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Long-term freshwater input and sediment load from three tributaries to Lake Pontchartrain, Louisiana

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LONG-TERM FRESHWATER INPUT AND SEDIMENT LOAD FROM THREE TRIBUTARIES TO LAKE PONTCHARTRAIN, LOUISIANA

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DEDICATION

This dissertation is dedicated to my family.

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ABSTRACT

Lake Pontchartrain and the drainage basin have experienced environmental degradation because of human settlement, land use and climate changes. A thorough understanding of hydrologic trends and variability associated with the changes is critical for sustainable water resources management and ecosystem restoration in the region. This study examined freshwater inflow (1940-2002) and suspended solids loadings (1978-2001) from three upper Lake Pontchartrain watersheds that contribute to the lake estuary: the Amite, Tickfaw, and Tangipahoa river watersheds. The relationships of freshwater inflow and suspended solids loadings with climate variables and population growth were investigated. Using observed daily discharge, a spatially-distributed hydrologic model (SWAT) was evaluated, and the model then was employed to assess hydrologic responses of the coastal watersheds to potential climate change. The study showed an annual freshwater inflow of 5 km^3 yr^{-1} and average suspended solids inputs of 210,360 tons yr^{-1} entering Lake Pontchartrain. More than 69% of annual water yield and 66% of suspended solids occurred from December to May and from January to April, respectively. Over 80% of the variation in annual freshwater inflow could be explained by annual precipitation. A significant increase in freshwater inflow was found in the Amite River watershed over the past sixty years, coinciding with both climatic variation and population growth. The hydrologic modeling showed a good agreement between the simulated and observed daily discharge, with a relatively high Nash-Sutcliffe model efficiency (> 0.811) and low mean error (< 5.6%). The simulation further indicated that, unlike upland watersheds, calibration of the surface and channel routing parameters in the SWAT model became most critical for lowland coastal watersheds with gentle relief. The climate change assessment showed a significant influence

of precipitation on annual freshwater yield with an increase of 19.3%-40.1% in response to a 10%-20% increase in annual precipitation. Potential air temperature increase would have only a marginal effect on freshwater yield as shown by a 1.4%-2.9% decrease in the annual freshwater yield for a 1.6 ^{o}C-3.3 ^{o}C increase in temperature. Warming, however, may pose risks of drought during spring and summer in this humid subtropical region.

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CHAPTER 1. INTRODUCTION

Sustainable management of freshwater resources is essential for economic and social well-being, but the conflicts between freshwater supply and demand have been increasingly aggravated since the beginning of the twentieth century (SEI, 1997). Water quality, especially that resulting from nonpoint source pollution, is still a challenge, although it is gradually improving locally (Stanners and Bourdeau 1995; USEPA, 2002). Because of human population growth, land cover has changed substantially and it is estimated that approximately one acre of land has been lost due to urbanization and highway construction for every person added to the U.S. population (Alig et al., 2004; Pimentel and Giampietro, 1994).

Over the 20th century, global average surface temperature increased by $0.6 \pm 0.2\ ^{o}C$ (IPCC, 2001). It is widely believed that future climate change would have a considerable impact on water yield (Stone et al.,2003; Stonefelt et al., 2000) and water quality (Cruise et al., 1999) at the catchment, drainage basin, and continental scales (Arnell, 2000). Hydrologic responses to climate change under different land use types have also been studied in forest (Fontaine et al., 2001), agricultural (Abler et al., 2002), and urban watersheds (Interlandi and Crockett, 2003).

Lake Pontchartrain and its surrounding lakes are among the most important estuary systems along the Gulf Coast of the United States (Penland et al., 2002). Diverse natural resources in the lake and its drainage basin areas have served one third of Louisiana's population for a century. However, long-term resource exploitation has resulted in environmental degradation and posed a threat to the environmental integrity in the basin area.

In this study three major watersheds adjacent to Lake Pontchartrain, the Amite River, the Tickfaw River, and the Tangipahoa River watersheds, were chosen for the research. These watersheds are typical of drainage basins in the northern Gulf of Mexico in both natural and

anthropogenic aspects. These features include: varied landform from upland to floodplain and coastal marsh; variable land cover from agriculture, forests to pastures and urban areas; increased conflict caused by population growth, development, potential climate change, and environmental integrity; and diverse natural and cultural resources. All of these characteristics make the drainage basin an interesting site to evaluate hydrologic changes in the past and responses to potential climate change and land use change in the future.

The primary objective of this research is to investigate long-term changes of freshwater inflow and sediment loading from the three river basins to Lake Pontchartrain. While doing so, hydrologic responses to potential climate change were assessed. The research comprises three interrelated studies: (1) discharge and sediment data will be used to analyze freshwater and sediment baseline characteristics, such as spatial and temporal variations and their correlation with hydro-meteorological variables, (2) a hydrologic modeling system, Soil and Water Assessment Tool (SWAT), will be calibrated and validated for the three watersheds individually, and (3) the calibrated models will be employed to predict future climate change impacts on water yield based on assessment of current freshwater inflows by integrating spatial data with land use, soil types and other watershed parameters. Specifically, the objectives of this research are to:

1) Investigate the long-term trends of freshwater input and sediment loadings from the three major tributaries to Lake Pontchartrain;
2) Identify the spatial and temporal variations of discharge and sediment from the three river basins;
3) Determine the relationships among discharge and sediment loadings, population densities, and hydro-meteorological conditions;

4) Analyze the applicability of a spatially-distributed model for coastal lowland watersheds; and
5) Assess hydrologic impacts of potential climate change in the Lake Pontchartrain drainage basin.

The findings in the research provide insight into the characteristics of long-term flow patterns and surface hydrologic changes in the Amite River, Tickfaw River, and Tangipahoa River watersheds. The knowledge gained from the analyses on the relationships between discharge, sediment, and hydro-meteorological variables is useful in identifying and predicting environmental risks. The assessment of climate change effects on freshwater delivery to Lake Pontchartrain yield information on how current land management practices and potential changes in climatic variables would affect the environmental integrity of Lake Pontchartrain and the coastal regions of the Gulf of Mexico. Such information is needed to guide coastal planners and managers to improve and/or maintain desirable environmental conditions within the basins as well as in the coastal waters of the Gulf of Mexico. The findings will be useful for resource managers and local and state policy makers alike in the effort of maintaining and improving water quality and creating and restoring wetlands in coastal Louisiana.

This dissertation is organized in six chapters. Chapter 2, following this introduction, provides an intensive literature review on current research status and needs for solving environmental challenges related to water resources management in the Lake Pontchartrain area. It introduces some of the research concepts, methods, and analytical tools used in this study. Chapter 3 focuses on the study of long-term freshwater input and sediment loadings to Lake Pontchartrain. It discusses the results on spatial and temporal aspects of discharge distribution and sediment loadings from the Amite River, Tickfaw River, and Tangipahoa

River watersheds. In Chapter 4, the hydrologic modeling study for the river basins is introduced and the modeling results are discussed. Chapter 5 discusses the modeling assessment of potential climate change impacts, identified as air temperature and precipitation increases, on water yields in the Lake Pontchartrain basin. Chapter 6 summarizes relevant findings and identifies future research needs. Chapters 3, 4 and 5 are written as stand-alone journal articles. They have been submitted to refereed publications, and therefore, minor replications in each chapter's introduction occur.

CHAPTER 2. LITERATURE REVIEW

2.1 Long-term Patterns of Streamflow under Climate Variation and Land Use Change

Long-term patterns of discharge reflect integrated responses of a basin to climatic condition, morphological characteristics and land use. Because of its importance in water resources management, long-term patterns of discharge for many rivers in the world have been studied (Kahya and Kalayci, 2004; Lins and Slack, 1999; Lettenmaier et a l., 1994; Chiew and McMahon, 2002; Zhang et al., 2001; Yue et al., 2003; Lindstrom and Bergstrom, 2004; McCabe and Wolock, 2002). Lettenmaier et al. (1994) examined streamflow trends in the continental U.S. with datasets from 1,036 weather stations and 1,009 stream gauge stations from 1948 to 1988. Lins and Slack (1999) investigated secular trends of 395 streams in the conterminous United States. Zhang et al. (2001) and Yue et al. (2003) studied the long-term trend of 30-50 years streamflow data in Canada. In western Turkey downward trends were found with 31-year period of monthly streamflow (Kahya and Kalayci, 2004). Lindstrom and Bergstrom (2004) studied long-term discharge change from 1901 to 2002 for all rivers in Sweden.

Both increased and decreased trends of long-term discharge have been observed among wide climatic and geographic conditions. Zhang et al. (2001) found a decreased discharge pattern in most parts of Canada, with a significant decreasing trend in the Southern region. Lins and Slack (1999) found the same pattern of discharge in parts of the Pacific Northwest and Southeast U.S. Mauget (2003) observed a decreased annual streamflow in the Western U. S. during later 1980's, which was considered to be related to the onset of high air temperature trend and increased evapotranspiration (ET) in the same region.

Though long-term pattern of discharge would reduce because of increased ET in these studies, research also found increased patterns of discharge (McCabe and Wolock,

2002; Peterson et al., 2002; Mauget, 2003; Yue and Wang, 2002). Among these increased discharge patterns, studies showed that some of them were caused by increased precipitation in the region. Using data collected from 400 gauge stations for 1941-1999 in the conterminous United States, McCabe and Wolock (2002) found a noticeable increase in annual median daily streamflow and annual minimum daily flow in the 1970s. The increased trend of streamflow primarily occurred in the eastern U.S., coinciding with the increased precipitation. Mauget (2003) observed the similar trend that the streamflow pattern in the eastern U.S. in the 1970's was correlated to climate wetness. However, some of the increased discharge trends have been attributed to increased ice and snow melting, due to increased air temperature. Peterson et al. (2002) found a 7% increase of long-term average annual discharge from the six largest Eurasian rivers to the Arctic Ocean from 1936 to 1999, caused by ice and snow melting due to a possible air temperature increase. A 5% increase in annual discharge over the past century was found for all rivers in Sweden from 1901 to 2002 (Lindstrom and Bergstrom, 2004). Yue and Wang (2002) examined streamflow pattern in ten major homogeneous climate regions of Canada from 1967 to 1996 and found that annual mean daily steamflow increased significantly in the region of Yukon and northern British Columbia mountain regions.

With increased air temperature in some climatic zones, temporal shifts of monthly discharge were also witnessed. Using newly created Canadian Reference Hydrometric Basin Network database, Zhang et al. (2001) found for most of the year, monthly mean streamflow decreased, with the greatest decrease occurring in August and September. However, in March and April, a significant increase in streamflow was observed. Lettenmaier et al. (1994) found a significant increase of streamflow in the period of November-April, at a maximum of almost half of the 1009 gauge stations. Most of the stream stations were in the North and Central U.S.

While long-term patterns of discharge were affected by climate variation, the relationships between long-term pattern of discharge and population growth and population density, and urbanization-induced land use change were also intensively studied (Alig et al., 2004; Kim et al., 2002; Arnold et al, 1987; Paul and Meyer, 2001; Paul and Meyer, 1999; Barringer, 1994). With an increased global population and urbanization, population growth and personal income have resulted in a significant increase in developments, which further led to a conversion of crop land and forest land to urban impervious land (Alig et al., 2004). A number of impacts on freshwater ecosystem by such landscape transformation from pristine land to impervious land have been observed. Weng (2001) found an increased annual runoff of 8-10 mm associated with a notable uneven spatial pattern of urban growth during 1989 to 1997 in the Zhujiang Delta, China. The author stated that the area that experienced more urban growth would have a greater potential for increasing annual surface runoff because urbanization lowered potential maximum storage in soil profile. A study by Arnold et al. (1987) showed that in the White Rock Lake watershed, Texas, urbanization resulted in an increased of 16 mm annual runoff, where urban area was accounted for 77% of the total watershed area. In a study conducted in the Indian River Lagoon Watershed, Florida--a 3575 km^2 watershed, Kim et al. (2002) found a 49% increased of average annual runoff from 1920 to 1990 because of the urbanization.

In addition to maximum soil moisture storage, the most direct effect of land use change on watershed hydrology is alteration of the magnitude and distribution of evapotranspiration (ET) and consequently streamflow (Dow and DeWalle, 2000; Spanner et al., 1994; Lu et al., 2003). Although long-term patterns of discharge have been investigated intensively, studies on long-term patters of ET, caused by land use, are few.

In the Lake Pontchartrain drainage basin, especially in the Amite River watershed, drastic changes in population and land cover types have been witnessed since World War II (Emmer, 1992). These changes may have possible impacts on water resources management in the region. Though modeled runoff was used to assess discharge patterns in Louisiana (Keim et al., 1995), the conclusions drawn from the study may be weak because (1) division of watersheds across the entire Louisiana was based on traditional political boundary rather than natural watershed boundaries, and (2) the discharge used in the study were estimated with precipitation rather than with observed streamflow data. Templeton (1998) made an effort to connect human activities, represented by population, total income, per capita income, with streamflow in the Amite River watershed. However, due to multicollinarity of economic and demographic variables, a usable relationship was not built. Long-term pattern of discharge (including seasonal, annual, and interannual) and relationships among discharge, population density, and hydro-meteorological variables (precipitation) still are few in the Lake Pontchartrain drainage basin and the coastal Louisiana.

2.2 Sediment Loadings from Forest, Agricultural and Urbanized Lands

Soil erosion is a natural process that has been accelerated by human activities such as agricultural practices. Soil erosion causes not only productivity decline, but also water quality degradation. According to latest EPA's report (USEPA, 2002), sediment remains one of the most widely spread pollutants in the U.S. Sediment loadings within a watershed is affected by land cover and land use practices (Patric et al., 1984; Milliman and Meade, 1983; Erskine et al., 2003; Thorud et al., 2000; Brooks et al., 2003; Knox, 2001). Land use impacts on sediment yield vary spatially and temporally. It has been well documented that sediment yield was lowest in undisturbed forested watersheds. Quinn and Stroud (2002) found that streams draining native forest had lower temperature, lower sediment, lower nutrient

concentrations, and higher water clarity than those draining pasture. Patric et al. (1984) reported annual sediment loads for forested watersheds in the U.S. ranging from 0.0002 to 1.1 tons km^{-2}. Numerous studies have observed a large increase in sediment yield after timber harvesting and road construction (e.g., Swank et al. 2001; Verry, 1986; Rishel et al., 1982; Martin et al., 2000). While the impact of harvesting on sediment decreases as harvested sites redevelop a vegetative cover, roads continue to be a major erosion source after forest regeneration. Sediment loading from agriculture land is generally higher than those from forested lands. Lenat and Crawford (1994) found that suspended sediment yield of three streams in North Carolina was greater for the agricultural catchments than that for the forested watersheds and suspended sediment concentrations during storm events followed the same pattern. Miller et al. (2002) found that increased agricultural and urban areas and declined grassland in the upper San Pedro River in Sonora, Mexico resulted in decreased water quality due to sediment loading. Even with small areal percentage within a watershed, the impacts of agriculture on sediment loading could be higher. Howarth (1991) found a larger portion of sediment and organic carbon inputs into Hudson River estuary from agricultural fields and urban areas, although the watershed for the estuary was dominated by forests. Due to the correlation between sediment loadings and land use practices, such as tillage and planting, it is possible that sediment loadings would be higher during spring seasons in agriculture dominated areas. However, studies are few on seasonality of sediment dynamics.

Urbanization has been attributed to be among the most detrimental land use practices to sediment runoff. Based on research conducted in a rapidly urbanized watershed in western Washington, Nelson and Booth (2002) found that nearly 50% of a 44 tons km^{-2} increase in annual sediment yield was caused by urban development which included: the landslides (50%), channel-bank erosion (20%), and road-surface erosion (15%). Erskine et al. (2003)

studied two watersheds in western Sydney and reported that an urban watershed exhibited annual sediment yield of 650 tons km^{-2}, whereas a woodland watershed yielded 250 tons km^{-2}. Biggs et al. (2004) found that changes of Cl, N and P concentrations in streams have been found to be closely related to urbanization and regional deforestation at wide range of scales, from small pasture streams to large river systems. They further found that the deforestation extent and urban population density could explain most of the variance in stream chloride and total dissolved nitrogen concentrations. Based on data from 1947 to 1996, Ren et al. (2003) found that a rapid degradation of water quality positively corresponded with a rapid urbanization in Shanghai, the largest city in China.

While studies have showed that sediment loading was significantly affected by land cover and soil surface disturbance from agricultural and forest activities and urbanization, the relationships between sediment loading and hydro-meteorological variables such as precipitation and discharge were also examined. Tuan and Shibayama (2003) found variations of sediment loading were significantly correlated to precipitation change in four river basins in Asia. Lu and Higgitt (1999), with 62 long-term gauge stations in the Upper Yangtze River, China, showed that sediment yield increased with precipitation and runoff in the area. Similarly, Borah et al. (2003) found a positive relationship between suspended sediment concentration and discharge in smaller watersheds. In large watersheds, however, no relationships were found.

Due to reduced freshwater inflow and sediment inputs, increased wetland loss and declined productivity of forested wetlands have been recognized as the most pressing environmental challenges in the coastal Louisiana. Freshwater diversion and sediment inputs have been proposed for environmental restorations in the region (Turner and Boyer, 1997; Smith, 1994, Ismail et al., 1998; Francis and Poirrier, 1998; Turner et al., 2002). There are

still knowledge gaps about long-term sediment loadings from the entire Lake Pontchartrain drainage basin, their seasonal change and distribution, and how these trends were related to population growth, land use practices, and hydro-meteorological variations in the region.

2.3 GIS-based Hydrologic Modeling at a Watershed Scale

Geographic Information System (GIS)-based modeling has become a widely used approach in hydrologic studies, and its utilization has been especially profound for scaling up a process-level hydrology to a watershed scale assessment. Over the past decade, several nationwide spatially referenced databases have been created. This includes State Soil Geographic Database (STATSGO; USDA 1994), compiled by the Natural Resources Conservation Service (NRCS) of the USDA, Land Use and Land Cover (LULC), prepared by the USGS, and The National Hydrography Dataset (NHD), jointly developed by the USEPA and USGS. Concurrently, computing technology has advanced the ability of scientists to utilize these rich resources of data for solving complex problems in natural and human systems.

With consideration of the complexity and variability involved in hydrologic processes either in temporal or spatial scale, especially in lowland Louisiana, a spatial analysis framework is considered to be one of the most effective ways to describe various components and processes of a hydrologic cycle within a watershed (Singh and Woolhiser, 2002). Though many hydrologic models are available, such as CREAMS (a field scale model for Chemical, Runoff, and Erosion from Agricultural Management Systems, Kinsel, 1980), HSPF (Hydrologic Simulation Program-Fortran, Crawford and Linsley, 1966), SWAT (Soil and Water Assessment Tool, Arnold et al., 1998), AGNPS (Agricultural Non-Point Source, by Young et al., 1989), and PRMS (Precipitation Runoff Modeling System, Leavesley et al., 1983), previous studies indicated that SWAT was a widely used model in the assessment of

hydrologic response to land use and potential climate change in a watershed (Weber et al., 2001; Stone et al., 2003; Stonefelt et al., 2000).

SWAT was developed by the USDA ARS to predict the impacts of land use management on water, sediment and agricultural chemical yield in large complex watersheds, with varying soil, land use and management conditions over a long-period of time (Arnold et al.,1998). The system, embedded within a GIS, can integrate a variety of spatial environmental data, including soil, land cover, climate, and topographic features. As a spatially distributed hydrologic model, SWAT uses hydrologic response units (HRUs) to describe spatial heterogeneity in land cover and soil type within a watershed. Hydrologic response units in SWAT were defined as “lumped land area within the subbasin that is comprised of unique land cover, soil, and management combinations.” The model estimated relevant hydrologic components such as evapotranspiration, surface runoff, soil moisture, and ground water recharge at as much details as each of HRUs (Figure 2.1). SWAT has been used to predict various impacts of land management on water quantity (e.g., Srinivasan and Arnold 1994; Muttiah and Wurbs, 2002) and sediment yield (e.g., Luzio et al., 2002). SWAT was also often used for evaluation of hydrologic responses to potential climate change (Jha et al., 2004; Van Liew and Garbrecht, 2003; Stone et al., 2003; Fontaine et al., 2001; Rosenberg et al., 2003; Ritschard et al., 1999; Bouraoui et al., 2002; Stonefelt et al., 2000; Hotchkiss et al., 2000).

The SWAT model consists of an array of model parameters. These parameters can be classified into three categories: (1) parameters that govern surface water processes, including curve number (CN), soil evaporation compensation factor (ESCO), plant uptake compensation factor (EPCO); (2) parameters that control subsurface water processes, including capillary coefficient from groundwater (REVAP), ground water delay (DELAY);

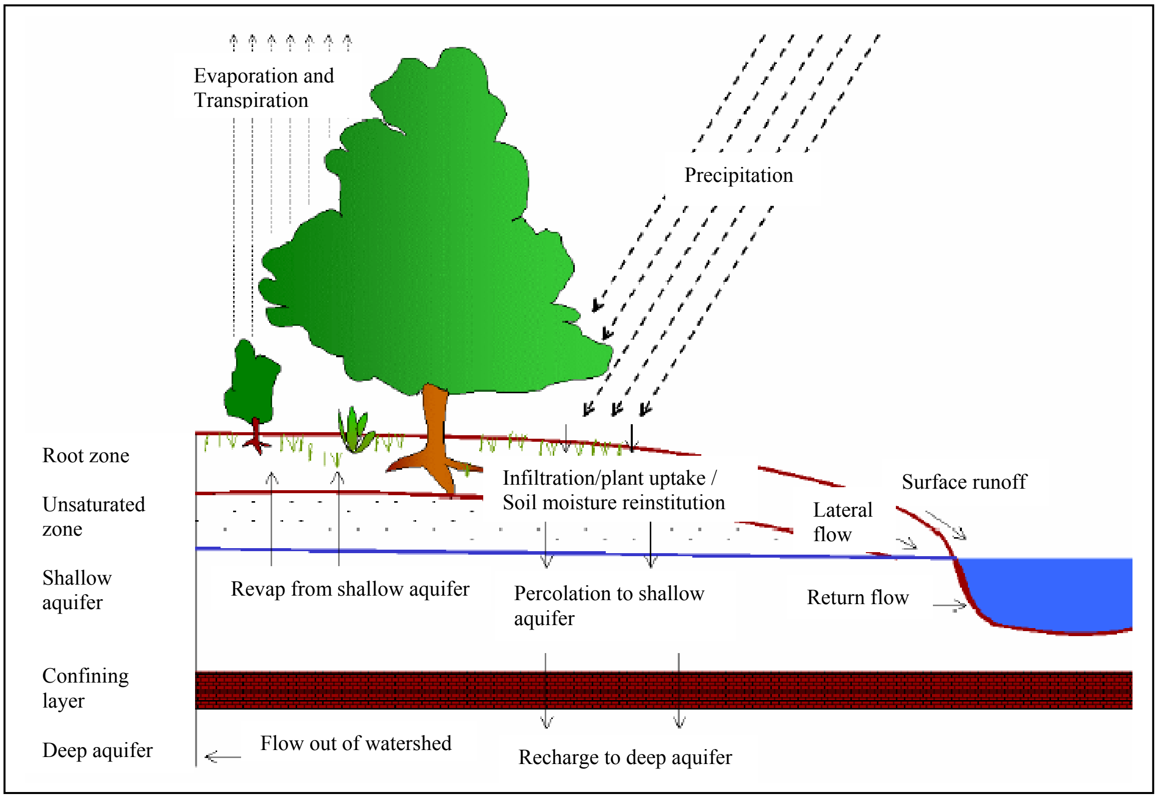


Figure 2.1. Schematic representation of the hydrologic cycle and most hydrologic processes which were simulated in the SWAT model (Adapted from Neitsch, et al., 2001, p.8).

and (3) parameters that influence routing processes, including Manning's roughness coefficient for the main channel routing (CH_N(2). Studies showed that runoff curve number (CN), ground water delay (DELAY), revap coefficient (REVAP) were the most sensitive parameters (Van Liew and Garbrecht, 2003; Jha et al, 2003; Srinivasan et al. (1998). However, sensitivity of these parameters varied in different watersheds. For examples, Srinivasan et al. (1998) found that base flow recession (ALPHA_BF) was considered important in the upper Trinity River basin in Texas except CN and REVAP. Jha et al. (2003) found that evaporation compensation factor (ESCO) was one of the most sensitive parameters

in their study in Iowa. While parameters which govern surface processes and water movement in an aquifer have been examined in most studies, hydrologic variables in the SWAT model which govern routing processes were not fully studied, which might be critical in a large watershed (>1000 km^2) with flat topography, such as those in lowland Louisiana.

Some researchers have used SWAT to assess climate change impacts on water yield and most focused on large river basins. For instance, Rosenberg et al. (2003) and Arnold et al. (1999) have used SWAT for the conterminous U.S. Regionally, Hanratty and Stefan (1998) used SWAT for the Cottonwood River near New Ulm, Minnesota, Kirsch (2000) and Kirsch et al.(2002) for the southern Wisconsin, and Stonefelt et al.(2000) for the Upper Wind River Basin, Wyoming. Studies with the SWAT model were also conducted in the Southeastern U.S. (Cruise et al., 1999; Ritschard et al., 1999). Ritschard et al. (1999) suggested that maintaining or expanding existing crop yields under future climate regimes may require additional irrigation water and thus increase competition among other uses such as domestic, industrial, recreational, and ecosystem quality. However, very few studies have been done in the coastal region of the Southern and Southeastern U.S. One of the reasons might be difficulty of application of spatial distributed hydrologic model for the gentle and flat topography of these areas. Unique climatic and topographic features and intensive hydrologic alteration in coastal Louisiana make application of SWAT challenging and valuable.

2.4 Hydrologic Responses to Potential Climate Change

Potential climate change and its impacts on regional water resources management has been a public concern (Frederick, 1993; Frederick and Major, 1997; Gleick and Adams, 2000; Jackson et al., 2001; Lins and Stakhiv, 1998; Mauget, 2003; Middelkoop et al., 2001; Nilsson et al., 2003; Wood et al., 1997). To assess the impacts, hydrologic models are often used together with a regional scale climate change projection. Because of global population

growth, industrialization, and natural processes, global climate has changed. The average global surface air temperature has increased by about 0.6± 0.2^{o}C since the beginning of the 20th century (IPCC, 2001). Precipitation and air temperature are the two most widely climatic variables in the impact assessments and water yield is the biggest concern to public and water resource managers (Simonovic and Li, 2003; McCabe and Wolock, 2002; Stonefelt et al., 2000).

It has been found that change in annual discharge was directly related to change in precipitation in most climate change scenarios (Fontaine et al., 2001). Stonefelt et al. (2000) showed that a 10% decrease and a 10% increase of annual precipitation in the Upper Wind River Basin, Wyoming, would cause a 17.6% decrease and a 18.5% increase of annual water yield, respectively. Jha et al. (2004) found that a 21% increase of precipitation in future climate change, as projected by a regional climate model (RCM), would result in a 51% increase of surface runoff and a 50% increase of total water yield in the upper Mississippi River basin. Based on a study with 1337 watersheds across the U.S., Sankarasubramanian and Vogel (2003) concluded that, on average, a 1% change in precipitation would result in a 1.5%-2.5% change in stream runoff.

Although many studies have suggested a significant impact of precipitation change on annual water yield, seasonal patterns of water yield to potential precipitation change have not been fully understood. Several questions remain unanswered: Does precipitation change have any impact on the seasonality of discharge? What is the implication of precipitation change to water yield in both dry seasons and wet seasons? And what are the potential risks or benefits associated with precipitation change in a specific region?

