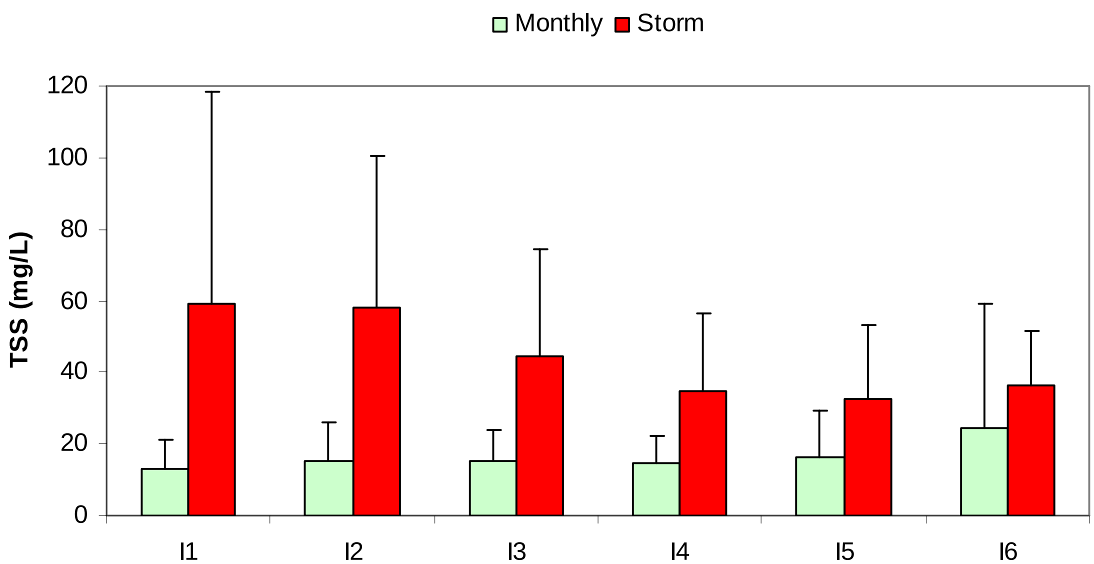


Figure 5.6. Average monthly baseflow and storm sample concentrations of Total Suspended Solids (TSS) for all intensive sites, with standard deviation bars.

Average storm samples of suspended solids consistently produced 2-5 times higher concentrations than average monthly baseflow samples for all sites (Figure 5.6). Sites I5 and I6, impacted most by beaver and debris dams, show the least differences between the two types of sampling. Increasing drainage area and stream size likely also contributed to the settling of sediments before reaching the most downstream sites, with dams simply increasing the magnitude of these effects. Higher concentrations of TSS were found in a North Carolina undisturbed forested inter-stream wetland where the 90th percentile baseline value was determined to be 33 mg/L, with seasonal highs and lows in

summer and winter, respectively (Catts 2006). Site variations in TSS were also much greater than any nutrient (N, P, OC) measured by the researcher, and therefore may be more location specific.

Compared to average monthly baseflow TDS, storm dissolved solids had higher average storm concentrations at I1 and I5, with lower concentrations at I2, I3, I4, and I6 (Figure 5.7). No explicit spatial or geomorphological patterns appear to govern the variation between baseflow and storm TDS, showing the complex hydrological flow processes in this region.

Storm TDS concentrations at site I1 may have increased due to its position on the landscape. Located in a deep, narrow channel, interflow may have traveled through a deeper soil profile and had more time to interact with the soil matrix before reaching the stream. Increased TDS concentrations in storm samples at I5 were possibly influenced by runoff from a paved road and bridge located directly upstream of the site. No other site was located near a paved road.