In the Southeastern U.S. extreme storm events with increased storm intensity and clustering have been projected. Such heavy storms would result in a more extreme peak flow,

but lower base flow and longer periods of drought (Mulholland, et al., 1997; Kunkel, 2003). There exists a knowledge gap of hydrologic responses to extreme storm events. For example, in the lower altitude and humid subtropical regions with saturated and near saturated soil during spring seasons, extreme storm events might imply a high risk of flooding and vulnerability for soil erosion.

Compared to a direct impact of precipitation change on water budget in a watershed, studies indicated that impacts of elevated air temperature in future climate change scenarios on water yield were complicated (Fontaine et al., 2001; Walter et al., 2004; Cunderlik and Burn, 2004; Legesse et al., 2003; Peterson, 2002). On the one hand, annual water yield would decrease by projected higher air temperature due to increased ET. For instance, Legesse et al., (2003) found a 15% decrease in discharge in response to a 1.5 ^{o}C increase in air temperate in the tropical areas of Africa. Similarly, Fontaine et al. (2001) found that a 39% decrease in annual streamflow was projected under a 4 ^{o}C increase of annual air temperature. On the other hand, water yield would increase in part of the year due to increased snow melting, but in other part of the year, it would decrease due to increased ET, which may be caused by an elevated air temperature in future. Stonefelt et al. (2000) found a significant change of monthly water yield in the Upper Wind River Basin, Wyoming, under the scenario of a 4 ^{o}C annual air temperature increase. An increased pattern of monthly water yield was estimated from November through May, with a peak flow shifting from June to May. However, from June to October, monthly water yield decreased. Vankatwijk et al. (1993) found a 185% increase of water yield in April and May caused by snow melting, while a 60% decrease in June and July under a 5 ^{o}C increase of air temperature. A similar hydrologic shift was also found in a California watershed by Knowles (2000). With a 2.1 ^{o}C temperature increase, the author projected that over 3 km^3 of runoff would shift from post-April to pre-April. The

higher snowmelt-driven runoff in April would be followed by lower streamflow in the subsequent months. A simulation study in the Rhine Basin by Middelkoop et al. (2001) demonstrated how a seasonality of hydrologic components in the snow-dominated watersheds would be affected by climate change. The authors found that intensified snow-melting and increased winter precipitation could cause higher winter discharge. Consequently, reduced winter snow storage and increased ET could lead to lower summer streamflow.

These studies have suggested that in the higher altitude region elevated air temperature would affect annual and monthly water yield through increased snow melting in winter and spring and through increased ET in summer. Little is known about the impacts of elevated air temperature on water yield in these lower altitude and higher humidity subtropical regions such as Southern Louisiana. The understanding of the effect of temperature change in the region is critical for water resources management, land planning and environmental restoration. Instead of increasing snow meting rate, which led to higher streamflow during spring months in higher altitude regions, an elevated air temperature would result in potential soil moisture deficit during spring and summer months in lower altitude areas with rainfall-dominated watersheds.

CHAPTER 3. FRESHWATER AND SEDIMENT INPUTS TO LAKE PONTCHARTRAIN IN LOUISIANA FROM THE AMITE, TICKFAW, AND TANGIPAHOA RIVER WATERSHEDS

3.1 Introduction

Sustainable water resources management is one of the major challenges to human society in the twenty-first century (Gleick, 2000; Luketina and Bender, 2002). Continuous population growth has resulted in increased exploitation and consumption of limited natural resources. Freshwater has already become critically scarce in many regions (Conway et al., 1996). With increasing population, irreversible land-cover change, potential global climate change, and other natural and anthropogenic disturbances, a conflict between freshwater demand and available freshwater resource will be increased.

Adequate quantity, quality, and temporal variability of freshwater inflow are essential for coastal ecosystems. Hydrological characteristics of the freshwater environment have been gradually disturbed by numerous anthropogenic factors, such as, changing land cover types, altering flow regime, eliminating marshes and wetlands, removing freshwater for other uses, contaminating water with industrial and human wastes, and intrusion of saltwater. In Louisiana, freshwater ecosystems are composed of rivers, streams, impoundments, bayous, estuaries and wetlands. Lake Pontchartrain and its surrounding sister lakes together constitute the largest contiguous estuarine zone in the Gulf States (Tarver and Savoie, 1976). The entire Lake Pontchartrain drainage basin is a 12,170 square kilometer watershed encompassing 16 parishes in southeast Louisiana and four counties in Mississippi. Nearly 1.5 million people live around the 1,619 square kilometer lake, which supports numerous species of fish, birds, mammals, and plants. Higher physiographical diversity and habitats not only leads to higher biodiversity but also results in an intensive interaction between terrestrial and estuary ecosystems.

As with many estuary ecosystems in the world, Lake Pontchartrain has been subjected to numerous changes in physical and chemical characteristics over the past fifty years (Howarth et al., 1991). Water quality and freshwater inflow from the upstream watersheds have become one of the most critical issues in sustainable freshwater ecosystem management and restoration efforts for the basin region (Sikora and Kjerfve, 1985; Calvert and Emmer, 1992; Mossa, 1995; Day et al., 2000; LDEQ, 2000; DeLaune et al, 2003). From a study on suspended solids in the upper Lake Pontchartrain basin, Smith (1992) showed substantial variations of streamflow and water quality from several north shore streams and bayous. Low dissolved oxygen (DO) concentrations (<5 mg l^{-1}) were found during summer periods in the downstream stations of the Amite River (Ismail et al., 1998). Using a five year water quality dataset (1986-1991), Smith (1994) reported a significant increase in instream concentrations of lead and total dissolved solids from the Amite River. Templeton (1998) made an effort to connect human activities, represented by population, total income, and per capita income, with streamflow in a subwatershed within the Amite River watershed. Due to multicollinarity of economic and demographic variables in his study, a statistically sound relationship between population variables and streamflow was not found. The Amite River watershed contributes the largest amount of freshwater to Lake Pontchartrain, and it is also the basin that experienced the greatest land use change in the region during the past four decades. Urbanization-induced land use changes and hydrologic alterations such as sand and gravel mining, urban runoff, sewage treatment plant discharges, and flood controls all have been attributed to water quality degradation in the region (Vernon et al., 1992; Mossa and McLean, 1997; LEDQ, 2000).

In addition to water quality and associated variations in the terrestrial environment, freshwater inflow has also been linked to estuarine productivity in Lake Pontchartrain. In a

recent study on relationships between fish habitats and environmental variables in Lake Pontchartrain, O'Connell et al. (2004) found that the fish assemblages collected by trawls in the lake have changed over the past 50 years. Changes in fish assemblages from nearshore and pelagic habitats were closely related to environmental fluctuations. Annual yield of penaeid shrimp in the Gulf of Mexico was inversely related to the annual discharge of the Mississippi River, which may have been likely associated with reduced salinity in the estuarine nursery areas with higher freshwater flow (Turner et al., 1992). Freshwater input has been considered to be the most important factor governing salinity distribution in Lake Pontchartrain (Sikora and Kjerfve, 1985), and it has, therefore, been attributed to controlling biological processes and the health and stability of wetlands around this large oligohaline estuary (Turner et al., 1992; Thomson et al., 2001).

Although a number of studies on freshwater inflow and sediment loadings to Lake Pontchartrain have been published, there is no comprehensive investigation on the long-term trends of freshwater and sediment inflows from the major river watersheds to the lake estuary complex during the recent decade. Researchers (e.g., Day et al., 2000; Turner, et al., 2002; Shaffer et al., 2004) have recognized that riverine freshwater and suspended solid inflows are among the most important resources for maintaining environmental integrity and restoring degraded wetlands in the Lake Pontchartrain drainage basin. However, there is generally a lack of knowledge as to how the freshwater inflows and sediment inflows seasonally, inter-annually and interdecadally fluctuate, and how the variations are associated with hydrometeorological variables, population growth and urbanization in the region. Such hydrological information is critical for coastal resource planners and managers to conduct integrated assessment on the coastal watersheds and develop the best management practices (BMPs) for maintaining desirable environmental conditions within the basin.

The objectives of this research were to:

1) Quantify monthly and annual freshwater inflow and total suspended solids loadings from the three major river basins to Lakes Maurepas and Pontchartrain;
2) Characterize interannual variability over the freshwater input for the past six decades; and
3) Determine relationships among freshwater input, total suspended solid loadings, hydro-meteorological variables, and population growth in the upper Lake Pontchartrain watersheds.

3.2 Methods

3.2.1 Site Description

3.2.1.1 Location

The study area is comprised of three watersheds in Southeast Louisiana, the Amite River, Tickfaw River and Tangipahoa river watersheds (Figure 3.1), with a total drainage area of 8,728 km^2 (Table 3.1). The area is geographically located between 30-31^{o}N and 90-91.5^{o}W. Its elevation ranges from 0 m to 150 m above sea level. The region covers ten Southeastern Louisiana parishes (East Feliciana, St. Helena, Tangipahoa, East Baton Rouge, Livingston, Iberville, Ascension, St. James, St. John the Baptist and St. Charles Parishes) and three Mississippi counties (Wilkinson, Amite, and Pike Counties). Dimensional width of the basin in the east-west direction is about 90 km, and in north-south direction is about 120 km.

The Lake Pontchartrain drainage basin can be classified into three distinctive geomorphic regions: the Pleistocene Terraces Region, Mississippi River Deltaic Plain Region, and Marginal Deltaic Basin Region. To the north of Lakes Maurepas, Pontchartrain and Borgne lies the Pleistocene Terraces Region, which provides most of the freshwater. The

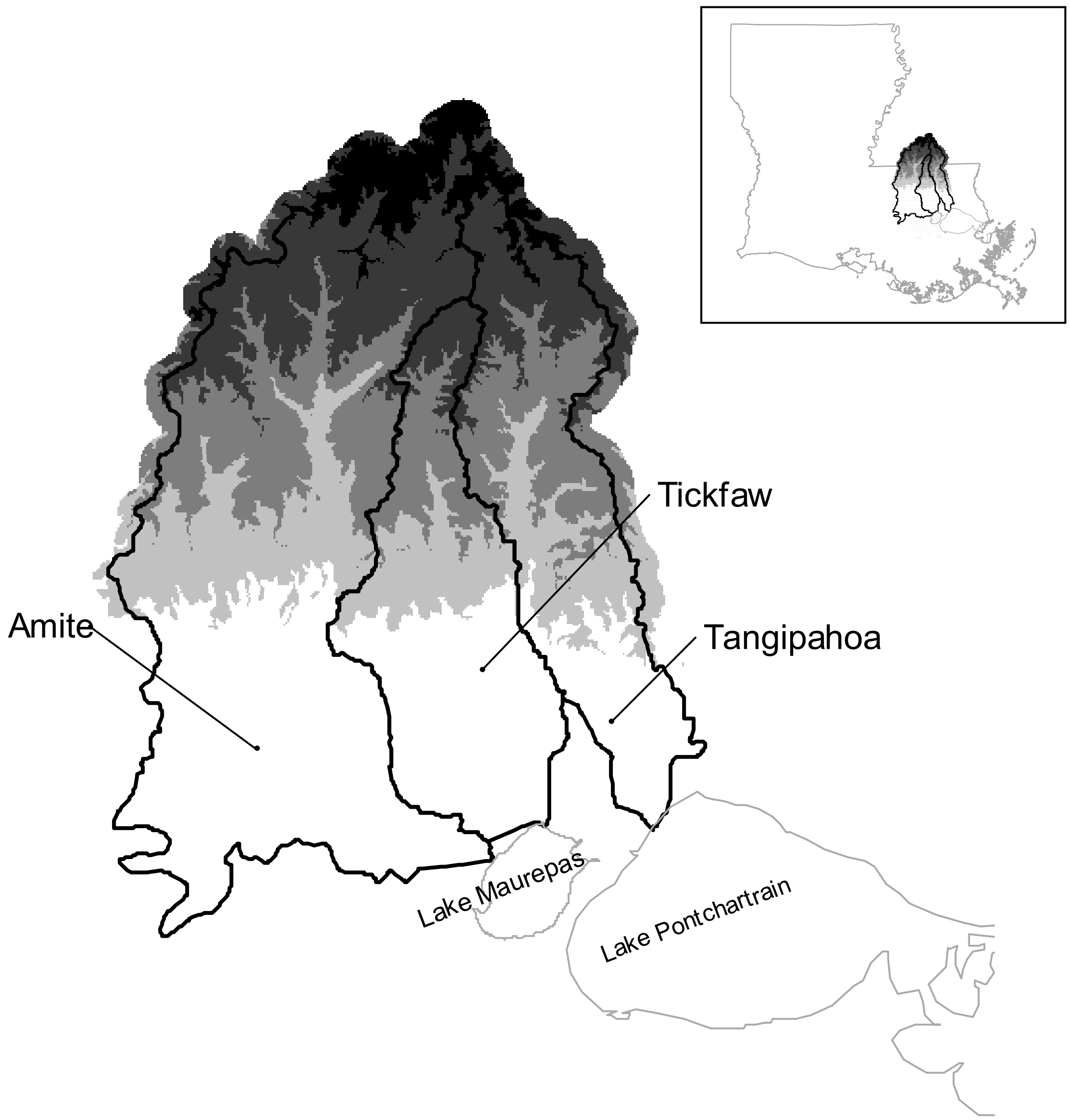


Figure 3.1. Geographic locations of the Amite River, Tickfaw River and Tangipahoa River watersheds and Lake Maurepas and Lake Pontchartrain, shading indicates elevation.

Mississippi River Deltaic Plain Region lies to the south of these lakes. Separating these two geomorphic regions is the Marginal Deltaic Basin Region (Penland et al., 2002).

Traditional definition of the drainage basin is not strictly based on natural watershed boundaries but mainly on political boundaries. Major tributaries include the Amite, Tickfaw,

Table 3.1. Total area of the three watersheds used in the study.

Watersheds	Area (km^2)	HUC[a]
Amite	4822	8070202
Tickfaw	1896	8070203
Tangipahoa	2010	8070205
Total	8728	-

[a]Hydrologic Unit Code.

and Natalbany rivers that drain into Lake Maurepas first and then to Lake Pontchartrain, and the Tangipohoa River which drains into the Lake Pontchartrain directly. In this study, three USGS 8-digit watersheds with larger drainage areas were used as Lake Pontchartrain drainage basin, which were generally described as north shore watersheds in other studies.

3.2.1.2 Climatic Conditions

The long-term annual average air temperature (1948-2000) is about 19 ^{o}C, with the lowest monthly average of 12 ^{o}C in January and the highest monthly average of 28 ^{o}C in July. The long-term annual average precipitation is about 1600 mm, varying from 1108 mm to 2178 mm. The highest monthly average precipitation in the area occurs in July (159 mm), while the lowest is in October (86 mm). Although generally the monthly precipitation is evenly distributed, winter and spring are the seasons when regional flooding often occurs. Approximately 70% of the annual total freshwater in the Lake Pontchartrain drainage basin occurs during winter and spring (Rohli and John, 1995).

3.2.1.3 Land Cover, Vegetation and Soil

Roughly 45% of the study area belongs to the Southern Coastal Plain, where hills and terraces are generally covered with forests (Penland et al., 2002). About 40% of the area is in the Mississippi valley silty upperlands, where scattered pasture farms and residential communities are embedded in bottom-land hardwoods. Forest and agricultural lands are two major land use types in the region. Nearly 58% of the total land area of the Amite River watershed is covered by forests. The Tickfaw River and Tangipahoa River watersheds have a forest cover of 66% and of 54%, respectively. Compared to the Tickfaw and Tangipahoa river watersheds, the Amite River watershed has the highest percentage of urban area (Table 3.2). Dominant soil types are Tangi-Ruston-Smithdale, distributed in very gently to moderately steep slopes, are moderately well-drained to well-drained soils, Toula-Tangi, with properties similar to Tangi-Ruston-Smithdale, and Maytt-Guyton which are level and poorly drained loamy soils (USDA ARS, 1994).

3.2.2 Data Collection

Data used in this study included daily discharge, water quality, climate, topography, and population census data.

3.2.2.1 Discharge Data

Daily discharge data was collected from three U.S. Geological Survey (USGS) gauge stations near the mouth of each the three rivers by way of the USGS National Water Information System website (NWISWeb) (Figure 3.2). The discharge data covered the periods from 1938 to 2002 for the Amite River near Denham Spring (USGS gauge station 7378500), from 1940 to 2002 for the Tickfaw River at Holden (USGS gauge station 7376000), and from 1938 to 2002 for the Tangipahoa River at Robert (USGS gauge station 7375500) (Table 3.3).

Table 3.2. Land use categories in the three watersheds.

Land category	Amite		Tickfaw		Tangipahoa	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Watershed area (km^2)[a]	3434.9	100	662.2	100	1682.3	100
Agricultural land	1201.9	34.9	206.5	31.2	657.8	39.1
Evergreen forest	766.3	22.3	264.4	39.9	432.5	25.7
Mixed forest	1055.9	30.7	176.9	26.7	479.2	28.5
Deciduous forest	193.7	5.6	0	0	8.9	0.5
Forested wetland	17.5	0.5	5.7	0.8	20.2	1.2
Water	4.17	0.1	0.1	0.02	3.9	0.2
Urban[b]	182.1	5.3	7.4	1.1	70.7	4.2
Others	14.4	0.6	1.2	0.3	9.1	0.6

[a]Delineated watershed area, corresponding to a downstream USGS gauge station.
[b]Urban land category was combined with commercial, industrial, transportation and residential lands.

Table 3.3. Three USGS gauge stations used for estimation of freshwater inflow to Lake Pontchartrain.

ID[a]	Location	Latitude	Longitude	Area(km^2)[b]	Date Range
7378500	Amite River near Denham Spring	30.4639	-90.9903	3315	1938 to 2002
7376000	Tickfaw River at Holden	30.5036	-90.6772	639	1940 to 2002
7375500	Tangipahoa River at Robert	30.5064	-90.3617	1673	1938 to 2002

[a]USGS gauge station number.
[b]USGS defined watershed area, related to this gauge station.

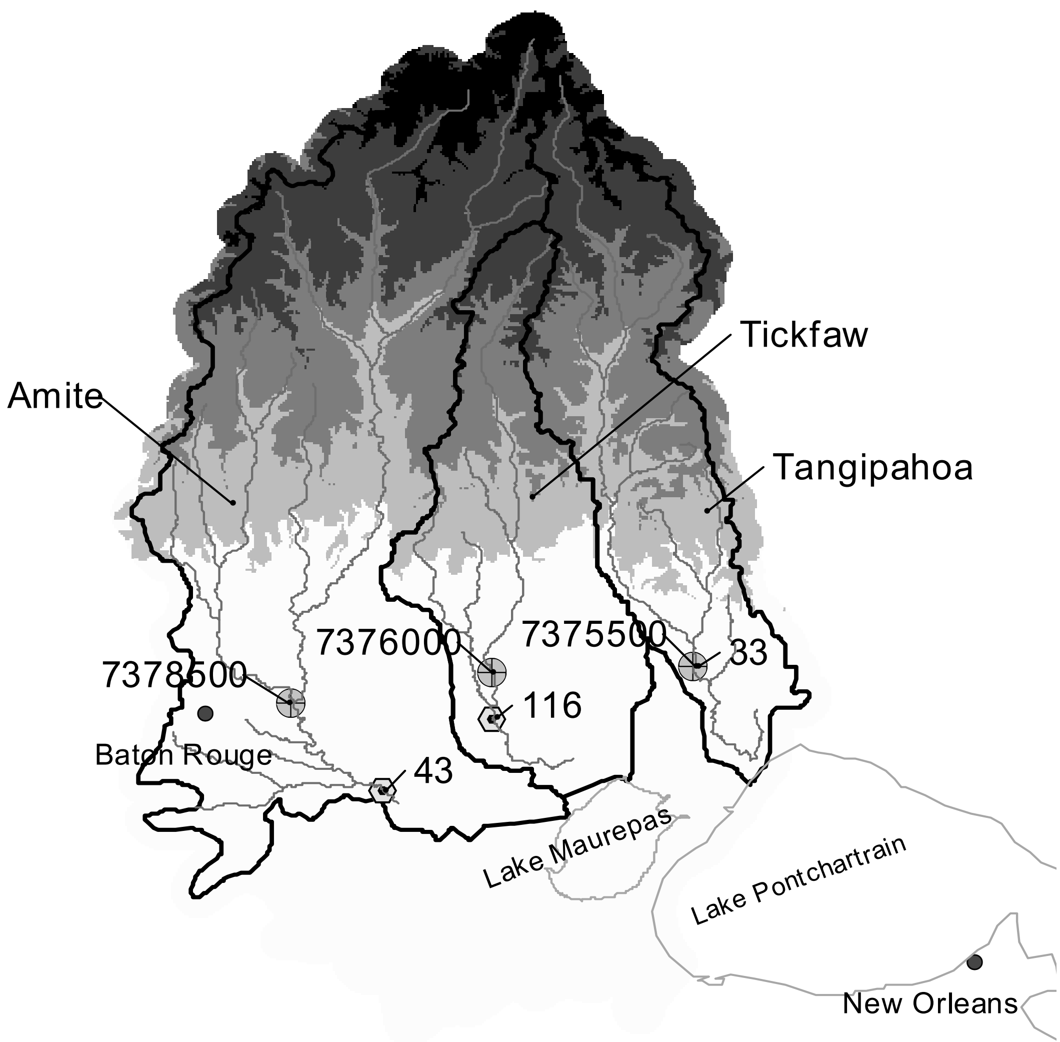


Figure 3.2. Geographical locations of three USGS gauge stations (a shaded circle with a plus sign, represented by the USGS gauge station number) and three water quality monitoring sites (a hexagon with a dot, represented by the LDEQ sampling site number), USGS gauge station 7375500 and water quality sampling site 33 were overlaid together.

3.2.2.2 Water Quality

Monthly water quality data from the available downstream sample sites in each of the three rivers were used to evaluate sediment loads from the drainage basins to Lake Pontchartrain (Figure 3.2). Water quality data was obtained from the Louisiana Department of Environmental Quality (LDEQ). Data used in this study included monthly measurements on a series of chemical and physical parameters, such as monthly concentrations of total suspended solids (TSS). The water quality measurements for the Amite River at Port Vincent and Tickfaw River at Springville covered the period from 1978 to 2001. For the Tangipahoa River west of Robert, the period was from 1968 to 2001 (Table 3.4).

Table 3.4. Three sampling sites for water quality monitoring[a].

Site[b]	Location	Longitude	Latitude	Date Range
33	Tangipahoa River west of Robert	-90.3617	30.5064	06/1966-12/2001
43	Amite River at Port Vincent	-90.8519	30.3325	03/1978-12/2001
116	Tickfaw River at Springville	-90.6775	30.4353	03/1978-12/2001

[a]Data were obtained from the Louisiana Department of Environmental Quality (LDEQ).
[b]LDEQ water quality monitoring site number.

3.2.2.3 Climate Data

Eleven weather stations in the study area were selected for estimation of long-term trends and average of precipitation and air temperature (Figure 3.3). The number and geographical location of the weather stations were considered to reflect the potential effects of topography and elevation on precipitation. The selected stations were evenly distributed over the study area. Seven of them were located in the upper half of the study area at an elevation above 50 m, while the remaining stations were in the lower half of the study area with elevation of less than 50 m. Daily maximum and minimum air temperature and precipitation

were obtained from the National Climatic Data Center (NCDC). The earliest available precipitation data began in 1930 (160549 and 161891), and six of eleven weather stations began in 1940s' (Table 3.5).

3.2.2.4 Digital Elevation Model

A 1:250,000 scale Digital Elevation Model (250K DEM) was used to characterize topographic features of a watershed and for watershed delineation. Three 250K DEMs, 8070202 (Amite), 8070203 (Tickfaw), and 8070205 (Tangipahoa), were retrieved from the Better Assessment Science Integrating point and Nonpoint Sources (BASINS)3.0 package, a GIS-based interface developed by the U.S. Environmental Protection Agency (USEPA, 2001). BASINS 3.0 provides a 250K DEM data for each 8-digit Cataloging Unit across the States. A single coverage DEM for the entire study area was then created in ArcView 3.2 by merging three individual DEM together.

Table 3.5. Geographic locations of eleven selected weather stations in the study area[a].

ID[b]	Station	Elevation (m)	Longitude	Latitude	Date Range
160205	Amite	51.0	-90.5250	30.7094	1948-2000
160549	Baton Rouge WSO AP	19.2	-91.1469	30.5372	1930-2000
161891	Clinton 4 ENE	75.0	-90.9500	30.8833	1930-1990
163867	Greenwell Springs	18.0	-90.9833	30.5667	1967-2000
164034	Hammond	27.0	-90.4667	30.4833	1948-2000
164859	Kentwood	69.0	-90.5167	30.9333	1948-2000
165620	LSU Ben Hur Farm	6.3	-91.1667	30.3667	1963-2000
167304	Pine Grove fire tower	57.0	-90.7500	30.7000	1948-2000
221578	Centreville	111.0	-91.0750	31.0925	1957-2000
225070	Liberty 5 W	103.5	-90.8942	31.1639	1949-2000
225614	Mccomb FAA Airport	123.9	-90.4708	31.1828	1948-2000

[a]Source: NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html).
[b]Cooperative Station ID, used in the National Weather Service's Cooperative Station Network.

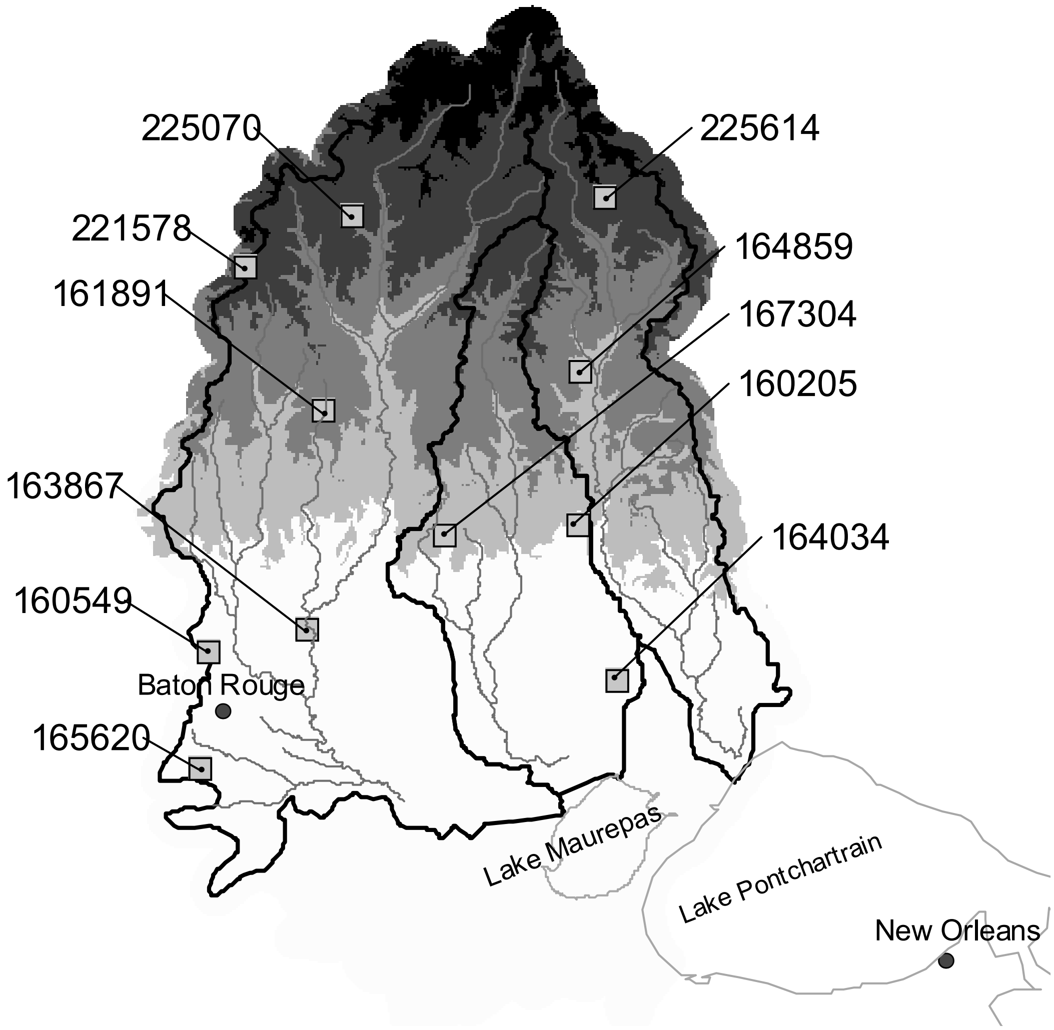


Figure 3.3. Geographical locations of eleven weather stations (represented by Cooperative Station IDs) and stream systems in the three watersheds.