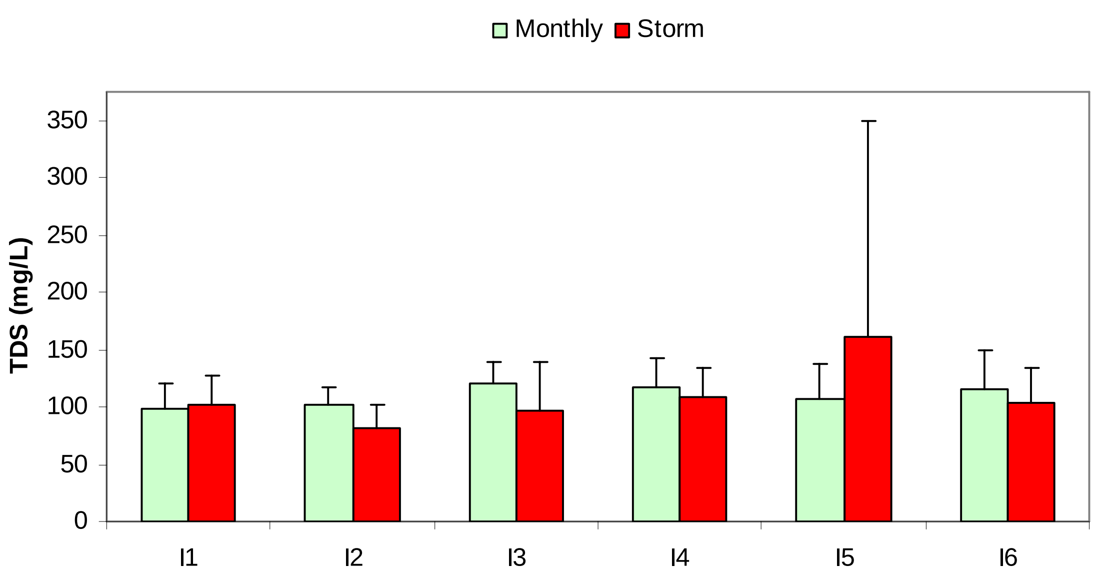


Figure 5.7. Average monthly baseflow and storm sample concentrations of Total Dissolved Solids (TDS) for all intensive sites, with standard deviation bars.

Soil samples analyzed for select chemical ionic species show higher levels in the upper section (0-10cm) than the lower section (10-20cm), except for Na^+ (Table 5.1). These results may indicate a greater amount of ionic species are transferred to water existing lower in the soil, due to increased time of saturation. The higher sodium values may also be a result from precipitation out of the seasonally elevated water table, but further tests on the chemical composition of the groundwater are needed for confirmation.

Table 5.1. Soil test results for selected ionic species (±SD).

Soil Depth	Ca (ppm)	Mg (ppm)	K (ppm)	Na (ppm)
0-10 cm	389.9 ±199.1	77.0 ±29.7	36.4 ±17.8	27.6 ±57.0
10-20 cm	225.4 ± 99.5	62.1 ±21.1	22.1 ± 8.9	42.9 ±72.3

Converting sediment yield from a 17 month average to an annual value for cross-study comparison, I1 has a flux of 53.8 kg ha^{-1} yr^{-1}. Using Beasley and Granillo's (1988) study again, located in a similar headwater region in Arkansas, the yield at I1 is higher than the five year range of the undisturbed control sites (4 – 52 kg ha^{-1} yr^{-1}) and lower than the four year post-harvest clearcut yields (63 - 264 kg ha^{-1} yr^{-1}). With a quarter of the drainage area clearcut between 2004-05, sediment yield in Flat Creek headwaters appears to occur at similar rates. A study in the Albemarle-Pamlico drainage area of North Carolina found annual coastal plain sediment yields to average 12 t mi^{-2} (46.3 kg ha^{-1}) (McMahon & Lloyd 1995). Base sediment concentration, calculated by dividing the sediment yield by precipitation, ranged from 0.9 kg/ha-cm to 1.8 kg/ha-cm in small forested catchments (<2.3 km^2) of the southeastern lowland coastal plain (Marion & Ursic 1993). Having a slightly larger catchment (3.0 km^2), the area draining to I1 has about half the lower concentration range at 0.47 kg/ha-cm, even with the partial clearcut.

Patric and others (1984) compared sediment yields across the United States and average annual yields for the eastern region were much greater than in Flat Creek, with 0.074 ton ac^{-1} (166 kg ha^{-1}) and 0.158 ton ac^{-1} (354 kg ha^{-1}) in watersheds less than and greater than 2 mi^2 (5.2 km^2), respectively. E2 (8.3 kg ha^{-1} yr^{-1}) and E4 (9.0 kg ha^{-1} yr^{-1}) were even lower than the lowest reported range of 0.01 ton ac^{-1} yr^{-1} (22.4 kg ha^{-1} yr^{-1}). Western regions in the study showed similar sediment yields, with only Pacific Coast forests showing significantly higher values (0.02 – 49.90 kg ha^{-1} yr^{-1}). Due to the watershed hydrologic and geomorphic characteristics detailed previously, forested land in the southeastern coastal plain appears to have among the lowest sediment yields in the United States.