3.2.2.5 Population Data

A GIS layer of Louisiana town was laid over the three watersheds. All cities, Census Designated Places (CDP), towns, or villages were selected if located within one of three watershed boundaries. A total of ten, two and five cities, CDP, town or villages were selected in the Amite River, Tickfaw River and Tangipahoa River watersheds, respectively. Population census data from 2000, 1990, 1980, 1970, and 1960 were collected from the U.S. Census Bureau and Louisiana State Census Data Center.

3.2.3 Data Analysis

3.2.3.1 Precipitation

Monthly and annual average precipitations were calculated for the Amite River, Tickfaw River and Tangipahoa River watersheds from 1948 through 2000. Annual average precipitation in low freshwater inflow period (1954-1973) and high freshwater inflow period (1975-1998) were calculated individually in each of the three watersheds.

3.2.3.2 Freshwater inflow and TSS loadings

Monthly and annual average water yields (WY) in volume were calculated using the daily mean discharge. Monthly and annual mean runoffs (R) in depth were calculated through dividing the monthly and annual water yield by the delineated watershed area (referred to as BASINS_area), as given in the equation 3.1:

$$runoff = \frac{WY(km^3) \times 1{,}000{,}000}{BASINS\_area(km^2)}(mm) \qquad (3.1)$$

Annual water yield for the entire watershed (WY_{entire}) was calculated with an area-weighted method (Table 3.6):

$$WY_{entire} = WY\ (km^3) \times C\ (\mathrm{km}^3\ \mathrm{yr}^{-1}) \qquad (3.2)$$

where $$C = \frac{total\_watershed\_area(km^2)}{BASINS\_area(km^2)}$$

Table 3.6. Characteristics of three upstream watersheds to Lake Pontchartrain.

	Amite River	Tickfaw River	Tangipahoa River
USGS gauge station ID[a]	7378500	7376000	7375500
Locations of gauge station	Amite River near Denham Spring	Tickfaw River at Holden	Tangipahoa River at Robert
Entire watershed area(km^2)	4822	1896	2010
USGS area (km^2)[b]	3315	639	1673
BASINS area (km^2)[c]	3453	662	1680
Area percentage (%)[d]	0.69	0.34	0.83
Date range	1938-2002	1940-2002	1938-2002

[a]USGS gauge station number.
[b]USGS predefined drainage area for a gauge station.
[c]Delineated watershed area for a gauge station with BASINS 3.0.
[d]USGS predefined drainage area divided by the entire watershed area.

Monthly TSS loadings in the watersheds were estimated by multiplying monthly water yield with TSS concentration. The monthly TSS loadings were summed up to provide annual TSS loadings. Annual TSS loadings for the entire watershed were estimated by an area-weighted method. Monthly TSS runoff was calculated through dividing monthly TSS loadings by the total watershed area.

For the Amite River at Port Vincent, the earliest river discharge data was available starting in October 1984, while the earliest data on TSS concentrations at the same sampling site was available starting in March 1978. Therefore, monthly water yields at the Port Vincent station, which were used in calculation of monthly TSS loadings at Port Vincent from 1978 to 1984, were estimated based on a simple linear regression with the monthly water yields at Denham Spring, which is located about 15 mile north of Port Vincent: monthly WY at Port Vincent = 18890464 + 0.909 × monthly WY at Denham Spring (r^2 = 0.90).

A log-linear regression model was developed for each of the three watersheds to estimate missing values of monthly TSS loadings due to missing data of concentration of TSS. The regression models for the Amite River (Eq. 3.3, $r^2 = 0.78$), Tickfaw River (Eq. 3.4, $r^2 = 0.67$), and Tangipahoa River (Eq. 3.5, $r^2 = 0.56$) are given below:

$$\ln(S) = -17.982 + 1.4036 \ln(WY) \tag{3.3}$$
$$\ln(S) = -15.222 + 1.2520 \ln(WY) \tag{3.4}$$
$$\ln(S) = -19.252 + 1.4610 \ln(WY) \tag{3.5}$$

where S is monthly TSS loadings, and WY is monthly water yield.

Population density was calculated through dividing a total population by a total watershed area.

A parametric trend test (Lins and Slack, 1999; Lindstrom and Bergstrom, 2004) was used to examine long-term patterns of annual precipitation and water yield. Regression analyses were used to investigate relationships among water yield, runoff, TSS loadings and precipitation. The Shapiro-Wilk test was used to examine the normality of residuals for the variables. A two sample *t*-test was used for the comparison of means of interested variables between the watersheds. All statistical analyses were performed using the SAS software package (SAS Institute Inc., 1999).

3.3 Results

3.3.1 Precipitation

A significant increasing trend in annual precipitation over the past fifty-three years was found in the Amite River watershed ($p = 0.005$). However, no statistically significant change in annual precipitation was found in the Tickfaw River ($p = 0.21$) and the Tangipahoa River ($p = 0.54$) watersheds. Annual average precipitations during the period from 1954 to 1973 (low freshwater inflow) and the period from 1975 to 1998 (high freshwater inflow) were

significantly different in the Amite River watershed, with a greater precipitation in the high freshwater inflow period (Figure 3.4). However, no significant difference in precipitation between the two periods was found in the Tangipahoa River watershed (Table 3.7).

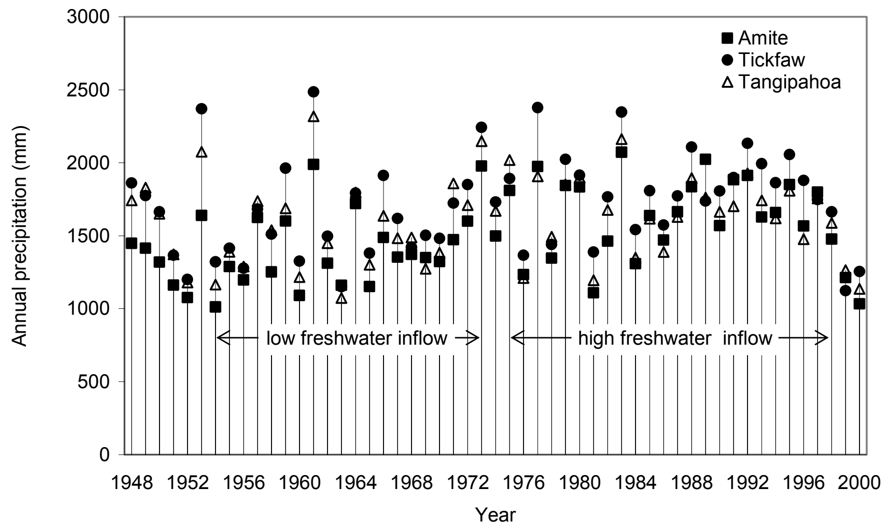


Figure 3.4. Long-term annual average precipitation in the Amite River, Tickfaw River, and Tangipahoa River watersheds.

The highest monthly precipitation (388.5 mm) was recorded in February, 1966 and the lowest (1.7 mm) was recorded in October, 1963. The average monthly precipitation in the study area was 133.3 mm over the fifty-three-year period, with the wettest month in July (159 mm) and the driest month in October (86mm) (Figure 3.5).

Table 3.7. Annual precipitation during the low flow (1954-1973) and the high flow (1975-1998) periods in three coastal watersheds (means and standard deviations are in mm).

	Period	N	Mean	Std	*t* value	Pr>|t|
Amite	1954-1973	20	1416	286	-3.13	0.0032
	1975-1998	24	1664	256		
	1954-1973	20	1627	336	-2.31	0.0300
Tickfaw	1975-1998	24	1837	266		
	1954-1973	20	1547	321	-1.57	0.1240
Tangipahoa	1975-1998	24	1680	243		

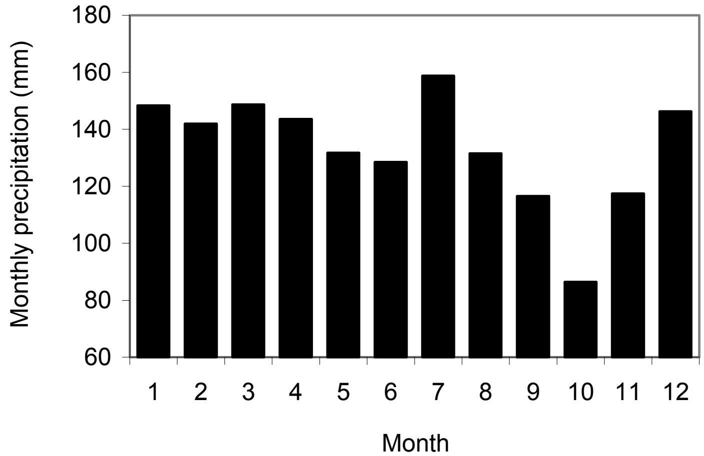


Figure 3.5. Seasonal pattern of long-term (1948-2000) average monthly precipitation in the study area.

Annual average air temperature in the study area was 19.1 ^{o}C, with the hottest month in July (27.4 ^{o}C) and the coldest month in January (9.7 ^{o}C) (Figure 3.6).

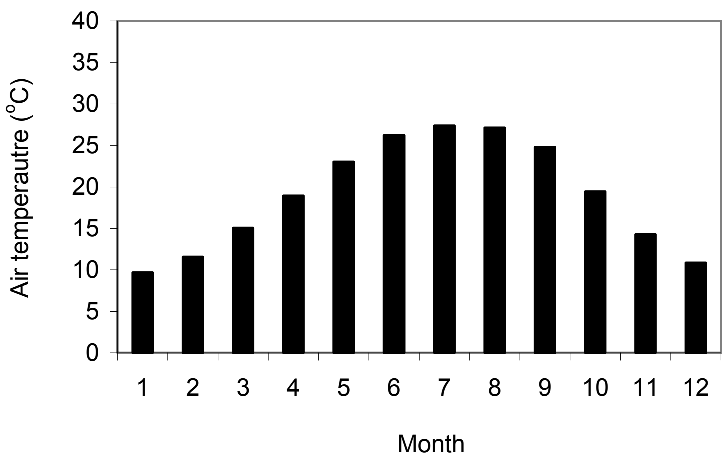


Figure 3.6. Seasonal patterns of long-term (1948-2000) monthly average air temperature in the study area.

3.3.2 Freshwater Inflow

3.3.2.1. Seasonal Pattern

Long-term monthly average water yields from the Amite, Tickfaw, and Tangipahoa rivers to the Lake Pontchartrain drainage basin are presented in Figure 3.7a. The Amite River

showed a monthly average of 0.16 km^3, ranging from 0.07 km^3 to 0.27 km^3. The Tickfaw River averaged a monthly water yield of 0.03 km^3, ranging from 0.01 km^3 to 0.05 km^3. The Tangipahoa River had a monthly average of 0.09 km^3, ranging from 0.04 km^3 to 0.14 km^3. On average, the monthly freshwater inflow from the three tributaries to the lake complex totaled 0.27 km^3. Long-term monthly average runoffs (area-adjusted water yield) were 48 mm, 45 mm, and 52 mm in the Amite, Tickfaw, and Tangipahoa river watersheds with a larger variation in winter and spring (Figure 3.7b). A significant seasonal pattern in freshwater inflow was observed in the three watersheds.

3.3.2.2. Annual and Interannual Pattern

Long-term daily discharge averaged 59.0, 10.9, and 32.9 $m^3\ s^{-1}$(cms) in the Amite River, Tickfaw River, and Tangipahoa rivers, respectively. Annual water yields from the Amite, Tickfaw and Tangipahoa rivers to the drainage basin averaged 1.90 $km^3\ yr^{-1}$, 0.34 $km^3\ yr^{-1}$, and 1.05 $km^3\ yr^{-1}$, respectively, resulting in a total of 3.29 $km^3\ yr^{-1}$. A considerably large variation of freshwater inflow during the past sixty years was found in all three watersheds: from 0.58 to 3.58 $km^3\ yr^{-1}$ for the Amite River, from 0.09 to 0.58 $km^3\ yr^{-1}$ for the Tickfaw River, and from 0.45 to 1.94 $km^3\ yr^{-1}$ for the Tangipahoa River (Table 3.8). Comparably, the interannual variation was highest in the Amite River (six times between the lowest and the highest flows) and was lowest in Tangipahoa River (four times). The results showed that annual runoff in the three watersheds were 573 mm, 534 mm, and 629 mm.

For the past sixty years, a significantly increased trend of both annual water yield in volume (p = 0.032) and annual runoff in depth (p = 0.006) was found in the Amite River (Figure 3.8). In the Tickfaw and Tangipahoa Rivers, however, neither an increasing nor a decreasing trend in water yield was found to be statistically significant (Table 3.9).

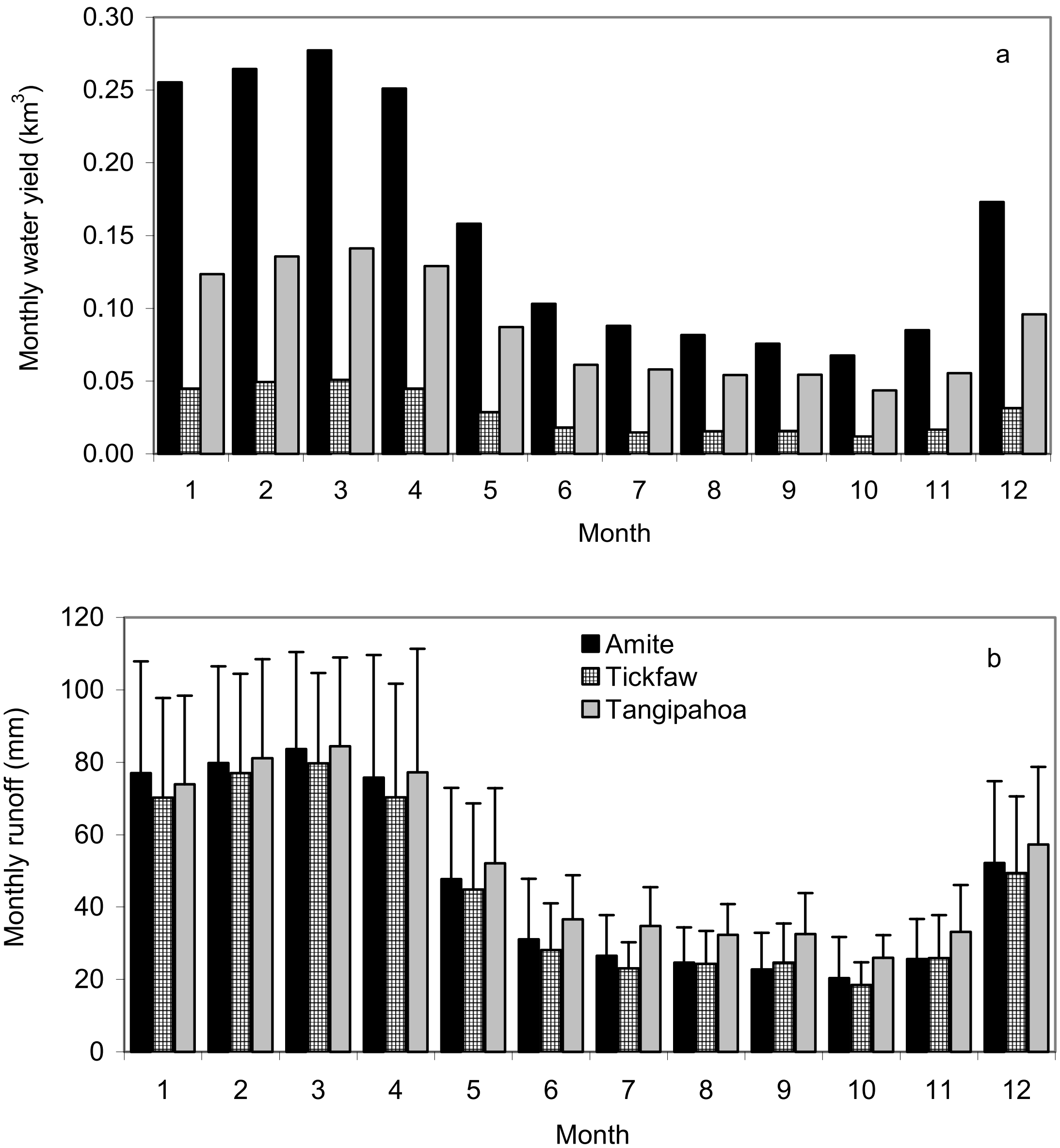


Figure 3.7. Long-term monthly average water yield (a) and monthly average runoff (b) from the Amite, Tickfaw, and Tangipahoa rivers.

Table 3.8. Long-term annual average freshwater inflows from the three major tributaries into Lake Pontchartrain.

	Area (km^2)[a]	Water yield ($km^3\ yr^{-1}$)		Runoff	Relative contribution
		Gauged[b] (range)	Entire[c]	(mm yr^{-1})[d]	(%)[e]
Amite	4822	1.90 (0.58-3.58)	2.76	573	54.8
Tickfaw	1896	0.34 (0.09-0.58)	1.01	534	20.0
Tangipahoa	2010	1.05 (0.45-1.94)	1.27	629	25.2
Total	8728	3.29	5.04	576	100

[a]Entire watershed area.
[b]Calculated annual freshwater inflow from a selected USGS gauges station.
[c]Estimation was made from the gauged watershed to the entire watershed through an area-weighted method, see Eq. 3.2.
[d]Annual discharge per unit watershed area.
[e]Individual contribution of annual water yield from each of the three tributaries.

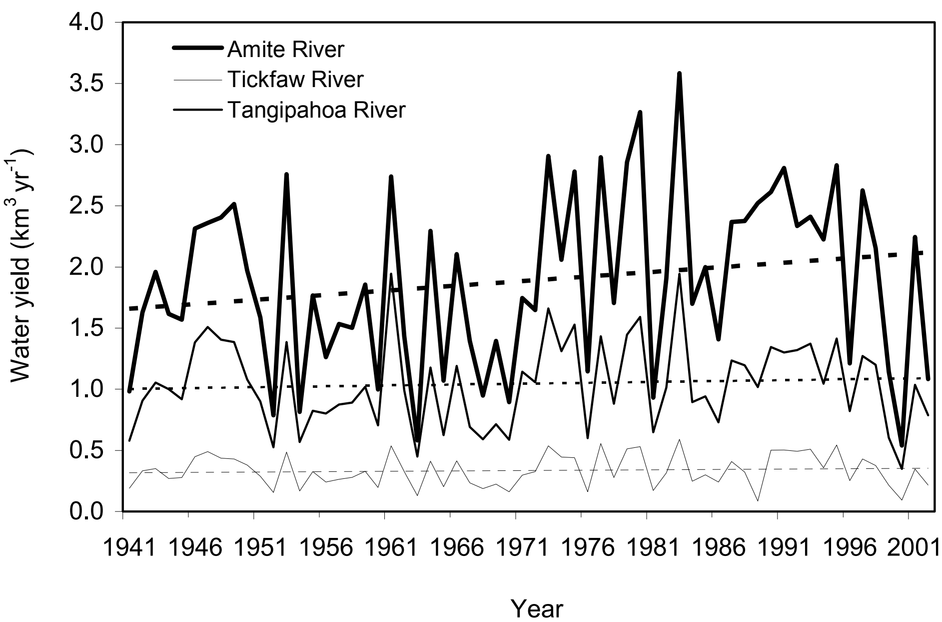


Figure 3.8. Comparison of long-term trends in annual water yield from the Amite, Tickfaw, and Tangipahoa rivers.

Table 3.9. Trend analyses of annual water yield (WY) and runoff (R) versus year (Y) in three coastal watersheds.

Watershed	Regression model	t[a]	p[b]	W[c]	p[d]
Amite	WY= -19.859+0.01103 Y	2.20	0.0318	0.9904	0.908
	R= -7501.8+4.09 Y	2.88	0.0055	0.9812	0.462
Tickfaw	WY= -1.828+0.0011 Y	1.10	0.2694	0.9722	0.179
	R= -2437.5+1.39 Y	1.07	0.2868	0.9731	0.191
Tangipahoa	WY= -6.293+0.0037 Y	1.42	0.1604	0.9906	0.917
	R= -3327.5+2.01 Y	1.26	0.2139	0.9732	0.219

[a]Student t-statistic for slope.
[b]Two-tailed probability associated with t-test for slope.
[c]Statistic for normality test with Shapiro-Wilk.
[d]p value for Shapiro-Wilk normality test.

Two distinct freshwater inflow periods were observed with five-year moving annual average water yield during the past sixty years. One was a twenty-year long low freshwater flow period from 1954 to 1973, and another was a twenty-four-year long high freshwater flow period from 1975 to 1998 (Figure 3.9). The twenty-year annual average water yield from the three rivers was 0.88 km^3 and individually was 1.47 km^3, 0.28 km^3 and 0.89 km^3 for the Amite, Tickfaw and Tangipahoa rivers, respectively. The twenty-four-year annual average water yield from the three watersheds was 1.45 km^3 and separately the averages were 2.28 km^3, 0.38 km^3, and 1.17 km^3 for the three rivers (Table 3.10).

Table 3.10. Annual average water yields during the low flow (1954-1973) and the high flow (1975-1998) periods in three coastal watersheds (means and standard deviations are in km^3).

Watershed	Period	N	Mean	Std	*t* value	Pr>|t|
Amite	1954-1973	20	1.47	0.54	4.22	0.0001
	1975-1998	24	2.28	0.67		
	1954-1973	20	0.28	0.10		
Tickfaw	1975-1998	24	0.38	0.14	2.67	0.0107
	1954-1973	20	0.89	0.34		
Tangipahoa	1975-1998	24	1.17	0.32	2.83	0.0072

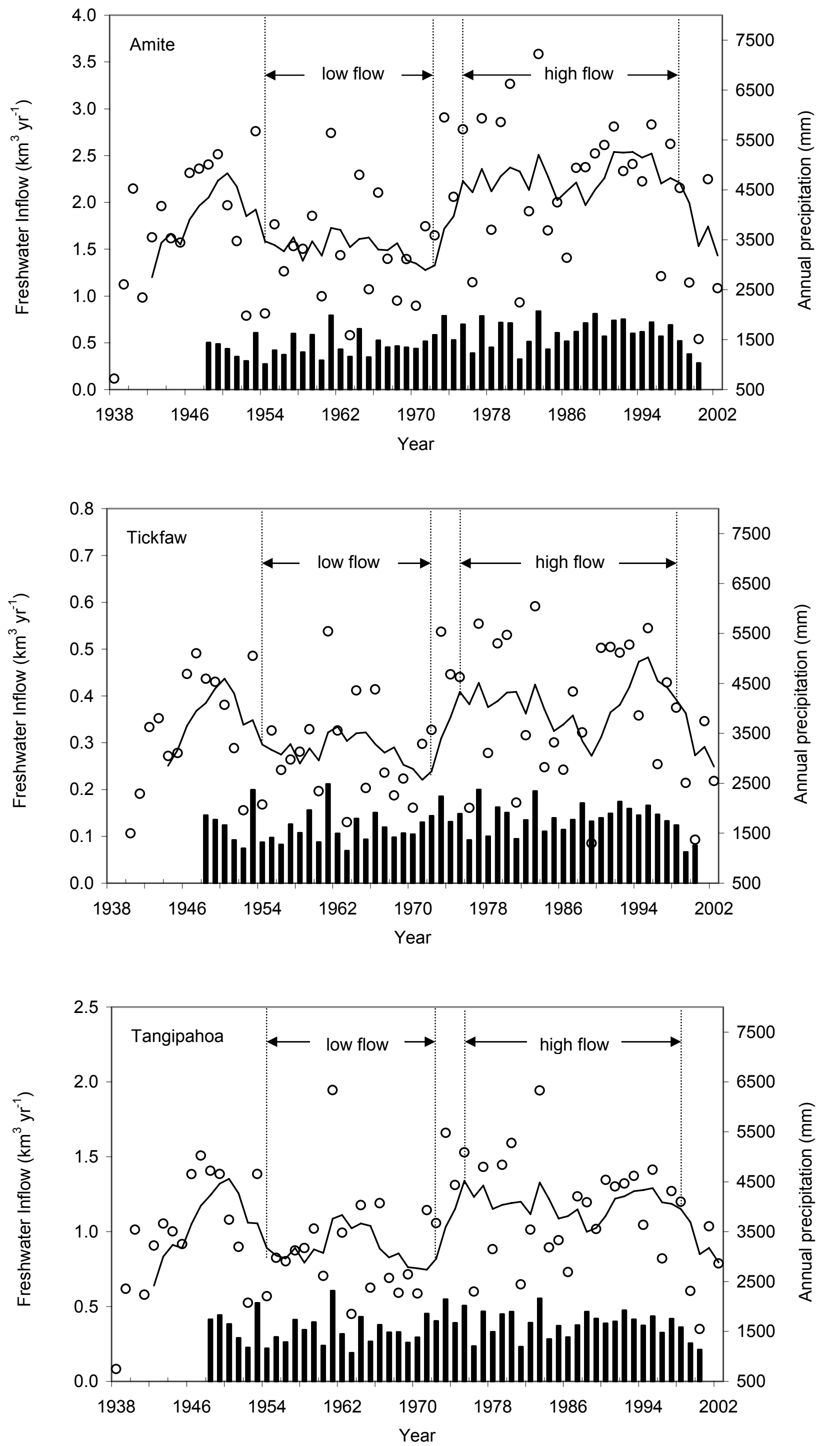


Figure 3.9. Time series plot of five-year moving average annual freshwater inflow from the Amite River, Tikfaw River, and Tangipahoa River to Lake Pontchartrain; circles indicate annual averages of freshwater inflow; Needles denotes annual average precipitation in the watershed.

A statistically significant difference between the two periods was found in all three watersheds (i.e., annual average water yield during the period from 1975 through 1998 was significantly higher than during the period from 1954 to 1973).

3.3.3 Suspended Total Solids

Long-term average concentrations of TSS were 45.7 mg L^{-1}, 22.6 mg L^{-1}, and 28.6 mg L^{-1} in the Amite River, Tickfaw River, and Tangipahoa River, respectively (Figure 3.10). A statistically significant higher concentration of TSS was found in the Amite River than in the Tangipahoa River and Tickfaw River, though the difference between the Tickfaw River and Tangipahoa River was statistically insignificant.

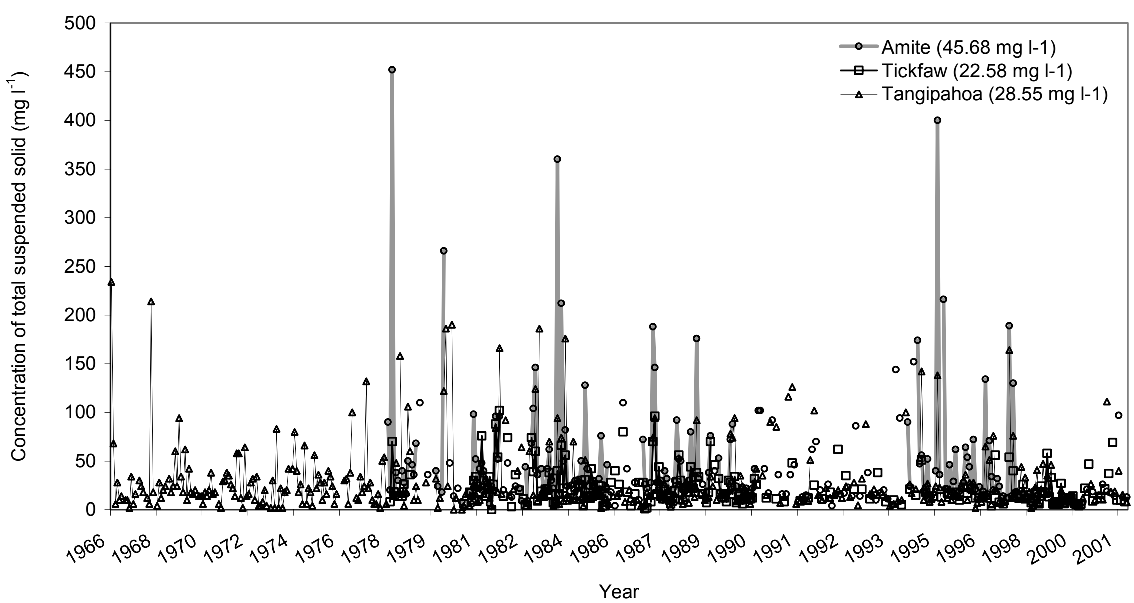


Figure 3.10. Long-term trends of TSS concentrations in the Amite, Tickfaw, and Tangipahoa rivers (the numbers in legend represent averages of TSS concentrations).

Annual TSS loadings from the Amite River, Tickfaw River, and Tangipahoa River averaged 141,074, 18,278, and 51,008 tons yr^{-1} (Table 3.11), respectively, resulting in a total annual average of 210,360 tons of TSS from the three watersheds into the Lake Pontchartrain

drainage basin. Annual means of TSS runoff (area adjusted suspended total solids loadings) from the three river watersheds were, 29.3, 9.6, and 25.4 tons km^{-2} yr^{-1}. The differences in annual average TSS loadings and runoff among the three rivers were statistically significant.

A seasonal pattern of higher TSS concentrations during the late winter and early spring (January to April) and lower TSS concentrations during the summer and fall (May to November) were found (Figure 3.11 and 3.12).

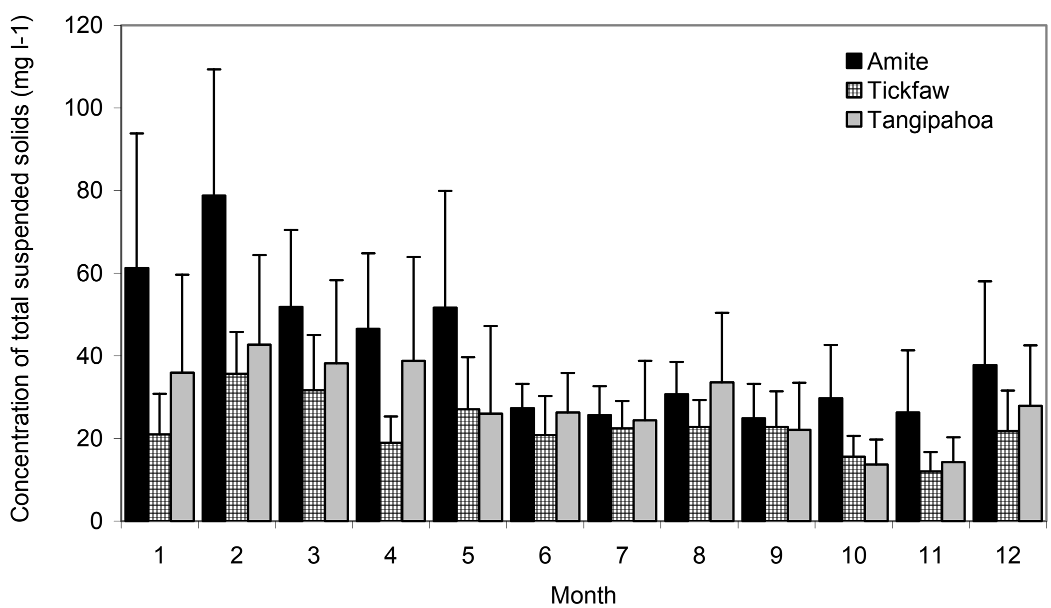


Figure 3.11. Seasonality of TSS concentrations in the Amite, Tickfaw, and Tangipahoa rivers.

3.3.4 Relationships between Runoff, TSS Loadings and Precipitation

3.3.4.1 Runoff and Precipitation Relationship

A close relationship between annual runoff and annual precipitation was found in all three watersheds (Figure 3.13). Over 80% of interannual variations in the runoff could be explained by the annual precipitation (Table 3.12).

Table 3.11. Long-term averages of annual TSS loading and runoff from three river watersheds to Lake Pontchartrain.

Watersheds	Period	Watershed area (km^2)[a]		Annual TSS loadings (tons yr^{-1})		Annual TSS runoff (tons km^{-2} yr^{-1})[b]	Percent[c] (%)
		Total	Gauged	Gauged	Total		
Amite	1978-2001	4822	4133	120,916[d]	141,074	29.26	67.0
Tickfaw	1978-2001	1896	982	9,467[e]	18,278	9.64	9.0
Tangipahoa	1968-2001	2010	1673	42,456[f]	51,008	25.38	24.0
Total/average	-	8728	6788	172,839	210,360	21.43	100.0

[a]Total watershed areas of each basin were obtained from the USGS. Gauged watershed areas were estimated through BASIN 3.0 delineation based on the sampling site in each river.
[b]Annual TSS runoff were calculated through annual TSS loadings in the gauged area divided by the delineated watershed area.
[c]Individual contribution of annual suspended solids loading from each of the three tributaries.
[d,e,f] Two sample t-test with Satterthwaite among three rivers showed a significant difference ($p<0.0001$).

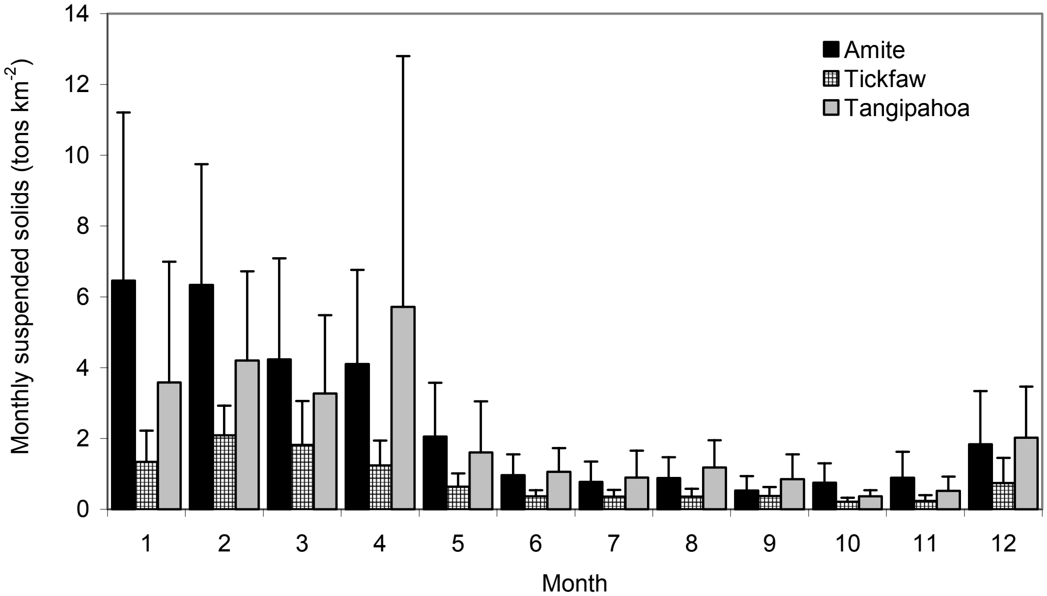


Figure 3.12. Seasonality of TSS runoff from the Amite, Tickfaw, and Tangipahoa river watersheds.

Table 3.12. Regression analyses with annual runoff (R) and annual precipitation (P) in the Amite, Tickfaw, and Tangipahoa river watersheds ($R = \beta_0 + \beta_1 P$).

Watersheds	β_o(intercept)	β_1(slope)	r^2	p[a]	W[b]	p[c]
Amite	-572.7	0.704	0.8476	<0.0001	0.9712	0.2370
Tickfaw	-495.4	0.635	0.8028	<0.0001	0.9924	0.9838
Tangipahoa	-508.8	0.709	0.8234	<0.0001	0.9680	0.1743

[a]p value associated with F statistic.
[b]Statistic for normality test for residual with Shapiro-Wilk approach.
[c]p value for Shapior-Wilk normality test.

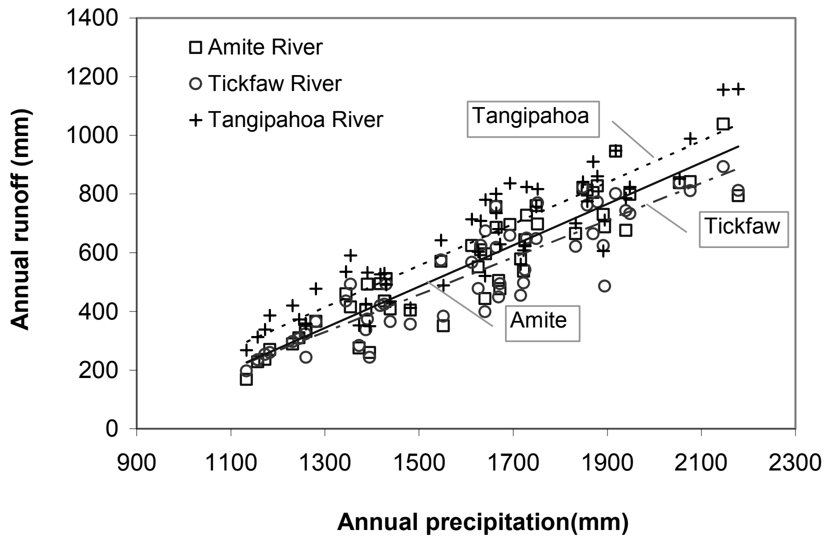


Figure 3.13. Linear relationships between annual runoff and annual precipitation in the Amite River, Tickfaw River, and Tangipahoa river watersheds.

A ratio of 0.34 for long-term annual average runoff to annual precipitation (runoff efficiency) was found in the study area. In the extreme high freshwater inflow years, runoff efficiencies were estimated by around 0.50, meanwhile, in the extreme low freshwater inflow years, however, runoff efficiencies were around 0.15.

A close exponential relationship of the monthly runoff with the monthly precipitation was found during the wet months (from December to May) (r^2 = 0.64), compared to that during the dry months (from June to November) (r^2 = 0.53) (Figure 3.14A and B).

3.3.4.2. Relationship between TSS Runoff and Precipitation

An r^2, ranging from 0.36 to 0.43 and from 0.47 to 0.59, of relationships between annual TSS runoff and annual precipitation (Table 3.13) and annual TSS runoff and total precipitation from January through April (Table 3.14) was found in all the three studied watersheds.

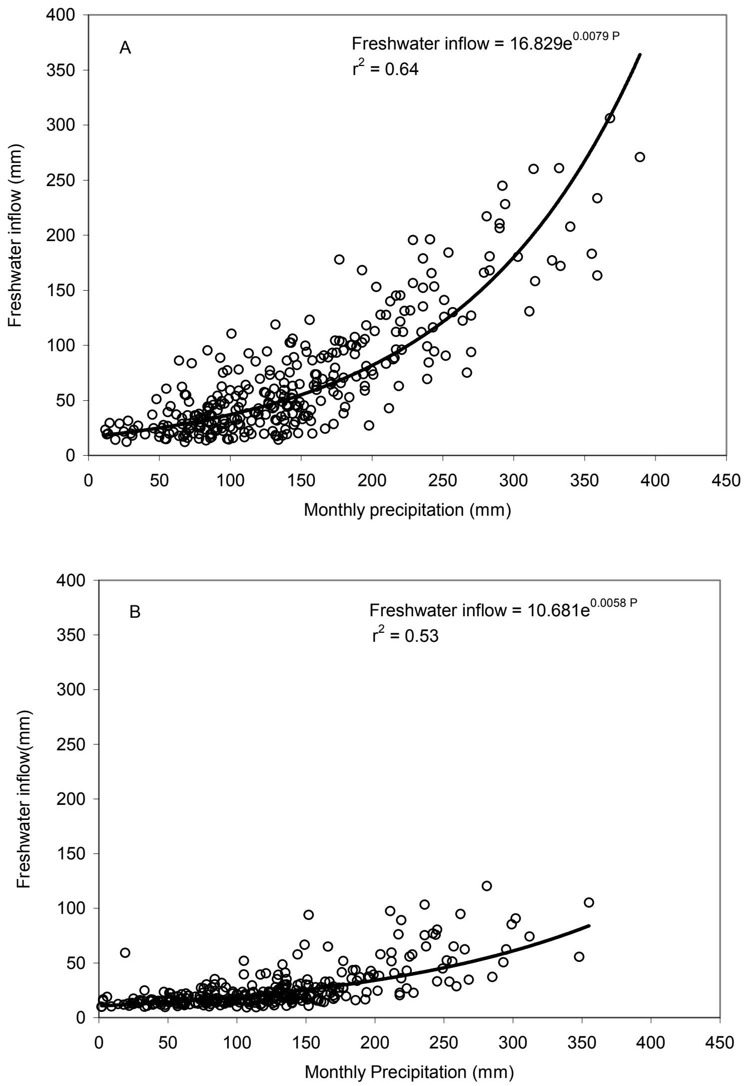


Figure 3.14. Relationships between monthly freshwater inflow and monthly precipitation during the wet months (A) and the dry months (B) in the studied watersheds.

Table 3.13. Regression analyses of annual TSS runoff (S) versus annual precipitation (P) in three river watersheds to Lake Pontchartrain ($S = \beta_0 + \beta_1 P$).

Watersheds	β_o(intercept)	β_1(slope)	r^2	p[a]	W[b]	p[c]
Amite	-35.76	0.039	0.434	<0.0006	0.949	0.2915
Tickfaw	-10.29	0.012	0.424	0.0008	0.889	0.0154
Tangipahoa	-56.56	0.049	0.364	<0.0001	0.851	0.0002

[a]p value associated with F statistic.
[b]Statistic of normality test for residual with Shapiro-Wilk approach.
[c]p value for Shapior-Wilk normality test.

Table 3.14. Regression analyses of annual TSS runoff (S) versus total precipitation (P) from January through April in the three watersheds ($S = \beta_0 + \beta_1 P$).

Watersheds	β_o(intercept)	β_1(slope)	r^2	p[a]	W[b]	p[c]
Amite	-4.8914	0.055	0.594	<0.0001	0.946	0.244
Tickfaw	0.0791	0.0151	0.471	0.0003	0.847	0.002
Tangipahoa	-20.509	0.077	0.536	<0.0001	0.862	0.001

[a]p value associated with F statistic.
[b]Statistic of normality test for residual with Shapiro-Wilk approach.
[c]p value for Shapior-Wilk normality test.

3.5 Discussion

3.5.1 Climatic Pattern

Rainfall has been often considered to be a driving force in hydrologic processes. Differences in long-term precipitation among the three watersheds suggests a spatial variation of rainfall processes in the study area. While the Amite River watershed showed a significant climatic change, the data showed relatively little change in meteorological conditions in the Tickfaw and Tangipahoa river watersheds over the past fifty-three years. However, average precipitation during the period from 1975 to 1998 among the three watersheds was higher than these during the period from 1954 to 1973 (Table 3.7). Variability in long-term

precipitation patterns might result in different responses of the hydrologic regime among the different watersheds.

3.5.2 Seasonal Pattern of Freshwater Inflow

A seasonal variation in monthly freshwater inflow was found in all the three watersheds: high flows in the winter and spring (wet months) and low flows in the summer and fall (dry months). A total monthly water yield in the six months from December through May accounted for 74%, 73%, and 69% of the total annual water yield in the Amite River, Tickfaw River, and Tangipahoa River (Figure 3.7), respectively. A stronger exponential relationship of monthly runoff and monthly precipitation was found with an r^2 of 0.64 during the wet months, compared with an r^2 of 0.53 during the dry months (Figure 14A and B). The results showed that during the wet months, when monthly precipitation increased from 200 mm to 300 mm, predicted average monthly runoff would increase from 80 mm to 170 mm. During the dry months, however, monthly runoff would increase from 35 mm to 65 mm with the same changes of monthly precipitation. During the wet months, due to low air temperature, ET could be low even with sufficient soil moisture, leading to a higher monthly water yield. During the dry months, however, ET could be high due to higher air temperature, resulting in lower monthly water yields because most of the rainfall was likely evapotranspired. The results imply that in subtropical watersheds, streamflow is generally dominated by surface runoff with baseflow making only a small contribution during the wet months. However, during the dry months, groundwater discharge contributes a larger proportion of streamflow.

Flow regimes, including magnitude, timing and duration of discharge, are critical for regulating biotic productivity and diversity and for protecting the fundamental ecological

function of rivers and aquatic systems (Postel, 1996). A strong rainfall-runoff relationship and saturated or near-saturated antecedent soil during wet months would indicate a higher risk of flooding and sever soil erosion in the region. A weak rainfall-runoff relationship and soil moisture deficits during dry months would suggest more biologically and ecologically detrimental consequences, because of low streamflow, higher temperature, lower dissolved oxygen concentration and poor water quality (Turner et al., 1992; Turner, 1997; DeLaune et al., 2003).

3.5.3 Long-term Trend of Freshwater Inflow

Long-term trends in annual water yield have been found to be related to both climatic variations and land cover changes. Among climatic variables, precipitation is the most important factor affecting the quantity of water yields (e.g., Karl and Riebsamel, 1989; Miller and Russell, 1992; Kletti and Stefan, 1997). Significant linear relationships between annual runoff and annual precipitation were found in the three watersheds, and more than 80% of the variation in the annual runoff could be explained by the annual precipitation ($r^2 = 0.85$, 0.80, and 0.82 in the Amite, Tickfaw and Tangipahoa river watersheds, respectively). The rainfall-runoff regression indicates a 3.8% increase in annual runoff with each 1% increase of annual precipitation in the Amite River, which is slightly greater than the reported a 1.5-2.5% increase in annual runoff for a 1% increase of precipitation based on a study of 1337 watersheds in the United States (Sankarasubramanian and Vogel, 2003). In this study, a significant increasing trend in annual water yield and annual precipitation over the past half century was found in the Amite River watershed, but no statistically significant changes in annual water yield and annual precipitation were observed in both the Tickfaw River and Tangipahoa River watersheds. These results strongly indicate a close association between

long-term pattern of freshwater inflow and precipitation within a watershed, as has been witnessed in other parts of Southeastern United States by McCabe and Wolock (2002).

While increased streamflows have been found to be associated with increased precipitation, many studies have also showed profound impacts of population growth and urbanization-induced land use change on long-term streamflow, in which fluctuation in population density is often used interchangeably with urbanization-induced land cover changes (Collins and Knox, 2003; Mauget, 2003; Arnold et al., 1987; Dale, 1997; Vorosmarty et al., 2000; Karl and Trenberth, 2003). In 1960, the Amite River watershed had a population density of 4.8 persons per km^2 (Table 3. 8). In 2002, the population density of the watershed changed to 10.8 persons per km^2, representing a 125% population increase during the past forty years. In 1960, the Tickfaw and Tangipahoa River watersheds showed a population density of 1.1 and 5.7 persons per km^{-2} (Table 3.15). In 2000, their population densities barely changed to 1.3 and 5.9 persons per km^{-2}, respectively, representing a 8.1% change and a 3.5% change in growth of the watersheds' population since 1960. The long-term trend in water yield over the half century among the watersheds appeared to be associated with population growth trends: the Amite River watershed, which has been experiencing the largest change in population density during the past forty years, also showed an increased pattern of annual water yield. However, significant increase in freshwater inflow from 1960s (1954-1973) to 1980s (1975-1998) in all three watersheds may imply that even though an increase in precipitation was not statistically significant, fluctuation of precipitation is still most possibly correlated to freshwater inflow in the study area.

Although the study suggested contributions from both climatic and urbanization-induced land use changes to long-term pattern of freshwater inflow in the study area, it is still

Table 3.15. Changes in population density in the Amite, Tickfaw, and Tangipahoa river watersheds from 1960 to 2000 (person/km^2).

Watershed	1960	1970	1980	1990	2000	Increase (%)
Amite	4.8	6.6	9.2	9.8	10.8	125.0
Tickfaw	1.1	1.3	1.3	1.2	1.3	18.1
Tangipahoa	5.7	5.8	6.2	5.9	5.9	3.5

a challenge to distinguish them. Therefore, a carefully designed study on urbanization-induced land use in the area is needed to quantify the magnitude of anthropogenic impacts on hydrologic regimes in the upper Lake Pontchartrain basin.

3.5.4 Seasonality of Total Suspended Solids Loadings

The higher annual water yield and the higher total suspended solid concentration in the Amite River have resulted in a much higher sediment loading (147 tons yr^{-1}), when compared to the Tickfaw (18 tons yr^{-1}) and Tangipahoa (51 tons yr^{-1}) rivers. Taking the difference in watershed size into account, the annual TSS runoff remained highest in the Amite River watershed (29 tons km^{-2} yr^{-1}), as compared to those in the Tickfaw River (10 tons km^{-2} yr^{-1}) and Tangipahoa (25 tons km^{-2} yr^{-1}) River watersheds. Availability of sediment sources, especially in the sites with severely disturbed surface soil which directly or indirectly connected to channel instabilities and alterations, could lead to a high risk of soil erosion (Mossa and McLean, 1997). In the Amite River, in-channel mining of gravel and sand has been identified as one of major sources of sediment loads, which was correlated to higher TSS loadings in streams (LDEQ, 2000). In the Tickfaw, the lowest TSS loadings may mainly because of minimal stream-channel sediment sources in the watershed.

In addition to sediment sources along the river channels, sediment level is also related to surface soil disturbance within a watershed. Studies have showed that urbanization-induced land cover change, such as conversion of natural forests to pine plantation, cropland and

impervious lands, is one of the most detrimental factors for surface soil disturbance (Nelson and Booth, 2002; Nilsson et al., 2003). In the Amite River watershed, population density, an indicator of urbanization as it has been often used in similar hydrologic studies (Lu and Higgitt, 1999; Biggs et al., 2004), has doubled since 1960, reaching 10.8 persons per km^2 in 2002. In the other two watersheds, however, increases in population densities were less then 20% during the past forty years (Table 3.8). The study suggests that the annual TSS runoff in a ten-year interval from the three studied watersheds was clearly associated with population density patterns: the annual TSS runoff increased while the population density increased (Figure 3.15). Different soils may be another reason for the higher sediment loads in the Amite River watershed. Loess soil, a fine wind blown sediment, occupies nearly 50% of the Amite River watershed area. Its vulnerability to surface erosion may have contributed to the higher sediment loads.

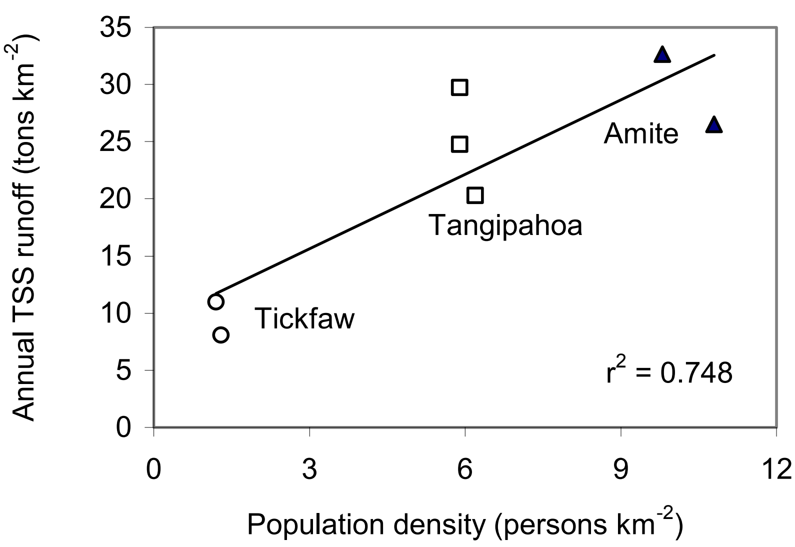


Figure 3.15. Relationship between annual average TSS runoff in a ten-year interval and population density in the study area.

While the spatial variation in sediment loadings among the three watersheds may have been caused by the availability of sediment sources in channels and the erodibility of surface soil, the seasonal fluctuation of sediment loadings was most likely associated with land use practices. Soil erosion is a function of the eroding power of raindrops, running water, flowing earth mass, and the erodibility of the soil. While climate (especially, precipitation), soil, and geology (slope degree and length) are the most important influences on erosion, vegetation cover mostly counteracts the effects on erosion of climate, topography, and soil characteristics (Hofmann, 1991). For instance, a 25-75% larger concentration of dissolved solids was observed in the burned watershed by Gerla and Galloway (1998), using two temporary sampling stations with one as a burned and another as an unburned watershed near Yellowstone National Park. TSS loadings were estimated through water yield and TSS concentration, therefore, seasonality of TSS loadings was also associated to seasonal variations in TSS concentration, except water yield. Our study shows that over 69% of the annual water yield occurred in six months from December to May and over 66% of annual TSS loadings occurred in four months from January through April. During spring months when vegetation cover is sparse and possible agricultural disturbances are likely, soil is vulnerable to erosion, therefore, resulting in higher concentration of TSS in all three watersheds. However, during summer months, heavy vegetation cover and decreased surface runoff would help prevent soil erosion and retard sediment washing into a stream, leading to a considerable decrease in concentration of TSS. The average concentration of TSS in the late winter and early spring (from January through May) were 2.01 times, 1.36 times, and 1.56 times higher than those in the rest of the year (from June through December) in the Amite, Tickfaw, and Tangipahoa rivers, respectively. Compared to the models of annual TSS runoff

and annual precipitation, a higher r^2 was found in linear regression models of annual TSS runoff and total precipitation from January through April in all three watersheds. The relationship between annual TSS runoff and annual precipitation was week, where r^2 ranged from 0.36 to 0.43, although the parameters in the linear relation regression appeared statistically significant (Figure 3.13). A stronger relationship between annual TSS runoff and total precipitation from January through April was found in all the three studied watersheds, because considerable greater annual TSS loadings occurred in the late winter and early spring months (Table 3.14).

Although annual sediment loads could be more accurately predicted with precipitation from certain times of a year, the results indicated a complexity of TSS runoff as suggested by Tuan and Shibayama (2003) to occur in other regions. Multiple analyses, including climatic, topographic, vegetative, and channel morphological parameters, would be helpful to build a statistically sound relationship between TSS loadings and precipitation, either on an annual, seasonally, or monthly basis. The higher concentration of TSS and greater TSS loadings in the Amite River during spring months implied a higher risk of soil erosion and nutrient loss in a watershed with highly intensive developed land use types and land use practices. Furthermore, it also indicated one of the alternative timings for erosion control, which is critical in designing and implementing all kinds of the Best Management Practices.