5.3 Applicability of the SWAT Model

Accurate simulation of baseflow appears to be the SWAT model's major failure in representing streamflow for this watershed, as baseflow could not be increased enough to match observed values (Figure 5.8). Due to the elevated groundwater table in areas adjacent to the stream, a coupled groundwater/surface water model may be needed to better represent this interaction. Storm peaks were also heavily overestimated, but may also be due to inaccuracies in the stage-discharge equations at the highest peak storm levels. Although headwater streams generally have quick responses to rainfall as well as dry periods, this response is mediated by the elevated water table and is not well represented in the SWAT model. Traditional hydrologic models work poorly in this type of system, as noted by Sun and others (1998), due in part to the shallow dynamic water table, ephemeral sheet flow, and high infiltration rates, so this result is not entirely unexpected.

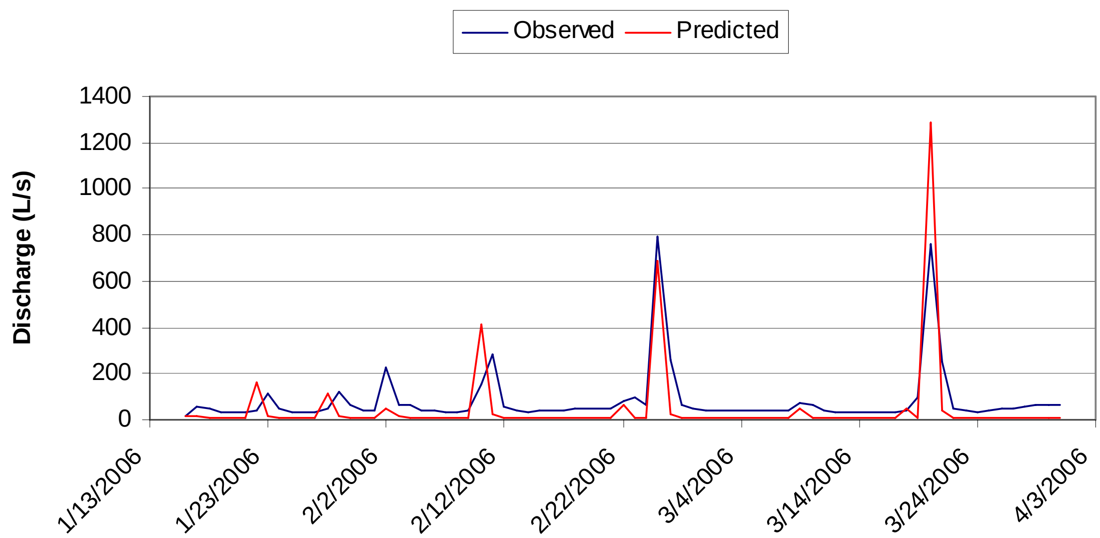


Figure 5.8. Comparison of observed and SWAT simulated average daily streamflow at site I1. Baseflow is consistently underestimated, with frequent overestimation of stormflow peaks. Note the premature flow peaks also present in the earlier storms.

The extensive underestimation of baseflow and overestimation of stormflow made calibration very difficult. Adjusting parameters to reduce stormflow also reduced baseflow. Increasing baseflow by adjusting other parameters subsequently increased stormflow. There are a higher number of days with baseflow, however, and accuracy improves more with better baseflow simulation. Using three statistical monitors (MAE, NS_e, RE) helped determine the overall improvement in this situation, as there were many times where one statistical measurement improved, but the other two showed a drop in simulation accuracy. In addition, to show significant improvement in either storm or baseflow, parameters had to be adjusted by a large number (e.g. GW_DELAY default: 31 days, adjusted: 500 days), which may not be representative. Parameters with high sensitivities to adjustment, such as available water content of the soil (SOL_AWC) and the soil evaporation coefficient (ESCO), were already at optimal levels.

SWAT estimations of the amount of precipitation leaving the watershed as runoff and evapotranspiration were compared with calculated values and found to be reasonably close (Table 5.2). Even though the daily and monthly estimates were off, the overall water balance of the watershed was comparable over a longer period, indicating that the level of runoff is accurate but the timing, even at a monthly time step, is unable to be simulated by this model. Again, the timing error is due to overestimation of direct stormflow and underestimation of baseflow periods, which compensate each other to arrive at a more accurate long term average.

Table 5.2. Observed and SWAT simulated runoff percentages for the entire 17 month study period.

Site	**Observed**	No Calibration (No Threshold)	Calibrated (No Threshold)	No Calibration (Threshold)	Calibrated (Threshold)
I1	**16.9%**	16.1%	20.0%	16.1%	19.9%
E4	**8.1%**	11.1%	12.7%	7.8%	8.9%

Although the most ideal models are the simplest ones, a single surface water model such as SWAT may not be able to accurately represent the complex streamflow generation processes present in this watershed. As previously mentioned, using a coupled groundwater/surface water model, or otherwise modifying the groundwater component of SWAT is recommended. In the FLATWOODS model, developed by Sun and others (1998) for this type of area, the researchers state that the central part of the model is groundwater flow, which would suggest that a model centralized around surface flow is not very applicable in this area. CREAMS-WT (Heatwole *et al.* 1987) is a version of the CREAMS model (Knisel 1980) also developed for this type of system by modifying the SCS CN process and adding water table simulation abilities.