CHAPTER 4. SPATIAL HYDROLOGIC MODELING

4.1 Introduction

Effective watershed management and ecological restoration require a thorough understanding of hydrologic processes within watersheds. Spatial and temporal variations in climate conditions, soils, vegetation covers, and land use practices make hydrologic cycling a complex system; therefore, mathematic models and geospatial analyses tools are needed for studying hydrologic processes and hydrologic responses to land use and climatic changes (Xu, 1999; Singh and Woolhiser, 2002; Jayakrishnan et al., 2000).

The Soil and Water Assessment Tool (SWAT), has been widely used and proved to be a useful tool in spatial analyses for many watersheds (Weber et al., 2001). The SWAT model was developed by the USDA ARS to assess the impacts of land use management on water, sediment and agricultural chemical yields in large complex watersheds with varying soil, land use and management conditions over a long-period of time (Arnold et al., 1998). The SWAT system, embedded within a geographic information system (GIS), can integrate various spatial environmental data, including soil, land cover, climate, and topographic features. As a physically-based hydrologic model, SWAT uses hydrologic response units (HRUs) to describe spatial heterogeneity in terms of land cover and soil type within a watershed. The model estimates relevant hydrologic components such as evapotranspiration, surface runoff, and ground water recharge with at as much detail as an HRU. SWAT has been used to predict various impacts of land management on water quantity (Srinivasan and Amold 1994; Muttiah and Wurbs, 2002), sediment yield and nutrient loading (Luzio et al., 2002), and potential climate change impacts in water resource management (Jha et al., 2004; Rosenberg et al., 2003; Muttiah and Wurbs, 2002; Ritschard et al., 1999).

Although previous studies covered a wide range of watershed scales, most of them were conducted geographically in the North, Northwest, and Midwest. For instance, the Cottonwood River near New Ulm, Minnesota by Hanratty and Stefan (1998), Southern Alberta, Canada by Chanasyk et al. (2003), Southern Wisconsin by Kirsch (2000) and Kirsch et al. (2002), Upper Mississippi River Basin by Jha et al. (2004), Missouri River Basin by Stone et al. (2003) and Hotchkiss et al. (2000), Upper Wind River Basin Wyoming by Stonefelt et al. (2000), central Iowa by Vache et al. (2002) and the Black Hills of South Dakota by Fontaine et al. (2001). Most of these areas belong to dry, semiarid and humid continental climatic regions, with cold winters receiving little precipitation and warm summers. Few of these studies were conducted in humid subtropical regions of Southern and Southeastern U.S., characterized by relatively humid weather during parts of the year, with flat to gently rolling topography, and with rainfall-dominated watersheds.

Lake Pontchartrain and its surrounding lakes in Southeastern Louisiana are among the largest estuaries in the Gulf Coastal region. The lake estuary system has served one third of the Louisiana population for centuries. As one of the most important areas in Louisiana, the basin has been experiencing the fastest population growth, most rapid land cover change, and most intensive hydrologic modification in the past half century (Mossa, 1995; LDEQ, 2000). Consequently, an intensive conflict has arisen among human activities, development, and environment. Potential climate change, even with uncertainty of its estimation and prediction, posed another stress on sustainable water resources management and environmental restoration (Barringer et al., 1994; Frederick, 1993 and 2002; Gerten et al., 2004; Hauer et al., 1997; Maheepala and Perera, 2003). Thus to this end, objectives of this study were to:

1) Characterize watershed features in the Amite, Tickfaw, and Tangipahoa river watersheds with spatial datasets;
2) Create a modeling environment through parameters calibration and validation in the three watersheds; and
3) Estimate seasonal patterns of water yield and other hydrological components in these watersheds and to evaluate the capability of SWAT for coastal Louisiana.

4.2 Methods

4.2.1 Site Description

The study area is located in the upper stream watersheds to Lake Pontchartrain (30-31^{o}N and 90-91.5^{o}W), including the Amite River, Tickfaw River, and Tangipahoa River watersheds, with a total drainage area of 8,728 km^2 (Figure 4.1). The elevation of the region ranges from 0 m to 150 m above sea level. Detailed descriptions of the study area were discussed in Chapter 3.

4.2.2 Data Collection

Spatial datasets used in this study include Digital Elevation Model (DEM), soil, land use and land cover, reach file (a vector database of streams), weather, and daily discharge. The UTM (Universal Transverse Mercator) projection based on the GRS 80 ellipsoid model, zone 15, was used for all spatial coverage in this study.

4.2.2.1 DEM

DEM data was used for watershed delineation and hydrologic simulation through providing raster based geomorphic information. Considering the drainage basin size and research purpose, a 1:250,000 scale DEM (250k DEM) was selected. The Better Assessment Science Integrating point and Nonpoint Sources (BASINS) version 3.0, a GIS-based

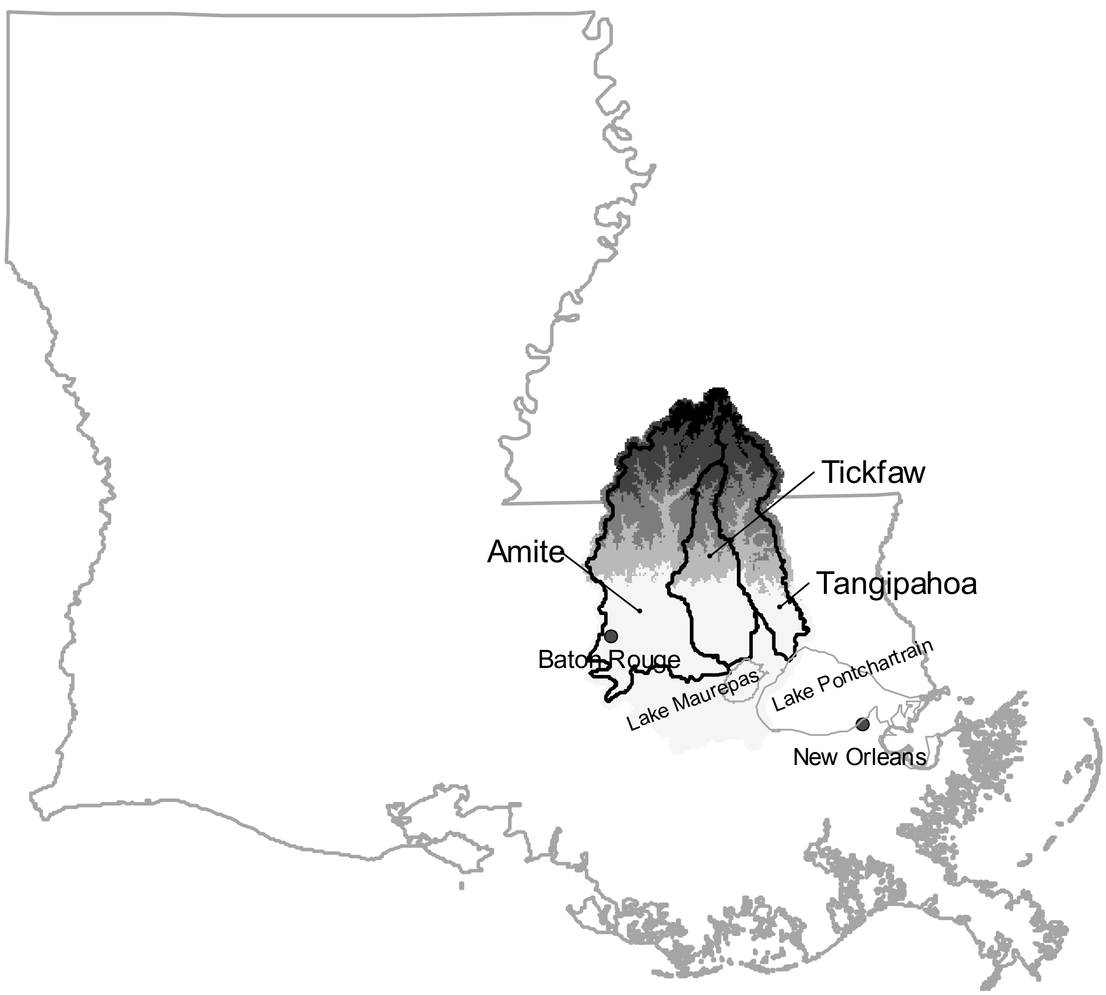


Figure 4.1. Location of the study area: the Amite, Tickfaw, and Tangipahoa river watersheds --the upper stream drainage basin to Lake Pontchartrain.

assessment tool for point and nonpoint source pollution, was used to delineate the studied watersheds. BASINS provided 250K DEM data for each 8-digit Cataloging Unit across the country. With three 250K DEMs--Amite, Tickfaw, and Tangipahoa--a single coverage DEM for the entire study area was created with ArcView 3.2.

4.2.2.2 Soil

Soil data were obtained from the State Soil Geographic Database (STATSGO, USDA ARS, 1994). This data set is a digital general soil association map developed by the National Cooperative Soil Survey and distributed by the Natural Resources Conservation Service (formerly Soil Conservation Service) of the U.S. Department of Agriculture. Soil properties were used to determine hydrologic parameters, which might affect infiltration, evapotranspiration, and other hydrologic processes in the hydrologic modeling.

4.2.2.3 Land Use and Land Cover

Land use and land cover data were obtained from USGS Land Use and Land Cover (LULC) database. Similar to soil data, land use and land cover data were used in the hydrologic modeling to determine land cover status and management factors.

4.2.2.4 Reach Files

Reach files are a series of national geographic and hydrologic databases that uniquely identify and interconnect the stream segments or "reaches" that comprise the surface water drainage system. There are three versions of Reach files. Version one (RF1), developed by the USEPA in 1982, is still in use while RF2 and RF3 have been replaced by the National Hydrography Dataset (NHD). Based on spatial resolutions of Reach files and the purpose of this hydrologic simulation, RF1 was selected in this study for automatic delineation as burnt-

in reach rivers, which would allow the GIS interface in BASINS 3.0 to segment sub-watersheds accurately, especially in lowland areas with flat topography.

4.2.2.5 Weather Data

A total of eleven weather stations were selected (Table 4.1). The selection of the weather stations was based on (1) simulation requirements on accurate climatic data on each sub-watershed and (2) 10-year period or more of data availability before and after the 1980's, when land cover and land use data were obtained and used in hydrologic simulation (Figure 4.2). The weather data, i.e., daily precipitation and maximum and minimum air temperature data, were obtained from the National Climatic Data Center (NCDC). And the weather data, i.e., daily wind speed, humidity, solar radiation, and the missing daily precipitation, maximum and minimum temperature data, were estimated by the weather generator embedded in SWAT. Daily precipitation was generated by a model developed by Nicks (1974), which was based on a first-order Markov Chain model. Air temperature and solar radiation were generated from a normal distribution; daily mean wind speed was generated by the model

Table 4.1. Eleven selected weather stations for hydrologic simulation in the SWAT model[a].

ID[b]	Station Name	Elevation (m)	Longitude	Latitude	Date Range
160205	Amite	51.0	-90.5250	30.7094	1948-2000
160549	Baton Rouge WSO AP	19.2	-91.1469	30.5372	1930-2000
161891	Clinton 4 ENE	75.0	-90.9500	30.8833	1930-1990
163867	Greenwell Springs	18.0	-90.9833	30.5667	1967-2000
164034	Hammond	27.0	-90.4667	30.4833	1948-2000
164859	Kentwood	69.0	-90.5167	30.9333	1948-2000
165620	LSU Ben Hur Farm	6.3	-91.1667	30.3667	1963-2000
167304	Pine Grove fire tower	57.0	-90.7500	30.7000	1948-2000
221578	Centreville	111.0	-91.0750	31.0925	1957-2000
225070	Liberty 5 W	103.5	-90.8942	31.1639	1949-2000
225614	Mccomb FAA Airport	123.9	-90.4708	31.1828	1948-2000

[a]Source: NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html).
[b]Cooperative Station ID, used in the National Weather Service's Cooperative Station Network.

developed by Richardson and Wright (1984), and daily average relative humidity was calculated by a relative humidity model, which used a triangular distribution to simulate the daily average relative humidity from the monthly average.

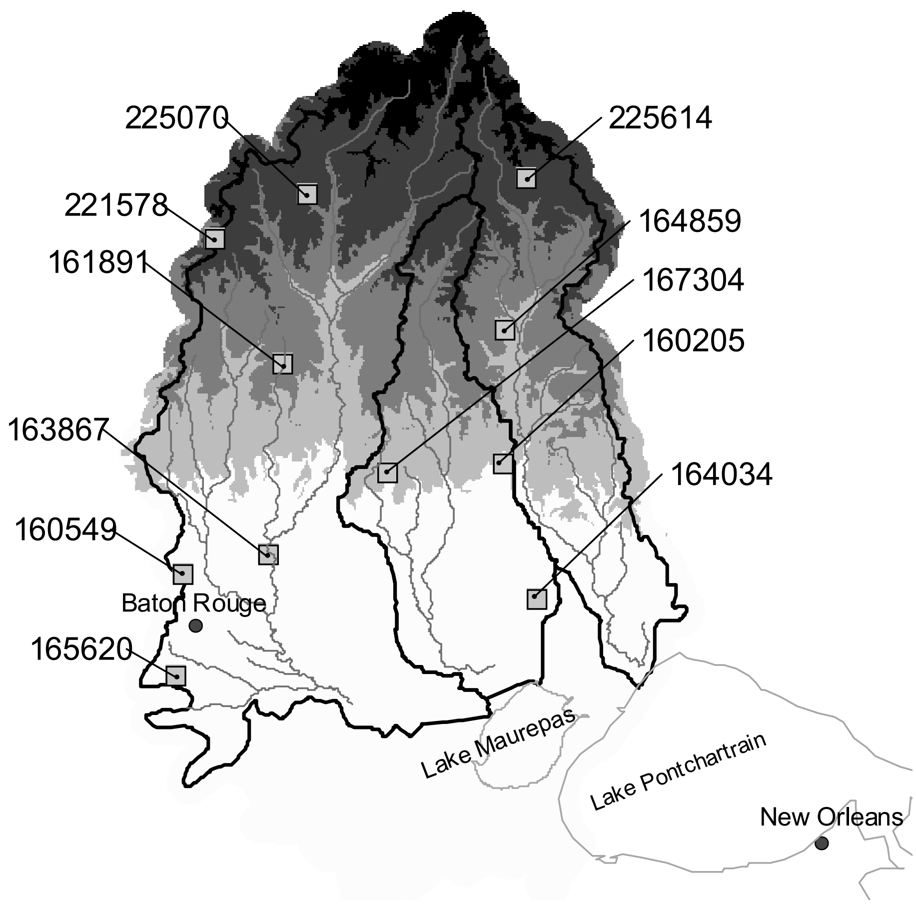


Figure 4.2. Geographical locations of eleven weather stations, represented by the station ID, in the study area.

4.2.2.6 Discharge Data

The daily discharge data obtained from the US Geological Survey (USGS) was used to calibrate parameters in the SWAT model. Data from the three gauge stations (7378500, 7376000, and 7375500) were selected for calibration and validation (Table 4.2 and Figure 4.3). These gauge stations were located at the downstream of the Amite, Tickfaw and Tangipahoa rivers.

Table 4.2. Three USGS stations used for calibration and validation of the SWAT models for the Amite, Tickfaw, and Tangipahoa rivers watersheds.

ID[a]	Location	Latitude	Longitude	Area(km^2)	Date Range
7378500	Amite River near Denham Spring	30.4639	-90.9903	3315	1938 to 2002
7376000	Tickfaw River at Holden	30.5036	-90.6772	639	1940 to 2002
7375500	Tangipahoa River at Robert	30.5064	-90.3617	1673	1938 to 2002

[a]USGS gauge station number.

4.2.3 Modeling

4.2.3.1 Model Description

The SWAT model was developed by the USDA ARS based on a series of previously developed models, including SWRRB (Simulator for Water Resources in Rural Basins, Williams et al., 1985), CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems, Kinsel, 1980), and GLEAMS (Ground Water Loading Effects on Agricultural Management Systems, Leonard et la., 1987). SWAT was mainly designed to predict the impacts of land management practices on water, sediment, and agricultural chemical yields in a larger watershed with varying land use and soil in a longer period of time on a drainage basin (Arnold et al., 1998). It also has been used in the assessment of climate change impacts on water resources management (Bouraoui et al., 2002).

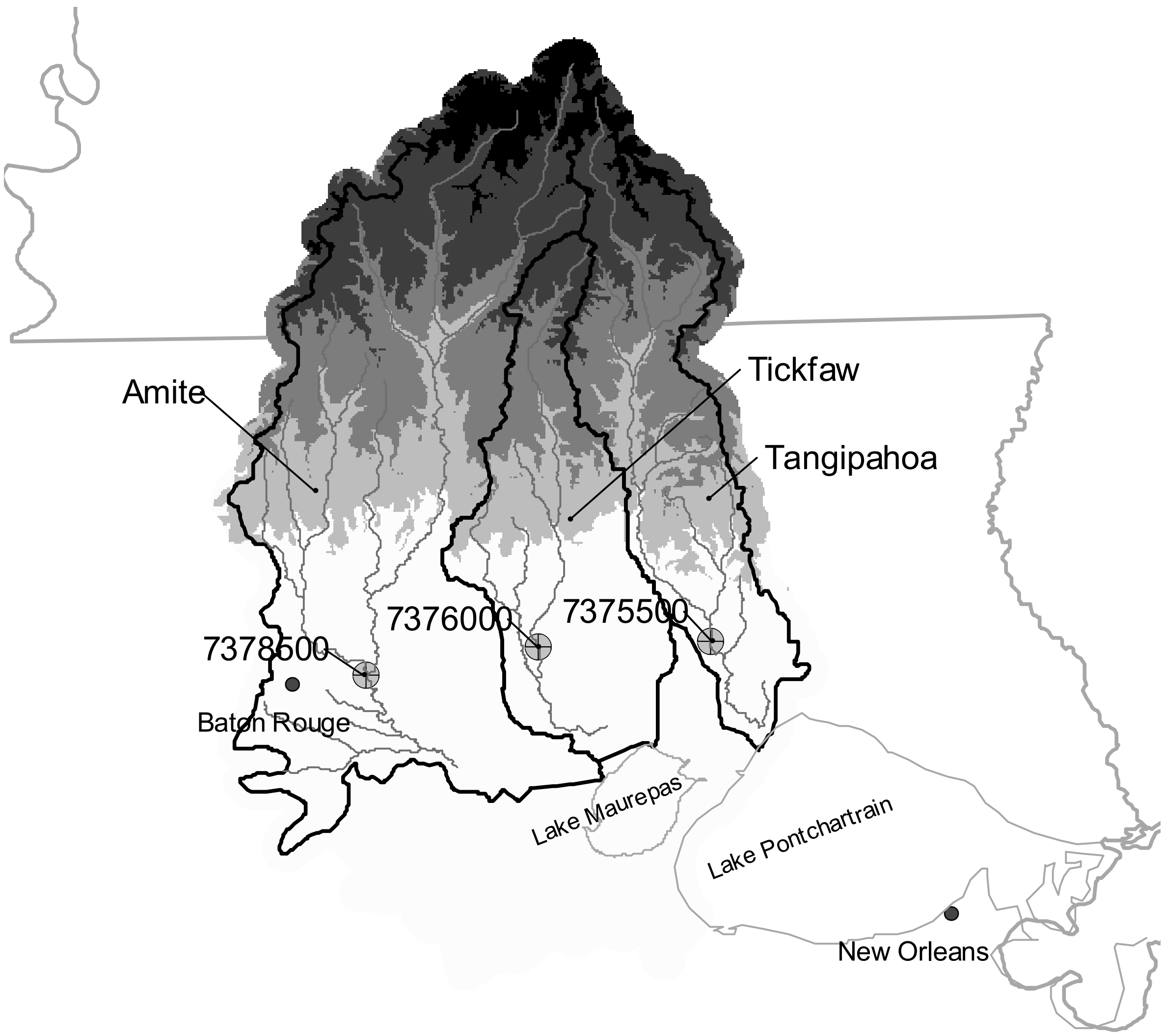


Figure 4.3. Three USGS gauge stations used for SWAT calibration and validation for the Amite (7378500), Tickfaw (7376000), and Tangipahoa (7375500) river watersheds.

The SWAT model simulates eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management (Neitsch et al., 2001). Major hydrologic processes simulated by the model include potential evapotranspiration (PET), surface runoff, infiltration, channel transmission losses, channel routing, shallow aquifer and deep aquifer flow, and percolation losses (Arnold and Allen, 1996). These processes are simulated in four subsystems: surface soil, intermediate zone, shallow aquifer and deep aquifer. Streamflow in the major channel is then determined by three sources: surface runoff, lateral flow from subsurface soil, and baseflow from shallow aquifers. In SWAT, the impacts of spatial variations in topography, land use, soil and other watershed characteristics on site hydrology are considered in subdivision. There are two-level scales of subdivisions: (1) a watershed is partitioned into sub-watersheds, which are treated as a homogenous area in terms of climatic variables, and (2) each sub-watershed is further divided into a number of hydrologic response units (HRUs) based on land cover and soil types. Each HRU is assumed to be spatially uniform in terms of soil, land use, and topography.

A daily water budget is established for each HRU based on precipitation, runoff, evapotranspiration, percolation, internal flow, groundwater flow, and soil moisture change. The SCS runoff curve number method is used to partition surface runoff and infiltration from daily precipitation. Curve numbers are determined by land use, soil hydrologic group, and soil moisture condition at the HRU scale. SWAT offers three options for estimation of potential ET: Penman-Monteith (Monteith, 1965), Priestley-Taylor (Priestly and Taylor, 1972), and Hargreaves models (Hargreaves and Samani, 1985).

Infiltrated water is redistributed in the soil profile by a percolation component, in which a storage routing is combined with a crack-flow model to predict flow through each soil layer. Lateral flow in the soil profile (0-2 m) is calculated simultaneously with percolation in each soil layer with a kinematic storage model (Sloan and Moore, 1984). Water that percolated below the bottom of the root zone is assumed to recharge the shallow aquifer first; this water can either flow laterally towards a stream as baseflow or percolate into a deeper aquifer. Once the water has percolated to the deep aquifer, it is considered to be lost from the system (Arnold et al., 1998). Flow routing through channel networks delineated by SWAT is performed by using either the variable storage coefficient method or the Muskingum river routing method (Williams, 1969).

4.2.3.2 Model Set Up

In this study, BASIN 3.0 was used to delineate the boundaries of the Amite, Tickfaw, and Tangipahoa river watersheds (Figure 4.4). The Amite River watershed was divided into 14 sub-watersheds, which were further divided into a total of 36 HRUs based on land use and soil types. The number of sub-watersheds was determined to reflect changes in land use, topography, soil types, their impacts on hydrologic processes, and to consider potential variations of precipitation within the watershed. HRUs were determined by the multiple hydrologic response unit option of 30% land use over sub-watershed area and 20% soil class over land use area (Neitsch et al., 2001). Characteristics of sub-watershed and HRUs were calculated and used in the SWAT simulation.

The Tickfaw River watershed was divided into 8 sub-watersheds and a total of 8 HRUs; the Tangipahoa River watershed was divided into 12 sub-watersheds and a total of 12 HRUs. All HRUs in the Tickfaw and Tangipahoa river watersheds were determined by a

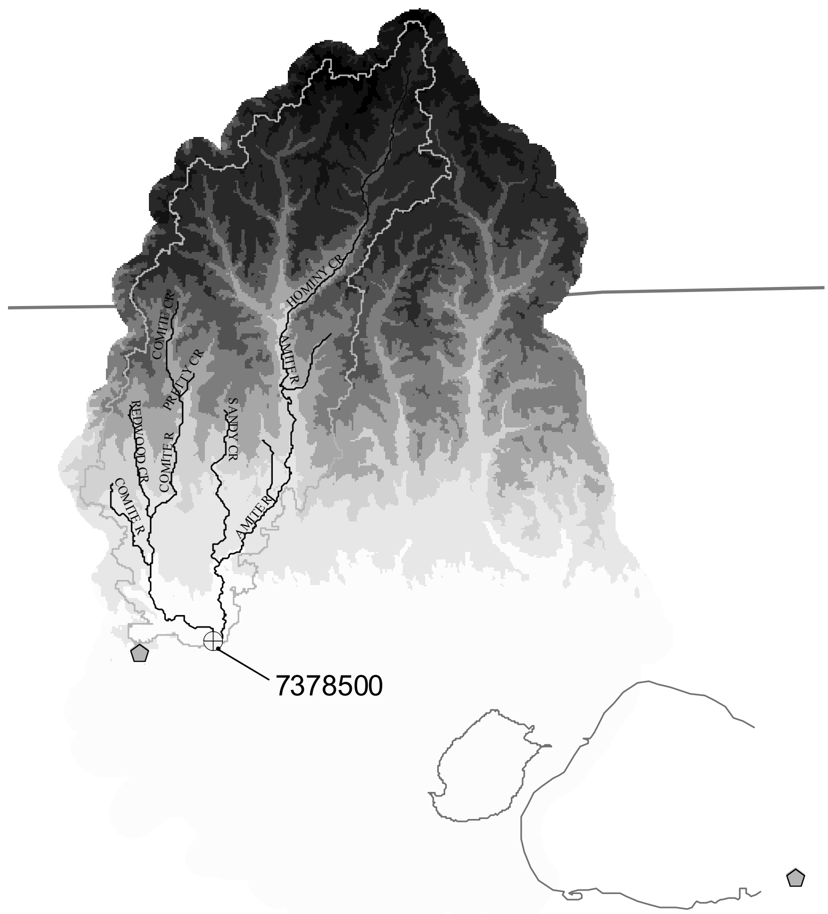


Figure 4.4. A delineated watershed boundary (gray line) for a USGS gauge station (7378500), used for model calibration and validation in the Amite River watershed.

dominant HRU distribution option. The reason for choosing this option rather than the multiple HRU option, which was used in the Amite River watershed, was that these two watersheds were dominated by only a few major land use and soil types.

Measured daily precipitation, daily maximum air temperature, and daily minimum air temperature from eleven weather stations (Figure 4.2) were gathered from this simulation study. Wind speed, solar radiation, relative humidity, and all missing data of precipitation and temperature were obtained using a weather generator embedded in SWAT. Data used in the weather generator in this study were from station Hammond 3 NW (30.53N, 90.48W, 12.2 m above sea level), which was the nearest weather station to the study area. The SCS curve number method was chosen to estimate surface runoff from daily precipitation. A comparison for PET estimation with three equations provided in the SWAT model was conducted, and the Hargreaves equation was selected for the final modeling assessment based on deviation of discharge. The Muskingum method was chosen in the channel flow routing. Simulation on a daily basis was repeatedly run until satisfaction was met by comparing the modeling discharge with the observed discharge (see 4.2.3.4 Calibration and Validation).

4.2.3.3 Drainage Characteristics of Sub-watersheds

Among the 14 sub-watersheds in the Amite River watershed (Figure 4.5), Sub-watershed 13 was the largest (1,122.27 km^2) and Sub-watershed 14 was the smallest (0.11 km^2). The upper stream sub-watersheds showed higher average slopes than the downstream sub-watersheds. The elevation decreased from the upland to Lake Pontchartrain (Table 4.3). The largest land use category in the watershed was forest land (59.2%), which was subdivided as Mixed forest (30.74%), Evergreen forest (22.31%), Deciduous forest (5.64%), and Forested wetlands (0.51%). The second largest land use type was agricultural land, accounting for 34.99% of the total watershed area (Table 4.4).

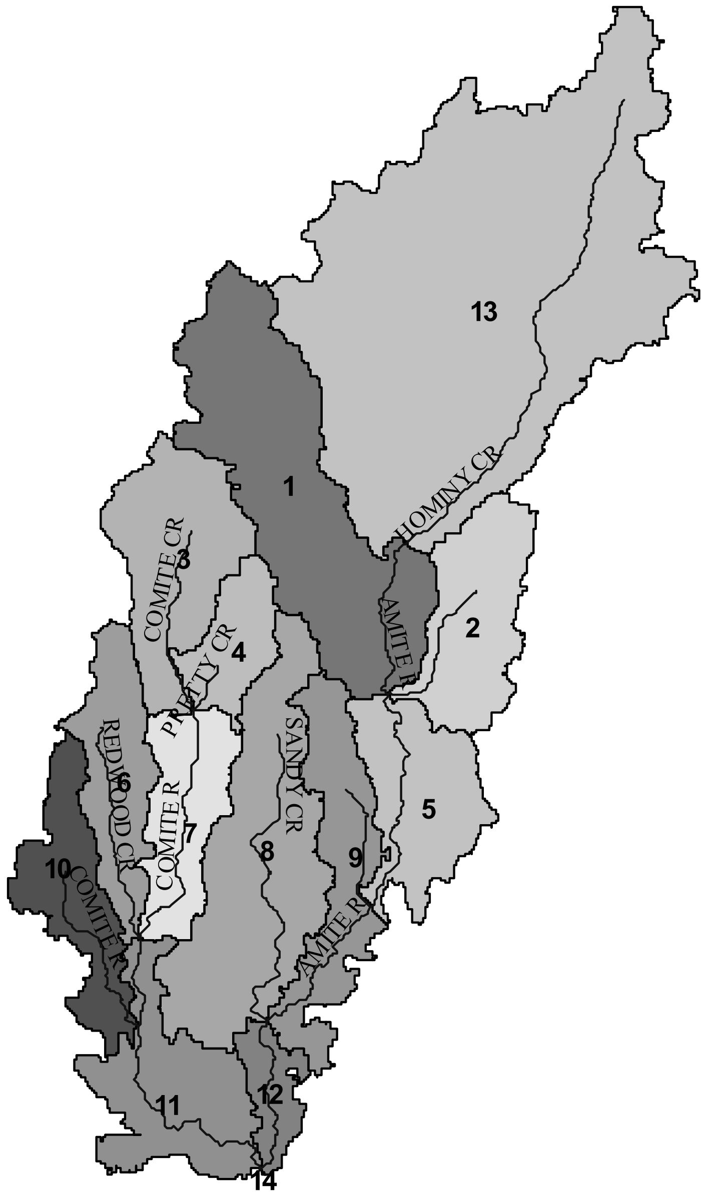


Figure 4.5. Delineated sub-watersheds in the Amite River watershed.

Table 4.3. Characteristics of sub-watersheds in the Amite River watershed.

Sub-watershed	Area[b]	Len1[c]	Slo1[d]	Csl[e]	Wid1[f]	Dep1[g]	Elev[h]
	km^2	m	%	%	m	m	m
1[a]	432.37	52049	1.48	0.16	49.22	1.47	91
2	177.34	28619	1.16	0.21	28.83	1.03	75
3	214.66	30291	1.41	0.21	32.33	1.11	73
4	88.18	18746	1.13	0.26	18.96	0.78	60
5	174.18	31654	0.83	0.15	28.52	1.02	45
6	149.15	37393	0.84	0.17	25.99	0.96	45
7	140.23	29887	0.7	0.17	25.04	0.94	40
8	347.34	50739	0.62	0.13	43.16	1.35	45
9	184.02	44338	0.69	0.16	29.48	1.05	29
10	148.66	37795	0.47	0.16	25.94	0.96	30
11	198.46	38187	0.31	0.07	30.85	1.08	18
12	57.86	20509	0.27	0.06	14.72	0.66	10
13	1122.27	65859	1.39	0.14	87.23	2.16	121
14	0.11	676	0	0.1	0.35	0.05	7

[a]Sub-watershed number.
[b]Sub-watershed drainage area, delineated with BASINS 3.0 based on DEM data.
[c]Stream reach, longest path within the sub-watershed.
[d]Sub-watershed slope.
[e]Reach slope.
[f]Stream reach width.
[g]Stream reach depth.
[h]Elevation of the sub-watershed centroid.

Table 4.4. Major land cover types in the Amite River watershed.

Code	Area(km^2)	Percentage of total area (%)	Land use
AGRL	1201.9	34.99	Agricultural Land_Generic
FRST	1055.9	30.74	Forest_Mixed
FRSE	766.3	22.31	Forest_Evergreen
FRSD	193.7	5.64	Forest_Deciduous
URMD	131.9	3.84	Residential_Medium Density
UTRN	28.9	0.84	Strip Mines
WETF	17.5	0.51	Wetlands_Forested
UCOM	14.1	0.41	Commercial
OHERS	24.5	0.72	-

The watershed had four soil groups whose aerial percentages were higher than 10%. Soil types with the largest area in these four soil groups were Providence, Bude, Ochlockonee and Tangi (Table 4.5). Most of the soils were silty loams with a hydrologic soil group of C and a soil bulk density ranging from 1.35 to 1.5 (g m^{-3}) (Table 4.6).

Table 4.5. Major soil types in the Amite River watershed.

Muid[a]	Area (km^2)	Percentage of total area (%)	Soil types (largest in area)
MS067	623.1	18.14	Providence
MS096	367.9	10.71	Bude
LA099	367.9	10.71	Ochlockonee
LA010	363.1	10.57	Tangi
LA062	230.5	6.71	Olivier
LA070	179.0	5.21	Calhoun
LA011	170.4	4.96	Lytle
LA009	167.6	4.88	Tangi
LA090	103.7	3.02	Loring
LA086	92.7	2.70	Satsuma
LA112	67.3	1.96	Toula

[a]Muid is STATSGO map unit identification code (USDA ARS, 1994).

The precipitation and temperature gauge stations used in each sub-watershed of the Amite River watershed are presented in Table 4.7. In every sub-watershed, one gauge station was selected for simulation according to the shortest geographical distance between the centroid of a sub-watershed and the location of a gauge station.

In the Tickfaw River Watershed, Sub-watershed 2 was the largest (141.47 km^2) and Sub-watershed 4 was the smallest (36.03 km^2) (Table 4.8 and Figure 4.6A). In most of the sub-watersheds, slopes were more than 1%. The average sub-watershed elevation ranged from 18 m to 92 m. The forest was the largest land use (66.6%), which was subdivided into Evergreen forest (39.93%) and Mixed forest (26.7%). The second largest land use type was

Table 4.6. Major soil properties related to hydrologic simulation in the Amite River watershed (represented by the soil with the larger area in the soil group).

Muid	SNAM[a]	TEXTURE[b]	HYDGRP[c]	SOL_ZMX[d]	SOL_BD[e]	SOL_AWC[f]	SOL_K[g]	CLAY[h]	SILT[i]	SAND[j]
				mm	g m^{-3}	mmH_2O mm^{-1}	mm h^{-1}	%	%	%
MS067	Providence	Silt	C	1524	1.4	0.22	4	8.5	69.9	21.6
MS096	Bude	Silty loam	C	1600	1.5	0.24	0.6	18.5	69.9	11.6
LA099	Ochlockonee	Fine sandy loam	B	1828	1.5	0.15	47	10.5	26.3	63.2
LA010	Tangi	Silty loam	C	1651	1.5	0.22	10	7	71.1	21.9
LA062	Oliver	Silty loam	C	2032	1.5	0.23	2.6	13	72.7	14.3
LA070	Calhoun	Silty loam	D	1828	1.6	0.23	1.5	18.5	69.9	11.6
LA011	Lytle	Silty loam	B	2057	1.5	0.19	27	7.0	58.9	34.0
LA009	Tangi	Silty loam	C	1651	1.5	0.22	10	7	71.1	21.9
LA090	Loring	Silty loam	C	1651	1.4	0.23	1.3	13	72.7	14.3
LA086	Satsuma	Silty loam	C	1651	1.5	0.22	10.0	7	71.1	21.9
LA112	Toula	Silty loam	C	1651	1.5	0.22	10	7	71.1	21.9

[a]Soil name.
[b]Soil texture of layer 1, data was not used by the model.
[c]Hydrologic group (A, B, C, D).
[d]Maximum rooting depth of soil profile.
[e]Moist bulk density of the layer 1.
[f]Available water capacity of the layer 1.
[g]Saturated hydraulic conductivity of the layer 1.
[h]Clay content of soil in the layer 1, the percentage of soil particles which are < 0.002 mm in equivalent diameter.
[i]Silt content of soil in the layer 1, the percentage of soil particles which have an equivalent diameter between 0.05 and 0.002 mm.
[j]Sand content of soil in the layer 1, the percentage of soil particle which have a diameter between 2.0 and 0.05 mm.

Table 4.7. Rainfall and air temperature stations used in SWAT simulation in the Amite River watershed[a].

Sub-watershed	Rainfall	Temperature
1	225070[b]	225070
2	167304	161891
3	225070	161891
4	225070	161891
5	167304	167304
6	160549	161891
7	163867	161891
8	163867	161891
9	167304	167304
10	160549	160549
11	160549	160549
12	163867	160549
13	225070	225070
14	163867	160549

[a]Source: NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html).
[b]Cooperative station ID, used in the National Weather Service's Cooperative Station Network.

agricultural land (31.15%)(Table 4.9). LA009 was a major soil group, about 40% of the total watershed area, where Tangi was a dominant soil type (Table 4.10).

Among the 12 sub-watersheds in the Tangipahoa River watershed (Figure 4.6B), Sub-watershed 4 was the largest one (285.48 km^2). Sub-watershed 8 was the smallest one (27.58 km^2). The average slope in most sub-watersheds was greater than 1% (Table 4.11). The average elevation in the sub-watersheds ranged from 14 m to 121 m. Similarly to the Amite and Tickfaw, the dominant land use in the Tangipahoa was forest, which was further divided into Mixed forest (28.5%) and Evergreen forest (25.7%). The second largest land use was agricultural land (39.1%) (Table 4.12). The largest soil group was MS107, 419.4 km^2 or about 25% of the total watershed area while the major soil type in this group was Ora (Table 4.13).

Table 4.8. Characteristics of sub-watersheds in the Tickfaw River watershed.

Sub-watershed	Area[b]	Len1[c]	Slo1[d]	Csl[e]	Wid1[f]	Dep1[g]	Elev[h]
	km^2	m	%	%	m	m	m
1[a]	112.94	23664	1.49	0.19	21.99	0.86	92
2	141.47	27231	1.38	0.22	25.18	0.94	74
3	43.21	15319	1.57	0.34	12.36	0.59	75
4	36.03	14887	1.12	0.30	11.08	0.55	75
5	54.08	14510	1.24	0.28	14.14	0.64	76
6	121.34	25934	1.02	0.24	22.96	0.89	60
7	73.50	21399	1.16	0.16	17.00	0.73	41
8	80.79	27478	0.34	0.11	17.99	0.75	18

[a]Sub-watershed number.
[b]Sub-watershed drainage area, delineated with BASINS 3.0 based on DEM data.
[c]Stream reach, longest path within the sub-watershed.
[d]Sub-watershed slope.
[e]Reach slope.
[f]Stream reach width.
[g]Stream reach depth.
[h]Elevation of the sub-watershed centroid.

Table 4.9. Major land cover types in the Tickfaw River watershed.

Code	Areas(km^2)	Percentage of total area (%)	Land use
FRSE	264.3	39.93	Forest_Evergreen
AGRL	206.2	31.15	Agricultural Land_Generic
FRST	176.8	26.70	Forest_Mixed
URMD	6.1	0.92	Redisential_Medium Density
Others	8.7	1.31	-

Table 4.10. Major soil types in the Tickfaw River watershed.

Muid[a]	Area (km^2)	Percentage of total area (%)	Soil type (largest in area)
LA009	265.8	40.07	Tangi
LA008	124.8	18.82	Ouachita
MS107	124.6	18.79	Smithdale
LA094	40.9	6.17	Myatt
Others	107.1	16.13	-

[a]Muid is STATSGO map unit identification code (USDA ARS, 1994).

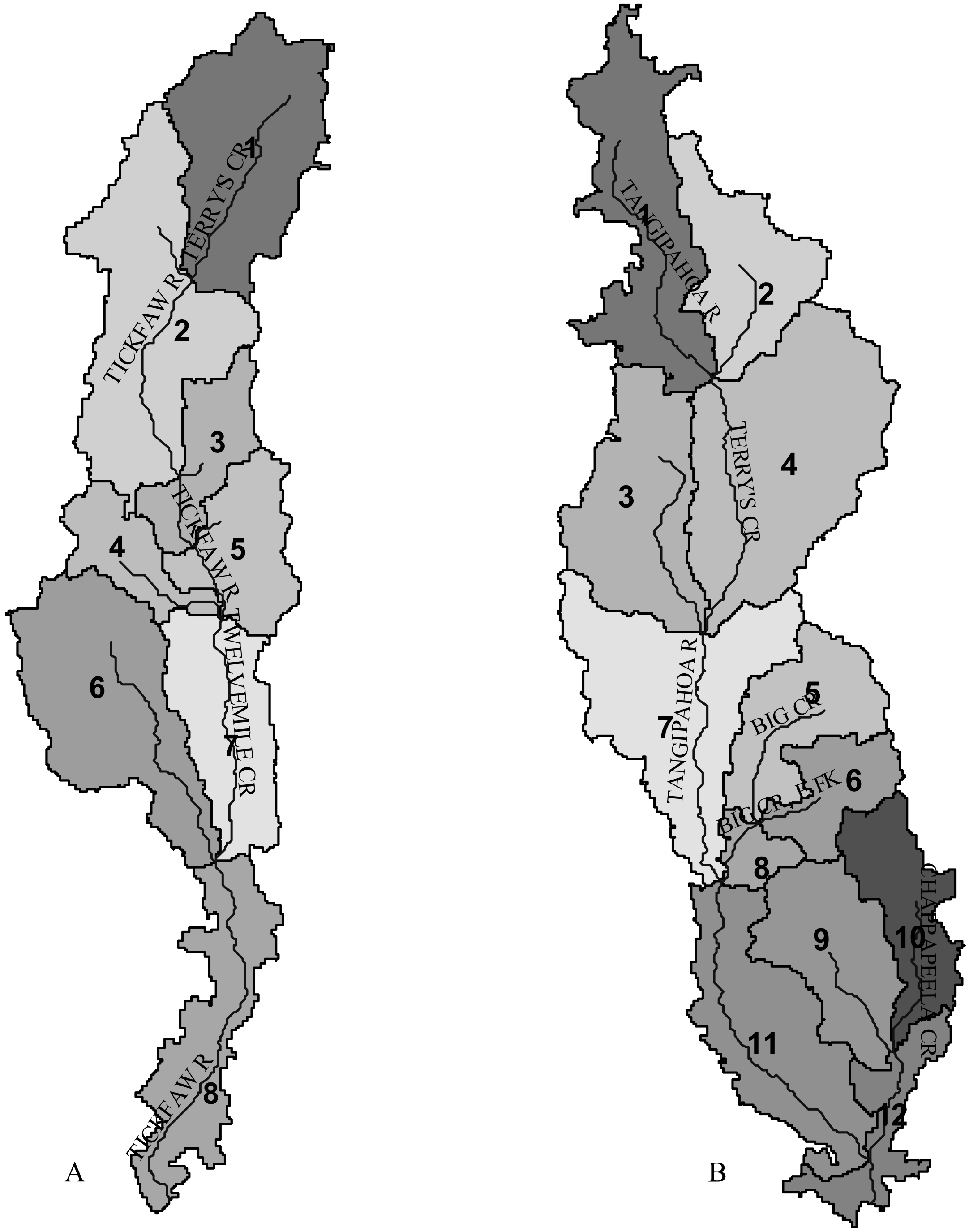


Figure 4.6. Delineated sub-watersheds in the Tickfaw River (A) and Tangipahoa (B) River watersheds.

Table 4.11. Characteristics of sub-watersheds in the Tangipahoa River watershed.

Sub-watershed	Area[b]	Len1[c]	Slo1[d]	Csl[e]	Wid1[f]	Dep1[g]	Elev[h]
	km^2	m	%	%	m	m	m
1[a]	189.93	42609.09	1.47	0.13	30.04	1.06	121
2	126.14	25246.31	1.53	0.23	23.50	0.90	118
3	169.84	32692.81	1.68	0.18	28.09	1.01	90
4	285.48	41533.35	1.45	0.15	38.37	1.25	76
5	113.46	23509.26	1.27	0.14	22.06	0.86	59
6	69.36	17900.07	1.10	0.17	16.42	0.71	58
7	228.01	37542.77	1.34	0.20	33.52	1.14	54
8	27.58	9470.80	1.49	0.43	9.44	0.49	65
9	126.64	21788.62	1.35	0.23	23.56	0.90	30
10	99.98	26430.27	1.29	0.21	20.44	0.82	50
11	177.78	33058.42	0.90	0.11	28.88	1.03	32
12	68.04	20824.85	0.56	0.17	16.23	0.70	14

[a]Sub-watershed number.
[b]Sub-watershed drainage area, delineated with BASINS 3.0 based on DEM data.
[c]Stream reach, longest path within the sub-watershed.
[d]Sub-watershed slope.
[e]Reach slope.
[f]Stream reach width.
[g]Stream reach depth.
[h]Elevation of the sub-watershed centroid.

Table 4.12. Major land cover types in the Tangipahoa River watershed.

Landuse	Area ($km^{2)}$	Percentage of total area (%)	Land use
AGRL	657.8	39.1	Agricultural Land_Generic
FRST	479.8	28.5	Forest_Mixed
FRSE	432.5	25.7	Forest_Evergreen
URMD	32.8	1.9	Redisential_Medium Density
WETF	20.2	1.2	Wetland_Forested
Others	58.9	3.5	-

Table 4.13. Major soil types in the Tangipahoa River watershed.

Muid[a]	Area (km^2)	Percentage of total area (%)	Soil type (largest in area)
MS107	419.4	24.9	Ora
LA108	265.3	15.8	Savannah
LA112	251.2	14.9	Toula
LA009	130.2	7.7	Tangi
MS096	116.3	6.9	Bude

[a]Muid is STATSGO map unit identification code (USDA ARS, 1994).

4.2.3.4 Calibration and Validation

Based on published studies with the SWAT model, sixteen model parameters were chosen for calibration in this study (Table 4.14). The parameters can be summarized in three categories: (1) parameters that govern surface water processes: curve number (CN), soil evaporation compensation factor (ESCO), plant uptake compensation factor (EPCO), available water capacity of the soil layer (SOL_AWC), and maximum canopy storage (CANMX); (2) parameters that control subsurface water processes: capillary coefficient from groundwater (GW_REVAP), groundwater delay (GW_DELAY), and deep aquifer percolation fraction (RCHRG_DP); and (3) parameters that influence routing processes: Manning's roughness coefficient in main channel routing (CH_N(2)) (Neitsch et al., 2001). The land cover data used in this study were obtained around year of 1980. Therefore, weather and discharge data from January 1, 1975 to April 30, 1978 were chosen for model calibration. The period from January 1, 1975 to December 31, 1975 was used as a warm-up period in order to set hydrologic processes to begin to come into equilibrium. Simulation results from January 1, 1976 to December 31, 1977 were used for evaluation of parameter calibrations. Parameter were optimized based on a deviation of daily discharge, coefficient of efficiency at both daily and monthly bases, and visual comparisons of the simulated and the measured daily discharge. In every run, only one parameter was adjusted while others were kept unchanged. And for each parameter, changes were made ten times within its allowable range to examine the model sensitivity to the parameter. Reiterations of optimization were taken until satisfactory results were met, which was based on graphical comparison and numeric evaluation of the simulated discharge against the measurements (see 4.2.3.5 Evaluation).

In the Amite River watershed, CH_N(2), Manning's roughness coefficient value for a main channel, was first changed from its default value 0.014 to 0.01 over all the sub-watersheds based on a preliminary test. CN values then were changed for two dominant land

Table 4.14. Major SWAT parameters used for calibration in the study[a].

Phase/parameters[b]	Spatial scale[c]	Range[d]	Default value[e]
Surface			
CN	HRU	35-98	59-92
SURLAG (days)	watershed	0-24	4
ESCO	watershed, HRU	0-1	0
EPCO	watershed, HRU	0.01-1	0
CANMX(mm)	HRU	0-100	0
CH_N(1)	watershed	0.01-30	0.014
OV_N	HRU	0.01-30	0.01-0.015
SOL_AWC(mm)	HRU	0-1	0.14-0.23[f]
Groundwater			
GW_DELAY(days)	HRU	0-500	31
ALPHA_BF(days)	HRU	0-1	0.048
GWQMN(mmH_2O)	HRU	0-5000	0
GW_REVAP	HRU	0.02-0.2	0.02
REVAPMN	HRU	0-500	1
RCHRG_DP	HRU	0-1	0.05
GWHT(m)	HRU	0-25	1.0
Channel routing			
CH_N(2)	watershed	0.01-0.3	0.014

[a]Source: Soil and Water Assessment Tool User's Manual, Version 2000 (Neitsch et al., 2001).
[b]Major hydrologic processes in SWAT and parameters used to define them.
[c]Spatial scales of parameters depend on how SWAT describes a specific hydrologic process.
[d]Range of calibratable parameters in SWAT were based on previous observations and literature.
[e]Default values depend on input information in a specific watershed.
[f]Only for soil layer 1.

covers, agricultural land (AGRL) and mixed forests (FRST), while holding optimum CH_N(2) value. And finally, RCHRG_DP (deep aquifer percolation fraction), GWQMN, ALPHA_BF, and ESCO (soil evaporation compensation factor) were also changed. In the Tickfaw River watershed, CN values were decreased proportionally at 5%, 10%, 15%, and 20% from the defaults. Deviation was increased from -37.11% to 2.17% when CN values were decreased by 10%. Then OV_N and CH_N(2)--Manning's roughness coefficient value

for overland flow and flow in main channels--were decreased to 0.01 from its default 0.1 and to 0.01 from its default 0.014, respectively. CANMX, canopy storage, was increased to 4 mm from its default value 0 for forest; RCHPG_DP and ESCO were also changed. In the Tangipahoa River watershed, GW_DELAY was tested from its default value 31 days up to 300 days. OV_N was increased to 2 from its default of 0.1 by 0.5, and CH_N(2) was also tested from 0.014 to 0.008. Referring to the parameter calibration in the Amite and Tickfaw River watersheds, canopy interception (CANMX) and soil evaporation compensation factor (ESCO) were also tested.

Daily discharge from January 1, 1979 to December 31, 1999 was used for validation of the SWAT model for the Amite River and Tangipahoa River. For the Tickfaw River, the validation was done by using the daily discharge data from January 1, 1979 to September 30, 1988 because of the data availability. Annual average runoff, monthly runoff, and monthly average runoff of both simulated and observed from 1979 to 1999 were calculated in the three watersheds. Monthly average ET, groundwater discharge from a shallow aquifer, and soil moisture content from 1979 to 1999 were also estimated by SWAT for the three watersheds.

4.2.3.5 Evaluation

Besides graphic comparison of the simulated discharge against the measured discharge, two numeric criteria were used to evaluate the modeling results: a deviation of discharge and a model coefficient of efficiency. The deviation of discharge (D) was calculated as follows:

$$D = \frac{Q_{usgs} - Q_{swat}}{Q_{usgs}} \times 100 \qquad (4.1)$$

where Q_{usgs} is the observed mean discharge and Q_{swat} is the simulated mean discharge for a specified period of time. In the modeling simulation, results were considered satisfactory when D was below 10% and excellent when D was less than 5%.

The model coefficient of efficiency (E) was estimated based on Nash and Sutcliffe (1970):

$$E = 1 - \frac{\sum_{i=1}^{n}(q_{usgs} - q_{swat})^2}{\sum_{i=1}^{n}(q_{usgs} - \overline{q_{mean}})^2} \qquad (4.2)$$

where q_{usgs} is the observed daily discharge (cms), q_{swat} is the simulated daily discharge (cms), and $\overline{q_{mean}}$ is the mean observed daily discharge (cms) during the evaluation period.

E is similar to a correlation coefficient obtained from a linear regression. However, E is to be compared to the measured values to the 1:1 line, in which measured values equals estimated values (perfect fit), rather than to the best-possible-fit regression line. In this study E was calculated for both daily (E, daily) and monthly intervals (E, monthly). Generally, the monthly coefficient of efficiency is higher than the daily coefficient of efficiency because averaging significantly decreases the variations among different days (Saleh et al., 2000; Van Liew and Garbrecht, 2003).

4.3 Results

4.3.1 Model Calibration

After calibration, the model performance was significantly improved. Deviations of the simulated mean discharge against the measurements (Eq. 4.1) were narrowed from -4.59% to -37.11% with the default parameters to -0.68% to 1.92% with the calibrated parameters in the three watersheds (Table 4.15). Daily coefficients of the model efficiency were improved to a

range of 0.834 - 0.926, compared to those obtained from the preliminary run with default parameters--0.542 to 0.815--for all three watersheds. Daily hydrograph plots between observed and simulated daily discharge also showed a significant improvement with calibration, in which a major discrepancy of a 1-3 days delay in peak flows was found in the preliminary simulation with default hydrologic parameters (Figure 4.7A and B).

Table 4.15. Evaluation of SWAT calibration in the three watersheds.

Watersheds	Simulation periods	D[a] (%)	E[b], daily	E, monthly
Amite	Jan.1, 1976-Dec.31, 1977 d[c]	-8.47	0.542	0.929
	Jan.1, 1976-Dec.31, 1977 c	1.25	0.926	0.935
Tickfaw	Jan.1, 1976-Dec.31, 1977 d	-37.1	0.815	0.771
	Jan.1, 1976-Dec.31, 1977 c	-0.68	0.902	0.940
Tangipahoa	Jan.1, 1976-Dec.31, 1977 d	-4.59	0.784	0.899
	Jan.1, 1976-Dec.31, 1977 c	1.92	0.834	0.960

[a]Deviation of discharge, see Eq. 4.1.
[b]Model coefficient of efficiency at daily and monthly basis, see Eq. 4.2.
[c]d: SWAT run with default parameters, c: SWAT run with calibrated parameters.

4.3.2 Model Validation

The SWAT model with the calibrated parameters was applied for the period of 1979-1988 for the Tickfaw River and for the period of 1979-1999 for the Amite and Tangipahoa rivers The modeling results showed an average water yield of 693.9 mm for the Amite River, 572.7 mm for the Tickfaw River, and 689.5 mm for the Tangipahoa River watersheds, respectively (Figure 4.8). Monthly coefficients of the model efficiency (*E*) were 0.851, 0.811, and 0.867 in the same order as above (Table 4.16).

Table 4.16. Evaluation of the SWAT validation in the three watersheds.