Using the SCS Curve Number method (SCS 1972) to estimate infiltration (Eqn. 5.1, 5.2), SWAT has an inherent inability to adjust infiltration with time, tending to overestimate storm runoff (Mishra and Singh 2004; Rallison and Miller 1982 *in* Choi *et al.* 2002):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{5.1}$$

where Q is runoff (mm), P is precipitation (mm), and S is a parameter given by the equation:

$$S = \frac{25400}{CN} - 254 \tag{5.2}$$

where CN is the known curve number, based upon land cover and hydrologic soil group.

The SCS infiltration equation (5.1) does not contain any expression for time, and is most applicable when estimating runoff from single storms with short duration. For a discontinuous storm that has intervals of no rain, recovery of infiltration rates during the dry intervals can occur. A time-adjusted infiltration equation, such as Horton's (1939), may be able to more accurately predict runoff levels (Eqn. 5.3).

$$f = f_c + (f_o - f_c)e^{-\beta t} \tag{5.3}$$

where f is the infiltration rate at time t (depth/time), f_o is the rate when t=0, f_c is the final rate, t is time, and β is a dimensionless coefficient.

The limited time period of observed data and lower than normal precipitation may have also affected the ability of SWAT to accurately simulate streamflow. Without a reasonably effective simulation of streamflow, sediment and nutrient simulation is not feasible, particularly as streamflow levels are the major influence of loading in the watershed. Although SWAT is used for many applications in numerous areas, including

TMDLs and land use changes, this type of model in its existing form may not be useful in this region. Future research on modeling in this area, or with this model, should involve using a more specialized model for the region, or modifying SWAT to better represent the complex groundwater-surface water interactions in this type of system.

CHAPTER 6. CONCLUSIONS

Headwater streamflow in this low-gradient forested watershed was highly variable, from intermittent/no flow conditions in the late summer, to high volume overbank conditions in the winter season. Transitioning from the headwater streams to the watershed outlet, stream hydrologic response and streamflow variability decreased. Headwater response to storm events was quick, while hydrographs of increasing drainage area had longer lag times and more gradual falling limb recessions. However the flat slopes, low permeable soils, and beaver/debris dams reduced peak discharges, later releasing the stored water to streamflow during dry periods. These effects were compounded, and are most prevalently shown, at the watershed outlet. The physical watershed characteristics impacting the stream hydrology are also the major influences on sediment loading in Flat Creek.

Suspended and dissolved solid concentrations during baseflow showed little seasonal variation, and loading was influenced more by the discharge regime than fluctuations in concentration. Sediment yield from the watershed was low due to the drier than normal period of study and subsequently low storm runoff. As most of the land use in the watershed is commercial pine plantation, the low runoff decreases erosion susceptibility from harvesting activities. However, caution must also be taken as harvest sites can become quickly saturated following precipitation events, creating the potential for excess runoff and sediment delivery to streams.

Dissolved solid concentrations in the watershed appeared to be highly influenced by individual location. The sources and flowpaths of runoff to a stream will affect concentrations during stormflow. Stream geomorphological differences, such as position

on the landscape, position relative to the water table, influence from dams and backwater areas, and flow velocity affect concentrations during baseflow. All of these stream characteristics affect surface-groundwater interactions and residence time of the water before reaching the stream, influencing the water's contribution to stream TDS levels. As the watershed is considered impaired for high TDS concentrations, further research on the complex hydrological processes present in the watershed, especially shallow groundwater influence, is needed to better determine the source of dissolved solids present in the stream.

Furthermore, this study assessed the applicability of a popular watershed hydrology model, the Soil and Water Assessment Tool, for simulating streamflow. The result implies that hydrologic modeling using the curve number method may not be applicable in low-gradient watersheds. The flat land surface and high storage capacity present in the seasonally elevated water table, resulted in lower peak stormflow and higher sustained baseflow than a more topographically variable watershed, and led to the timing of streamflow to perform poorly in the Soil and Water Assessment Tool. However, the overall water budget for the study period performed reasonably well, having comparable simulated and observed runoff percentages. Hydrologic models are useful for projecting changes in streamflow levels and water quality with land use modifications. However, either modification of SWAT (or similar hydrologic model) or the use of a more specialized model for this type of watershed is required for more accurate streamflow and loading assessments.

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