Watersheds	Simulation periods	D (%)	E, daily	E, monthly
Amite	Jan.1, 1979-Dec.31, 1999	-5.59	0.784	0.851
Tickfaw	Jan.1, 1979-Sep.30, 1988	1.49	0.713	0.811
Tangipahoa	Jan.1, 1979-Dec.31, 1999	0.21	0.689	0.867

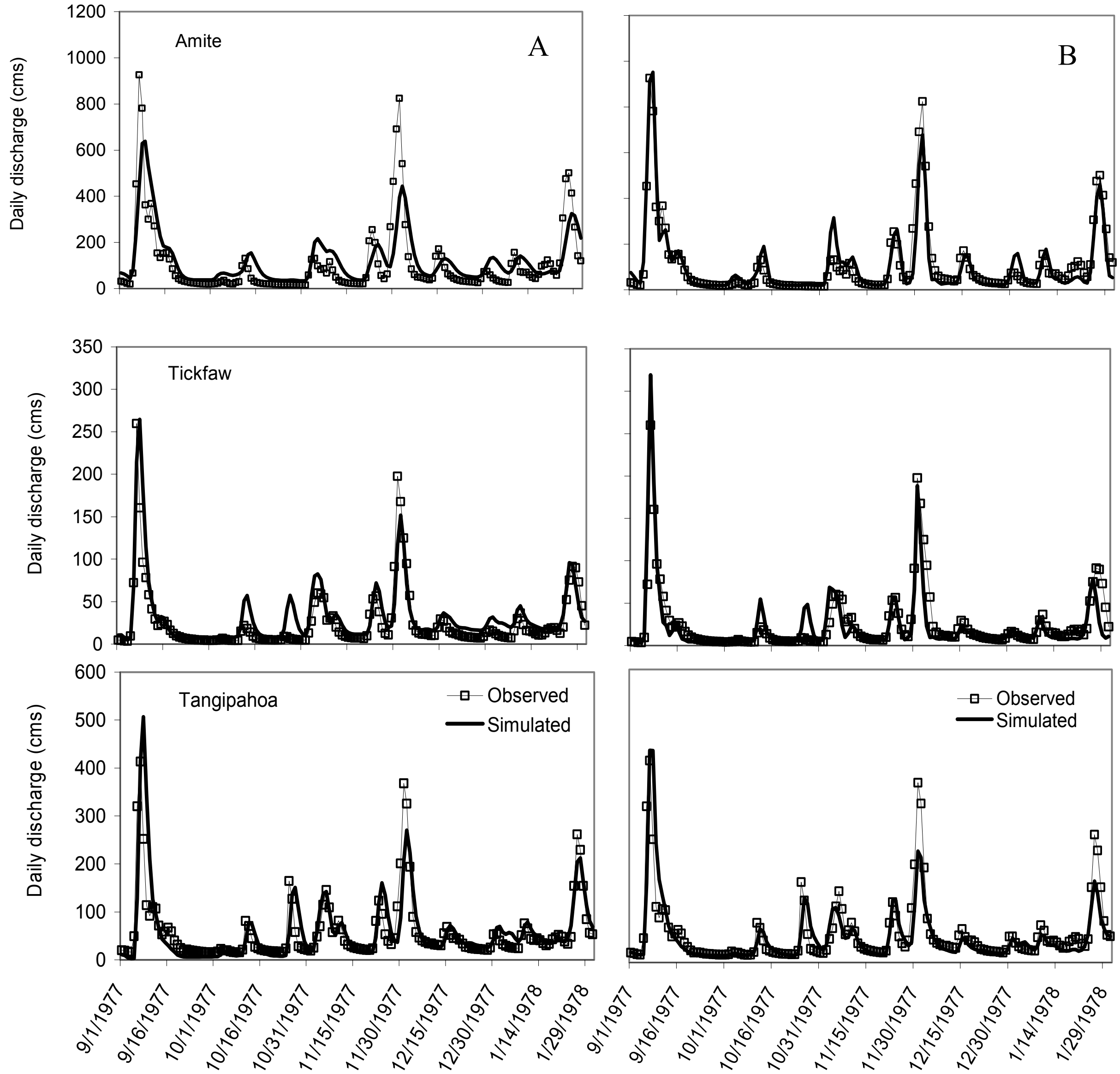


Figure 4.7. Comparison of observed daily discharge with simulated daily discharge using the SWAT default parameter values (A) and using optimized parameters (B) in the three coastal lowland watersheds.

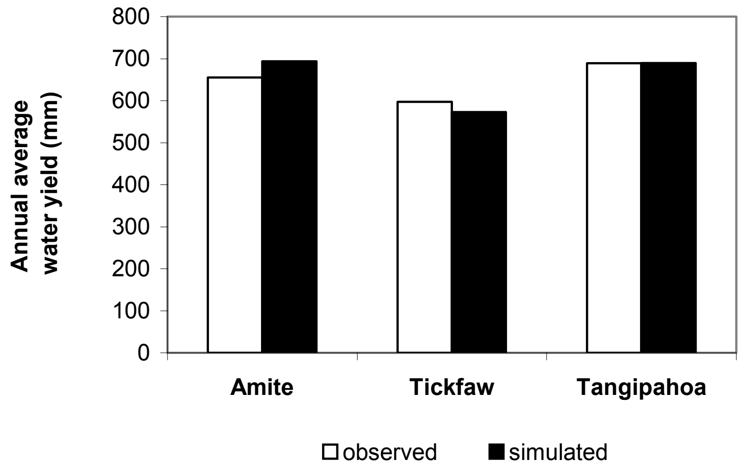


Figure 4.8. Comparison of annual average water yield between simulated (■) and observed (□) values in the Amite, Tickfaw, and Tangipahoa river watersheds.

4.3.3 Other Simulated Hydrologic Components

The simulation with SWAT has also produced the estimates of other relevant hydrologic components, including evapotranspiration, soil water content, and groundwater discharge. Simulated daily estimates were summed up to monthly and annual totals, and the long-term averages were presented in Table 4.17 and Figure 4.9. Modeled annual average ET ranged from 955 mm to 965 mm with highest in the Amite River watershed; estimated groundwater discharges among the three watersheds were from 207 mm to 246 mm with largest in the Tickfaw River watershed.

Table 4.17. Summary of simulated annual averages of water yield, ET, and groundwater discharge in the three watersheds.

	Amite	Tickfaw	Tangipahoa
Water yield (mm)	693.9	572.7	689.5
ET(mm)	965.4	961.9	955.3
Groundwater (mm)	206.8	246.4	223.3

4.4 Discussion

4.4.1 Model Calibration

A number of studies (Arnold and Fohrer, 2005; Chaubey et al., 2005; Chu and Shirmohammadi, 2004; Manguerra and Engel, 1998; Saleh and Du, 2004) have demonstrated that SWAT is capable to reproduce stream discharge under a wide variety of drainage basins and hydrological conditions. Manguerra and Engel (1998) also suggested that better simulation results might be obtained with a detailed calibration of one or two of the most sensitive parameters in the model. This study resulted in the same conclusion and showed much better performance after the parameter calibration. In this study, five hydrologic parameters have been found to be most critical for the model's performance in these coastal lowland watersheds. They were the Manning's roughness coefficient for a main channel (CH_N(2)), SCS curve number (CN), deep aquifer percolation fraction (RCHRG_DP), and soil evaporation compensation factor (ESCO) as given in Table 4.18. These results were in the agreement with the studies by Jha et al. (2003) and Van Liew and Garbrecht (2003).

For larger watersheds with a flat to gently rolling topography, simulation of discharge may have a time lag of several days compared to the observed values. This was clearly seen in this study and it was found that calibration of the routing parameter CH_N(2) was critical to eliminate the time lag. A slightly lower roughness value in the Tangipahoa River may have reflected the difference in channel geomorphology compared to those in the Amite and Tickfaw rivers. Critical roles of CH_N(2) in the SWAT simulations suggested a considerable difference in topography, stream-channel geomorphology, and riparian vegetations between Southeastern lowland watersheds and those in other regions (Stone et al., 2003; Hotchkiss et al., 2000; Stonefelt et al., 2000; Vache et al., 2002). Different values of RCHRG_DP between

the two larger watersheds--the Amite and Tangipahoa--and the smaller watershed--Tickfaw--may suggest an importance of watershed size and geometry in water movement through the soil profile and shallow aquifer. ESCO was related to soil moisture depletion for evaporation demands. The optimized value of 0.9 in all three watersheds might indicate site-specific

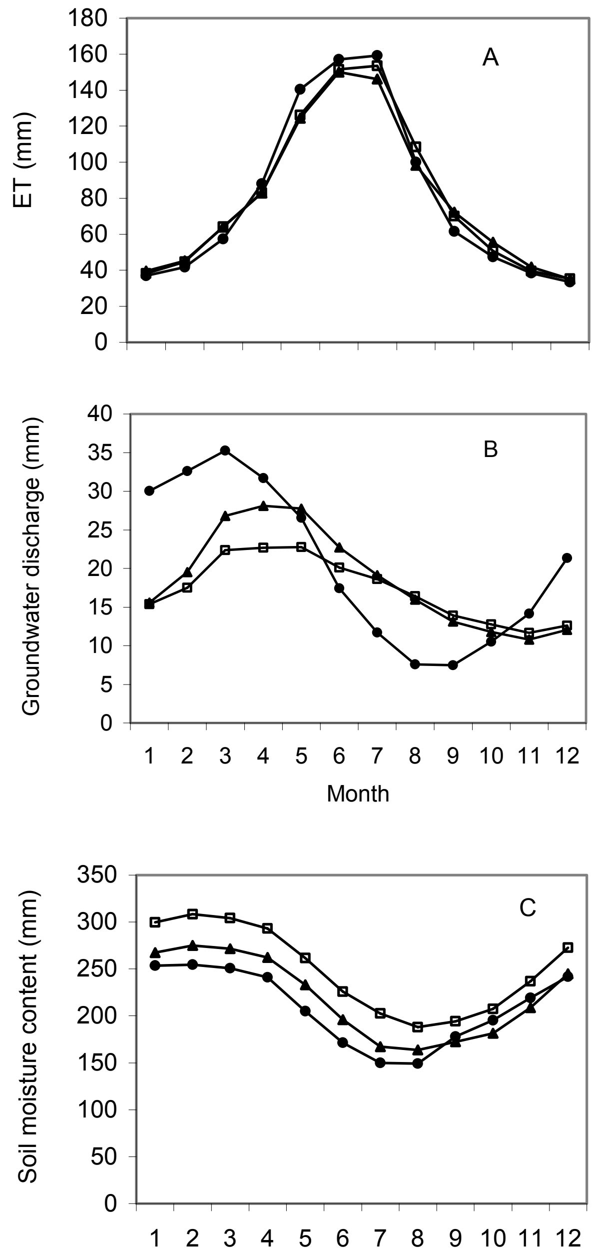


Figure 4.9. Simulated monthly ET (A), groundwater discharge (B), and soil moisture content (C) in the Amite (-□-), Tickfaw (-•-), and Tangipahoa (-▲-) river watersheds.

Table 4.18. Optimum parameters for the SWAT model in the three watersheds[a].

Parameters	Amite	Tickfaw	Tangipahoa
CH_N(2)[b]	0.01	0.01	0.008
RCHRG_DP[c]	0.6	0.6	-
GW_DELAY[d] (days)	150	-	150
CANMX[e] (mm)	4 for forests	4 for forests	4 for forests
ESCO[f]	0.9 for all HRUs	0.9 for all HRUs	0.9 for all HRUs
CN[g]	-	-10%	-
	-	66 (FRST/MS107)	-
	-	75 (AGRL/LA009)	-
	-	63 (FRSE/LA009)	-
	-	63 (FRSE/LA009)	-
	-	63 (FRSE/LA009)	-
	-	63 (FRSE/LA009)	-
	-	75 (AGRL/LA009)	-
	-	69 (FRSE/LA094)	-

[a]Source: Soil and Water Assessment Tool User's Manual, Version 2000 (Neitsch et al., 2001).
[b]Manning's roughness coefficient.
[c]Deep aquifer percolation fraction.
[d]Delay time for aquifer recharge.
[e]Maximum canopy storage.
[f]Soil evaporation compensation factor.
[g]Curve number, a parameter used in the SCS curve number method in estimation of surface runoff.

features in the lowland Louisiana. CN values were found to be sensitive in the three watersheds as other studies also suggested (Jha et al., 2004; Van Liew and Garbrecht, 2003). However, default CN values, which were automatically determined by the SWAT model, well represented watershed characteristics in both the Amite and Tangipahoa river watersheds. Only 10% decreases in CN values were needed in the Tickfaw River watershed. This result indicates a reliability of the method in determining CN values based on land cover and soil types in the studied areas.

However, there were still storm events, for instance, which occurred in October 1977 in both the Amite and Tickfaw rivers, could not be simulated satisfactorily. The results suggested that within a short period of time such as months, uncertainty in the discharge prediction with the SWAT model might be high. In certain storm events, spatial variations

and measurement errors in precipitation and human-induced disturbances within the watersheds and channels might be other possible reasons for the poor fits.

4.4.2 Model Validation

The results showed an estimation error of 5.6% in the Amite River watershed, 4.3% in the Tickfaw River watershed, and less than 1% in the Tangipahoa River watershed. The monthly model coefficients of efficiency (E) between the long-term observed and simulated discharge were high: 0.851, 0.811, and 0.867 for the Amite, Tickfaw, and Tangipahoa river watersheds. Compared to other modeling studies with SWAT (e.g., Chu and Shirmohammadi, 2004; Saleh and Du, 2004), the simulation results from this study showed a good model fitting for the coastal watersheds (Figure 4.10).

In this study, however, underestimations in discharge during the winter months were witnessed for all the three watersheds. This was also found by Arnold et al. (2000). Analyses with a long-term monthly average runoff during the validation periods indicated temporal variations of simulation errors among the three watersheds. In the Amite River, the SWAT simulation underestimated monthly runoff during January and February, while in summer and fall, it overestimated monthly runoff. In the Tickfaw and Tangipahoa rivers, however, the simulations were much closer to the observed monthly runoff during summer and fall, though it still underestimated the monthly runoff during winter months (January and February) (Figure 4.11).

One of the reasons for the discrepancy might be an overestimated PET with the Hargreaves model, which may have resulted in a higher ET and, therefore, the simulated monthly runoffs were lower than the observed values during the winter months. Another possible reason of the discrepancy may be an outside groundwater source in the watersheds.

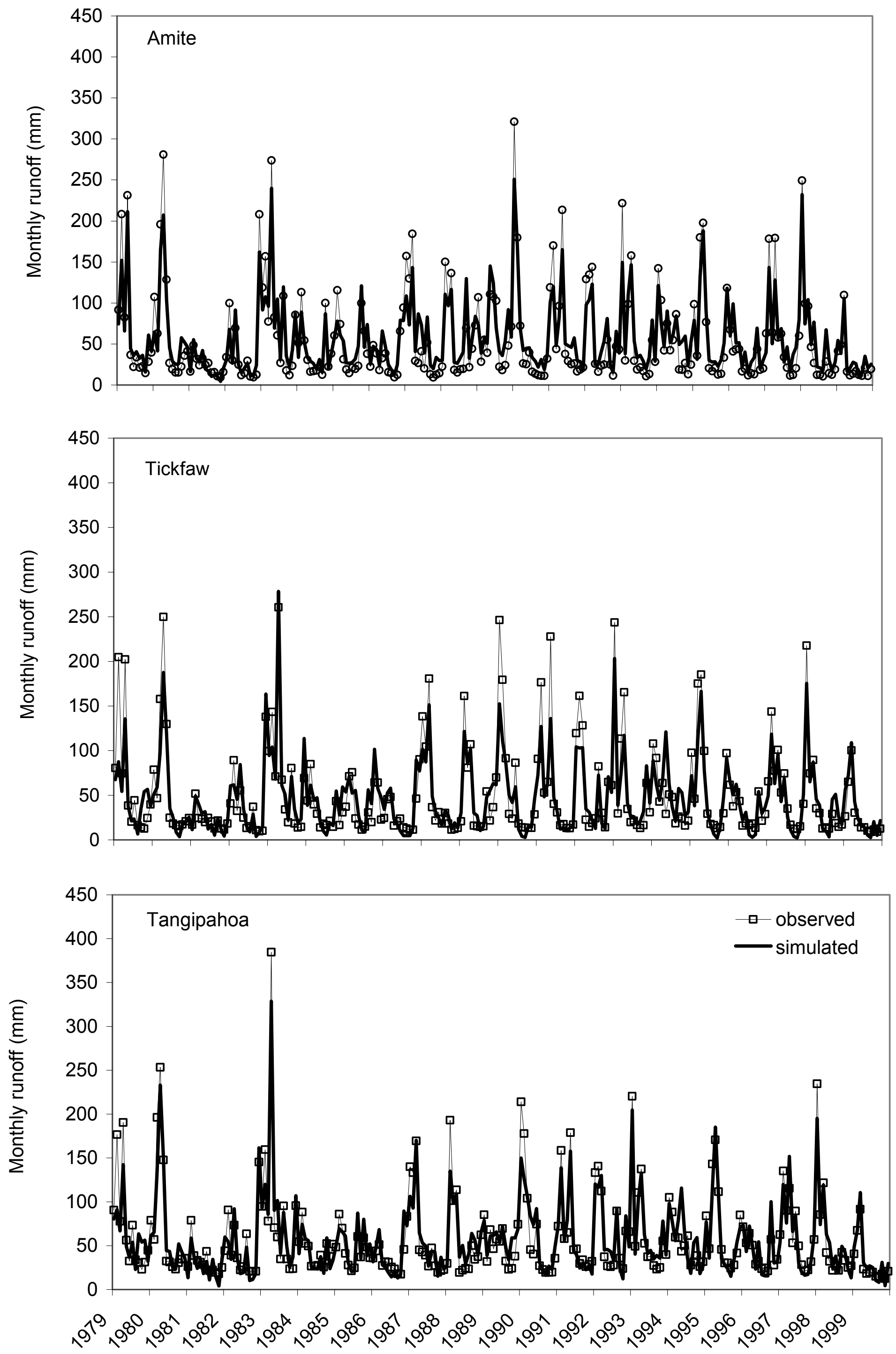


Figure 4.10. Comparison between observed and simulated monthly runoff in the three coastal lowland watersheds for the validation period from 1979 to 1999.

In a 3.4 km^2 watershed in the Piedmont of Maryland, Chu and Shirmohammadi (2004) found that SWAT underestimated subsurface flow and total streamflow, especially during the period from winter to early spring. The authors speculated a considerable groundwater contribution from outside the watershed. Studies have showed that along with increasingly greater urbanized watersheds, more precipitation would become surface runoff and less would percolate into aquifers due to lower infiltration volume, decreasing baseflow during summer and fall months (Shaw and Shaw, 1998). Compared to other two watersheds in this study, the Amite River watershed has been experiencing the most intensive development of urbanizations and hydrologic alterations over the past half century (Autin and Mossa, 1997). During summer and fall months, the overestimation of runoff over the validation period in the Amite River might imply a significant change in land use and land cover from vegetated watersheds to urbanized areas. It might also suggest a possible impact of land use practices on hydrologic cycles in the region. Furthermore, the results imply that for a long-term hydrologic simulation with the SWAT model, multiple temporal land use data were necessary to obtain more accurate estimates, especially in those areas that have experienced fast land use changes.

4.4.3 Relevant Hydrologic Components

In addition to runoff, the SWAT model can also estimate other relevant hydrologic components such as ET, groundwater discharge, and soil moisture content for the studied watersheds. The simulation showed that annual average ET was highest in the Amite River watershed and lowest in the Tangipahoa River watershed. Annual groundwater flow was highest in the Tickfaw River watershed and lowest in the Amite River watershed. Annually, groundwater contribution to streamflow was 29.7% in the Amite River and higher in the Tangipahoa River (32.2%) and the Tickfaw River watersheds (43.1%).

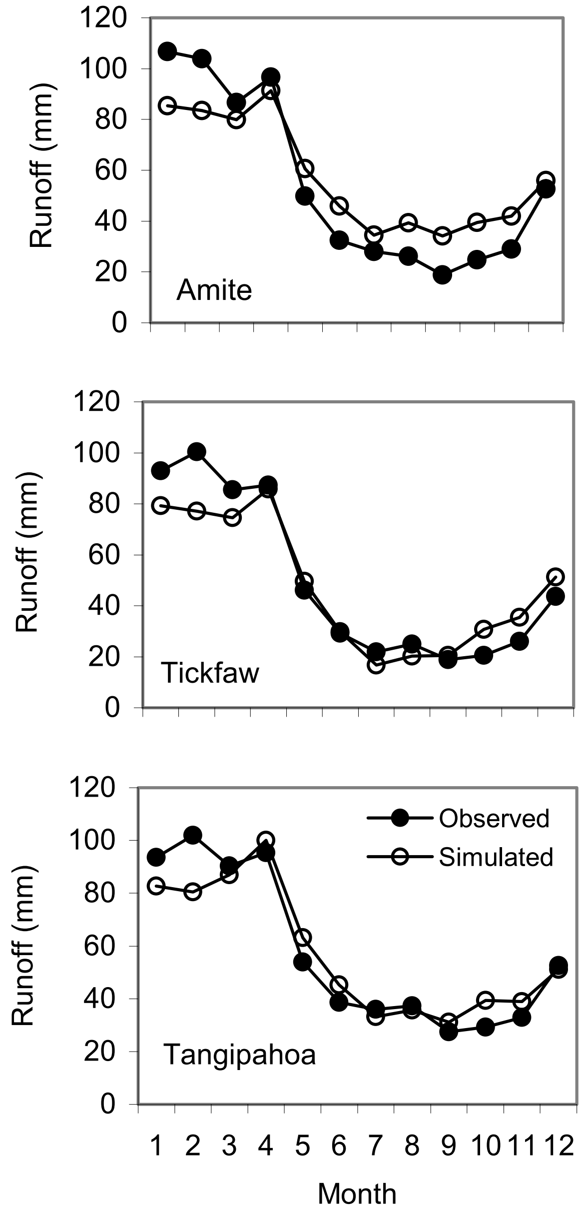


Figure 4.11. Comparison of between observed and simulated monthly averages of runoff in three coastal lowland watersheds.

A seasonal change of groundwater discharge indicated that contribution from a shallow aquifer to streamflow was higher in spring months than that in later summer and fall, although relatively higher proportions of baseflow contribution were found during summer than other seasons among the three watersheds (Figure 4.9B).

Soil moisture contents in the three watersheds also showed a clear seasonal pattern. Soils were driest in August and wettest in the spring months (February and March). Soil moisture contents in the Amite River and the Tangipahoa River watersheds showed a similar seasonality, except that the soil moisture contents in the Amite River watershed were generally about 30 mm higher than those in the Tangipahoa River watershed. Soil moisture contents in the Tickfaw River watershed were low during most months of the year, compared to those in the Amite and Tangipahoa river watersheds. However, it became slightly higher than that in the Tangipahoa from September to November. This change might be related to low CN values, which would result in more infiltration of precipitation into the soil profile in the Tickfaw River watershed (Figure 4.9C).

CHAPTER 5. HYDROLOGIC RESPONSES OF THE LAKE PONTCHARTRAIN DRAINAGE BASIN TO POTENTIAL CLIMATE CHANGE

5. 1 Introduction

Sustainable water resources management is critical in an increasingly changing socioeconomic and natural environment (Baron et al., 2002; Doll et al., 2003). An essential aspect of the sustainability in water resources management is its capability of anticipation in future changes and potential impacts (Loucks, 2000). Because sustainability is a function of various economic, social, environmental, ecological, and physical objectives, these changes, which involved in sustainable water resources and environmental management, should include both anthropogenic and natural variables.

Induced by population growth, industrialization, and natural processes, climate has changed. Historical records show that the surface temperature has increased by about 0.6 ± 0.2 ^{o}C since the beginning of the 20th century (IPCC, 2001). Potential climate change scenarios in the United States have been summarized in the National Assessment of Climate Change Impacts on the United States (Mulholland et al., 1997; Burkett et al., 2000). Based on the national assessment, the following major potential climate changes for Southeastern U. S. are anticipated: (1) an increase in air temperature, (2) a large uncertainty in precipitation pattern, and (3) an increased frequency of both hot and dry conditions and precipitation intensity (Ritschard et al., 1999). Since 1988 when the Intergovernmental Panel on Climate Change (IPCC) was founded, future climate changes and their potential impacts on the availability of freshwater and hydrologic processes have been a public concern (Frederick and Major, 1997; Gleick and Adams, 2000; Jackson et al., 2001).

To assess the impacts of potential climate changes, hydrologic models are often used together with climate model projections and specified incremental temperature and precipitation changes. Several studies have been done in the assessment of potential climate changes on hydrologic processes at the river basin scale. Knowles (2000) reported a 3 km^3 shift of streamflow from post-April to pre-April with a 2.1°C temperature increase in the northern California watershed. The author also found that a peakflow in April was accompanied by a reduced streamflow in the subsequence months. While air temperature was projected to affect the timing of streamflow, precipitation was described as an influential variable on water yield (Stonefelt et al., 2000). For instance, Jha et al. (2004) estimated that in the Upper Mississippi River basin, a 21% increase in projected precipitation would result in a 51% increase in surface runoff and 50% increase in total water yield.

Although there is an increasing number of studies on climate change impacts on hydrologic responses, few have been done in the subtropical and Gulf of Mexico coastal region. As two oligohaline lakes located in Southeastern Louisiana, Lake Maurepas and Lake Pontchartrain together constitute the largest contiguous estuarine zone in the Gulf States (Tarver and Savoie, 1976). The entire Lake Pontchartrain drainage basin is a 12,170 square kilometer watershed encompassing 16 parishes in southeast Louisiana and four counties in Mississippi. Nearly 1.5 million people live around the 1,619 square kilometer lake, which supports numerous species of fish, birds, mammals, and plants. Higher physiographical diversity and habitats not only lead to higher biodiversity but also result in an intensive interaction between terrestrial and estuary ecosystems. Over the past sixty years, fast population growth, intensive hydrologic alterations, and increasingly frequent extreme storm events in the region, along with subsidence and sea level rise, have resulted in a significant

environmental degradation (Day et al., 2000; Turner and Boyer, 1997). Climatic variability in the region has directly or indirectly affected the estuarine ecosystem. For instance, if streamflow from urban and agriculture areas increases under climate change scenarios, more fertilizers and pollutants will most likely enter into coastal waters, increasing the risk of eutrophication. Any changes in rainfall, surface runoff, and groundwater recharge may significantly impact freshwater inflow to and salinity in Lake Pontchartrain, which may influence estuarine habitat, productivity and ecosystems. Recently, Brammer et al. (2004) observed a rapid increase in mussels--a serious pest to Louisiana oyster products--in Lake Pontchartrain. The authors found that density, size and distribution of these hooked mussels were associated with reduced rainfall in the region and increased salinity in the waters. Studies showed that swamp forests in Falgout Canal and brown marsh in coastal Louisiana were attributed to the decreased freshwater runoff and raised sea-level (Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority, 1998), although these specific reasons are still not clear.

Therefore, quantitative estimates of hydrologic sensitivity in coastal watersheds and knowledge of hydrologic responses to potential climate changes are essential for understanding an intrinsic relationship among climatic, terrestrial, aquatic and estuarine ecosystems and helping in environmental restoration efforts in the Gulf Coastal regions. The objectives of this study were to:

1) Investigate hydrologic sensitivities of the upper Lake Pontchartrain basins to projected changes in air temperature and precipitation for the region; and
2) Examine seasonality of monthly water yield, ET, and soil moisture contents under such climate change scenarios.

5.2 Methodology

5.2.1 Study Area

Comprised of the Amite, Tickfaw, and Tangipahoa river watersheds, the study area is located in the upper stream watershed to Lake Pontchartrain, Southeastern Louisiana (Figure 5.1). With a total area of 8,728 km^2, the region is geographically located between 30-31°N and 90-91.5°W. The longest river is the Amite, 270 km long, with a drainage area of 4822 km^2 (Vernon et al., 1992). The daily mean discharges are 59.0 $m^3\ s^{-1}$, 10.9 $m^3\ s^{-1}$, and 32.9 $m^3\ s^{-1}$ in the Amite, Tickfaw, and Tangipahoa rivers, respectively. Topography is relatively flat, ranging from 0 m in the downstream to 150 m in the upper stream watersheds. Forest and agriculture are two dominant land use types, while the Amite River watershed has the largest urban area (Table 5.1).

Table 5.1. Land use categories in the three watersheds.

Land category	Amite		Tickfaw		Tangipahoa	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Watershed area (km^2)[a]	3434.9	100	662.2	100	1682.3	100
Agricultural land	1201.9	34.9	206.5	31.2	657.8	39.1
Evergreen forest	766.3	22.3	264.4	39.9	432.5	25.7
Mixed forest	1055.9	30.7	176.9	26.7	479.2	28.5
Deciduous forest	193.7	5.6	0	0	8.9	0.5
Forested wetland	17.5	0.5	5.7	0.8	20.2	1.2
Water	4.2	0.1	0.1	0.0	3.9	0.2
Urban[b]	182.1	5.3	7.4	1.1	70.7	4.2
Others	14.4	0.6	1.2	0.3	9.1	0.6

[a]Delineated watershed area, corresponding to a downstream USGS gauge station.
[b]Urban land category was combined with commercial, industrial, transportation and residential lands.

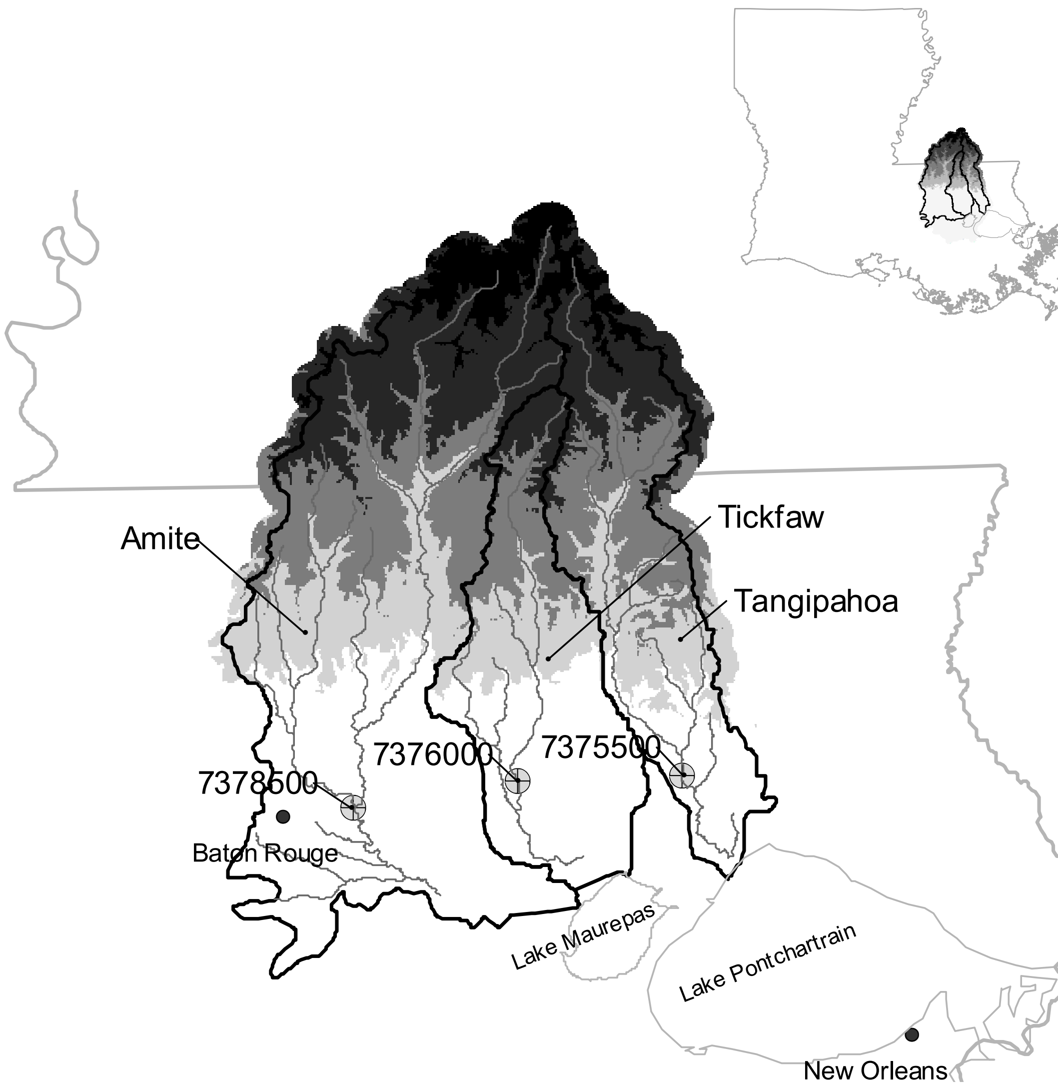


Figure 5.1. Locations of the Amite, Tickfaw, and Tangipahoa river watersheds. Three USGS gauge stations used for SWAT calibration and validation are shown with a shaded circle with a plus sign.

5.2.2 Modeling and Data Analysis

With the calibrated parameters (see Chapter 4), the SWAT model was used to test hydrologic sensitivities of the three coastal watersheds to projected climate change scenarios. The SWAT simulation was achieved using the daily precipitation and temperature data from January 1, 1975 to December 31, 1988. Hydrologic sensitivity was calculated by using the data from January 1, 1979 to December 31, 1988. The data from January 1, 1975 to December 31, 1978 were applied for the system equilibrium. Daily water yield, evapotranspiration (ET), and soil water content at a subwatershed scale were simulated for each of the three watersheds**.** The daily average value at the watershed scale for each of the three hydrologic components was calculated based on an area-weighted method. Then a ten-year annual average of water yield and ET were calculated. The change rates of annual average water yield and ET between the baseline historical climatic condition and climate change scenarios were calculated with the following equation:

$$Change\_rate(\%) = \frac{Y_b - Y_{sc}}{Y_b} \times 100 \qquad (5.1)$$

where Y_b is a simulated annual water yield or ET with baseline climatic data, Y_{sc} is a simulated annual water yield or ET with climate change scenarios data. A ten-year average of monthly water yield, monthly ET, monthly soil moisture content, and their change rates between the baseline conditions and climate change scenarios were also estimated.

5.2.3 General Concept

Climate change impacts on hydrology are usually assessed by defining climate scenarios from the outputs of general circulation models (GCMs). These scenarios, then, were used as inputs to a hydrologic model. Based on equilibrium of a doubled CO_2 concentration in

the atmosphere, future global climate patterns have been predicted by various GCMs (IPCC, 2001). Two widely used GCMs are the Hadley Model (HADCM2) and the Canadian Model (CANM). The HADCM2 was developed by the Hadley Centre for Climate Prediction and Research of the Meteorological Office of the United Kingdom (Johns et al., 1997). The CANM was developed by the Canadian Centre for Climate Modeling and Analysis. Predictions by the GCMs are mostly based on a spatial grid of 400×500 km (4-5^{o} latitude and longitude), while a manageable scale of watersheds generally is within 100×100 km. Therefore, assessments of climate change impacts at a watershed scale are rarely based on direct outputs from the GCMs alone.

Downscaling of GCM outputs to so-called regional climate models (RCMs) is needed to generate high-resolution climate change scenarios. In downscaling, GCM outputs were used as inputs to regional climate models in which detailed meteorological and hydrological processes were captured (Giorgi and Mearns, 1991; Giorgi et al., 1998). Even with complicated downscaling methods, uncertainties and disagreements among different models still remain. Consequently, a range of climate scenarios is usually considered in impact assessments; that is, a range of arbitrary changes of climate variables, which cover most possible projections of air temperature and precipitation from widely used GCMs and RCMs, would be utilized (Chiew et al., 1995). This approach has been used by Fontaine et al. (2001) for the Black Hills of South Dakota, U.S., Guo et al. (2002) for continental China, Stonefelt et al. (2000) for the Upper Wind River basin in Wyoming, U.S., and by Chiew et al. (1995) in Australia. Because the purpose of this study is to determine the hydrologic sensitivity to potential climate change rather than to compare variations from climate change projection models, this approach was adapted for the study.

Giorgi et al. (1994) developed regional climate change scenarios over the U.S. using a nested RCM (the NCAR/Penn State mesoscale model) driven by a modified version of the NCRA Community Climate model. The temperature and precipitation outputs from the RCM were presented in two formats: as regional averages and as contour maps for the continental U.S. Their results indicated that in the Southeast U.S. projected climate change scenarios would involve an annual average increase of 3.3 ^{o}C in temperature, with an increase of 4.2 ^{o}C in cold months and 2.2 ^{o}C in warm months. Therefore, an annual air temperature increase of 3.3 ^{o}C was used in this study. In order to detect hydrologic responses to a gradual temperature change, a 1.6 ^{o}C increase in annual air temperature was also used. In addition to temperature, Giorigi et al. (1994) also projected -50% to +50% changes in precipitation in the Southeast. However, another study based on the HADCM2 model (Ritschard et al., 1999) suggested a general pattern of significant reductions in precipitation for the Gulf Coastal region. Ritschard and his colleagues predicted that in the next 20-40 years, water availability along the coast between 30^{o} to 33^{o}N would decline as much as 10% during January to June; and increase as much as 9% from July to December. Considering higher uncertainty in precipitation projections and the historical pattern of long-term annual precipitation in the region, scenarios assuming both a 10% and a 20% increase in annual precipitation were used in this study. In order to understand an interactive impact from both elevated air temperature and increase precipitation, a 1.6 ºC increase in air temperature and a 10% increase and decrease in precipitation were adopted for this study. Frequency and severity of extreme weather, such as heavy rainfall events, were projected to increase in the Southeastern U.S., although heterogeneity within the region existed (Muller and Grymes, 1997). Therefore, a heavy rainfall of 200% increase in precipitation in April was used in this study.

5.2.4 Climate Change Scenarios

In this study seven climate change scenarios were projected: (1) a 1.6 ^{o}C increase in annual air temperature (+1.6 ^{o}C), (2) a 10% increase in annual precipitation (+10%), (3) a 3.3 ^{o}C increase in annual air temperature (+3.3 ^{o}C), (4) 20% increase in annual precipitation (+20%), (5) a 1.6 ^{o}C increase in annual air temperature plus a 10% increase in annual precipitation (+1.6 ^{o}C and +10%), (6) a 1.6 ^{o}C increase in annual air temperature plus a 10% decrease in annual precipitation (+1.6 ^{o}C and -10%), and (7) a 200% increase in precipitation in April (+200%) (Table 5.2).

Baseline climatic data from 1975 to 1988 were used in this study. Daily precipitation and daily maximum and minimum air temperatures were collected from the NOAA National Climatic Data Center (NCDC). Daily air temperature for each climate change scenario was created by adding temperature differences to daily historical data. Daily precipitation for each climate change scenario was adjusted by a different ratio to daily historic data. Daily relative humidity, solar radiation, and wind speed used in the simulation were from the SWAT generating model.

Table 5.2. Climate change scenarios of air temperature (T) and precipitation (P).

Scenarios	T(^{o}C)	P (%)	Note
Baseline	-	-	Observed historical data.
Scenario 1	+1.6	-	Ratio in precipitation and differences in air temperature were added into daily historic data to make different climate scenarios.
Scenario 2	-	+10	
Scenario 3	+3.3	-	
Scenario 4	-	+20	
Scenario 5	+1.6	+10	
Scenario 6	+1.6	-10	
Scenario 7	-	+200	Extreme event in April only.

5.3 Results

5.3.1 Hydrologic Sensitivity to an Elevated Air Temperature

5.3.1.1 Annual Water Yield and ET

The simulation showed that annual water yield decreased from 666.4 mm to 657.1 mm under Scenario 1 (1.6 ^{o}C annual air temperature increase) and to 653.4 mm under Scenario 3 (3.3 ^{o}C annual air temperature increase) in the Amite River watershed. In the Tickfaw River watershed, annual water yield decreased from 551.6 mm to 543.5mm and to 543.3 mm under Scenario 1 and Scenario 3, respectively. In the Tangipahoa River watershed, annual water yield decreased from 657.2 mm to 639.7 mm and to 638.2 mm under Scenario 1 and Scenario 3, respectively. Annual average ET increased to 985.9 mm in Scenario 1 and to 991.6 mm in Scenario 3 from the 975.6 mm baseline data in the Amite River watershed. Annual average ET increased from 964.7 mm to 975.1 mm and to 977.4 mm in the Tickfaw, and increased to 977.3 mm and to 978.5 mm from 958.8 mm in the Tangipahoa in Scenario 1 and Scenario 3, respectively (Figure 5.2). A larger decreased rate in annual water yield and a greater increased rate in annual ET were found in the 3.3 °C temperature increase scenario (Table 5.3).

5. 3.1.2 Seasonality of Water Yield, ET, and Soil Moisture

Seasonal patterns were found in monthly water yield, ET, and soil moisture contents in the three watersheds (Figure 5.3). The largest decrease rate in monthly water yield occurred in June in both Scenarios 1 and 3. For instance, in Scenario 3, 10.0%, 16.6% and 18.9% of decrease rates in monthly water yield were found in the Amite, Tickfaw, and Tangipahoa river watersheds, respectively.

Monthly ET increased during the first half of the year, but decreased during the second half of the year, with one exception that occurred in September in the Tickfaw and

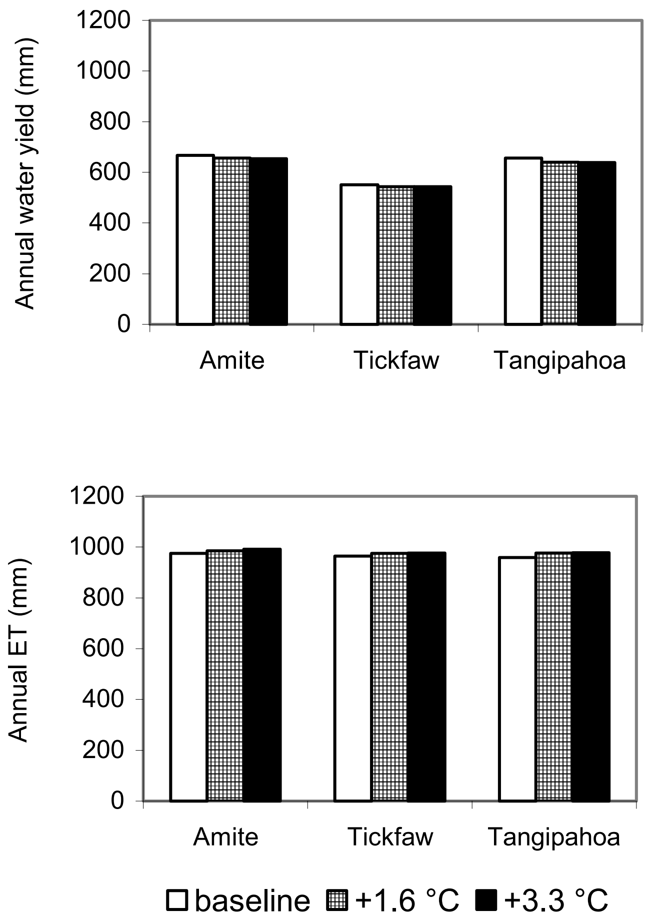


Figure 5.2. Comparison of long-term annual average of water yield in baseline, 1.6 ºC (Scenario 1) and 3.3 ºC (Scenario 3) increase in air temperature scenarios in the Amite, Tickfaw, and Tangipahoa river watersheds.

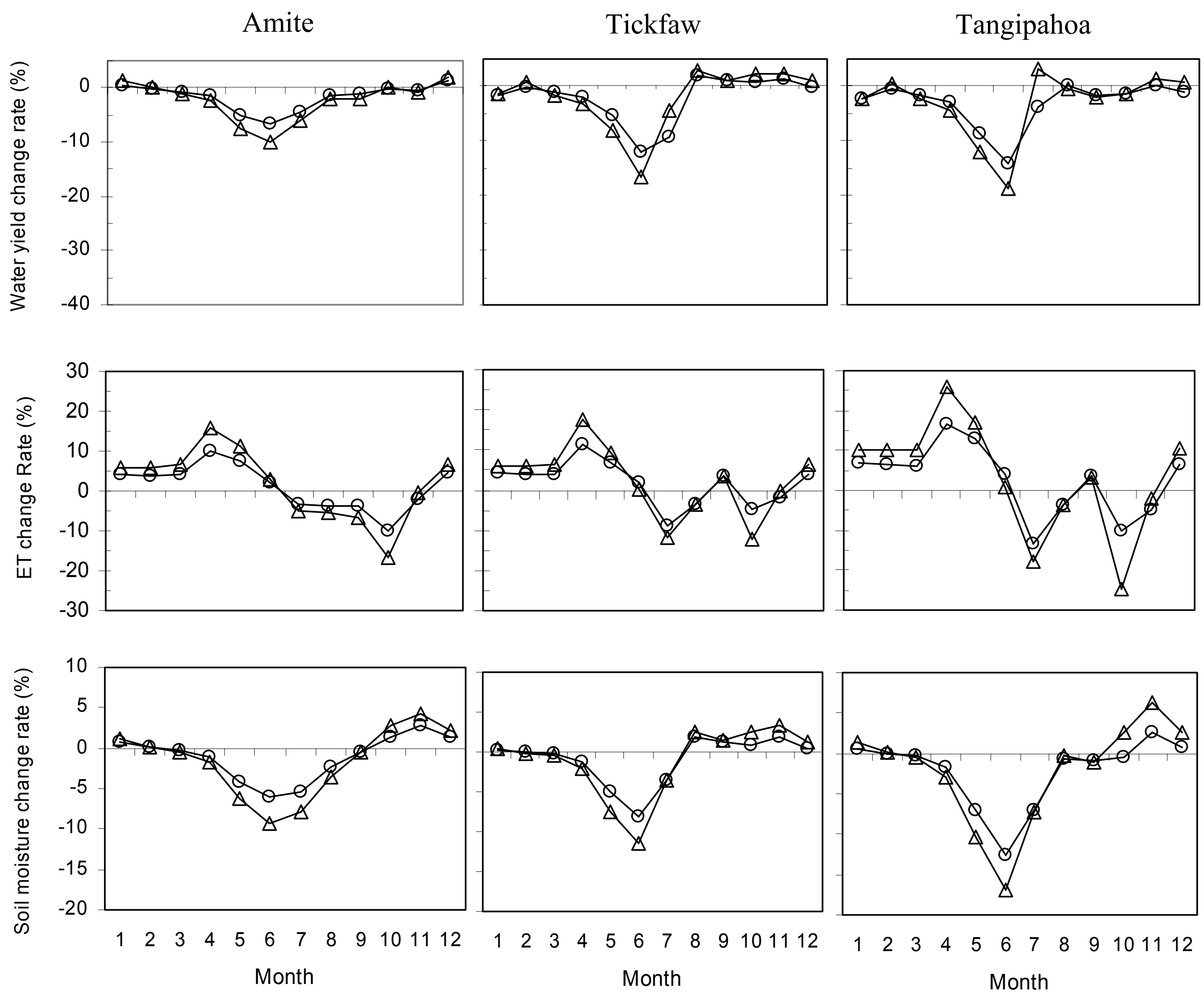


Figure 5.3. Seasonal patterns of change rates in monthly water yield, ET, and soil moisture with 1.6 ºC increase in air temperature (-o-) and 3.3 ºC increase in air temperature (-Δ-) scenarios in the Amite, Tickfaw, and Tangipahoa river watersheds.

Table 5.3. Change rates of ten-year annual average water yield and ET with 1.6 °C and 3.3 °C annual air temperature increase scenarios in the Amite, Tickfaw, and Tangipahoa river watersheds.

Watershed	Scenarios	Rate[a] (%)	Rate[b] (%)
Amite			
	baseline	-	-
	+1.6 °C	-1.4	1.1
	+3.3 °C	-1.9	1.6
Tickfaw			
	baseline	-	-
	+1.6 °C	-1.5	1.1
	+3.3 °C	-1.5	1.3
Tangipahoa			
	baseline	-	-
	+1.6 °C	-2.3	1.9
	+3.3 °C	-2.9	2.1

[a]Change rate for annual water yield, see Eq.5.1.
[b]Change rate for annual evapotranspiration (ET), see Eq.5.1.

Tangipahoa river watersheds, when the change rates increased. The largest increase rates occurred in April.

In Scenario 3, the change rates of monthly ET were 15.9%, 17.5% and 25.9% in the Amite, Tickfaw and Tangipahoa river watersheds, respectively.

Under the baseline conditions (i.e., natural conditions), the highest monthly ET occurred in July in the Amite River (155.4 mm), and in June in both the Tickfaw River (160.4 mm) and Tangipahoa River watersheds (151.7 mm). But, under the projected climate change scenarios 1 and 3, the highest monthly ETs in the Amite occurred in June (154.8 mm and 156.4 mm), a month earlier than that in the baseline condition (Figure 5.4). In the Tickfaw and Tangipahoa, the highest monthly ET in both Scenarios 1 and 3 occurred in the same month as those in the baseline condition. Monthly soil moisture showed a similar trend as monthly water yield, with the largest decreased rates in June.

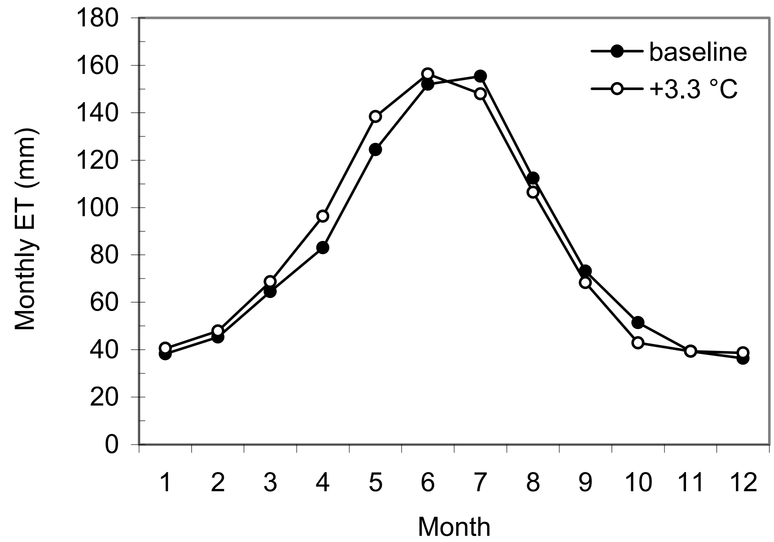


Figure 5.4. Seasonal patterns of monthly ET in the baseline (-•-) and a 3.3 ºC air temperature increase scenario (-o-) in the Amite River watershed.

5.3.2 Hydrologic Sensitivity to an Increase in Precipitation

5.3.2.1 Annual Water Yield and ET

The simulation results showed that annual average water yield would increase to 798.0 mm and to 933.7 mm from 666.4 mm if annual precipitation increased by 10% (Scenario 2) and 20% (Scenario 4) in the Amite River watershed, respectively. Under these two scenarios, annual water yield in the Tickfaw would increase from 551.6 mm to 658.0 mm and to 766.1 mm and annual water yield in the Tangipahoa would increase from 657.2 mm to 784.8 mm and to 914.1 mm (Figure 5.5). The increased rates in annual water yield in the three watersheds ranged from 19.3 to 19.9% and 38.9% to 40.1% under Scenarios 2 and 4, respectively (Table 5.4).

Under Scenario 2 and Scenario 4, annual ET in the Amite River watershed increased to 992.9 mm and to 1007.1 mm from 975.6 mm; annual ET in the Tickfaw increased to 981.6 mm and to 995.6 mm from 964.7 mm; and annual ET in the

Tangipahoa increased to 978.6 mm and to 994.8 mm from 958.8 mm, respectively (Figure 5.5). The increased rates in annual ET ranged from 1.8% to 3.8% (Table 5.4).

5.3.2.2 Monthly Water Yield, ET, and Soil Moisture

This modeling study showed that seasonality in monthly water yield, ET, and soil moisture could change if precipitation increased. The largest changes in water yield occurred in September, August, and October in the Amite, Tickfaw and Tangipahoa river watersheds, with a 54.4%, 81.2%, and 52.6% increase under Scenario 4 (20% increase in precipitation), respectively. The minimal increase rates in water yield occurred in April in all the three watersheds (Figure 5.6). The largest increase rates in ET and soil moisture among the three watersheds occurred in the later summer from July to September, while the minimal changes for ET occurred during the winter and early spring (from December to May), and for soil moisture in spring (from February to April).

Table 5.4. Change rates of ten-year annual average water yield and ET with 10% and 20% annual precipitation increase scenarios in the Amite, Tickfaw, and Tangipahoa river watersheds.

Watershed	Scenarios	Rate[a] (%)	Rate[b] (%)
Amite			
	baseline	-	-
	+10%	19.9	1.8
	+20%	40.1	3.2
Tickfaw			
	baseline	-	-
	+10%	19.3	1.8
	+20%	38.9	3.2
Tangipahoa			
	baseline		
	+10%	19.4	2.1
	+20%	39.1	3.8

[a]Change rate for annual water yield, see Eq.5.1.
[b]Change rate for annual evapotranspiration (ET), see Eq.5.1.

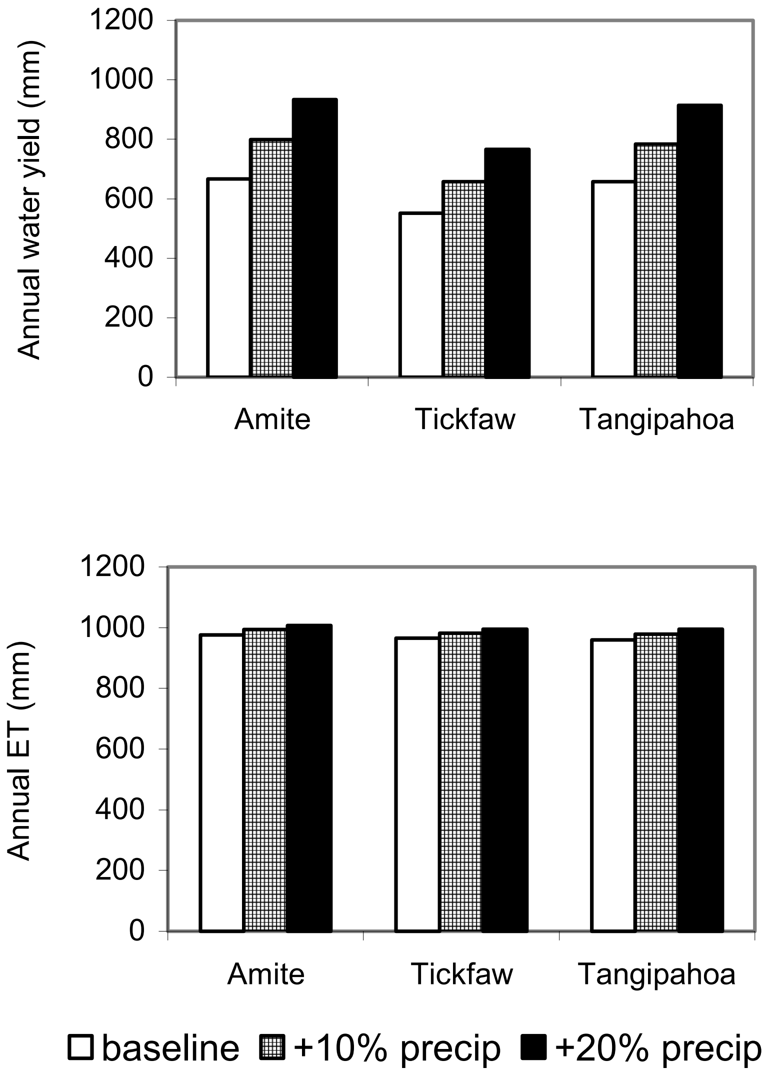


Figure 5.5. Comparison of long-term annual average of water yield and ET in baseline, 10% (Scenario 2), and 20% (Scenario 4) increase in precipitation scenarios in the Amite, Tickfaw, and Tangipahoa river watersheds.

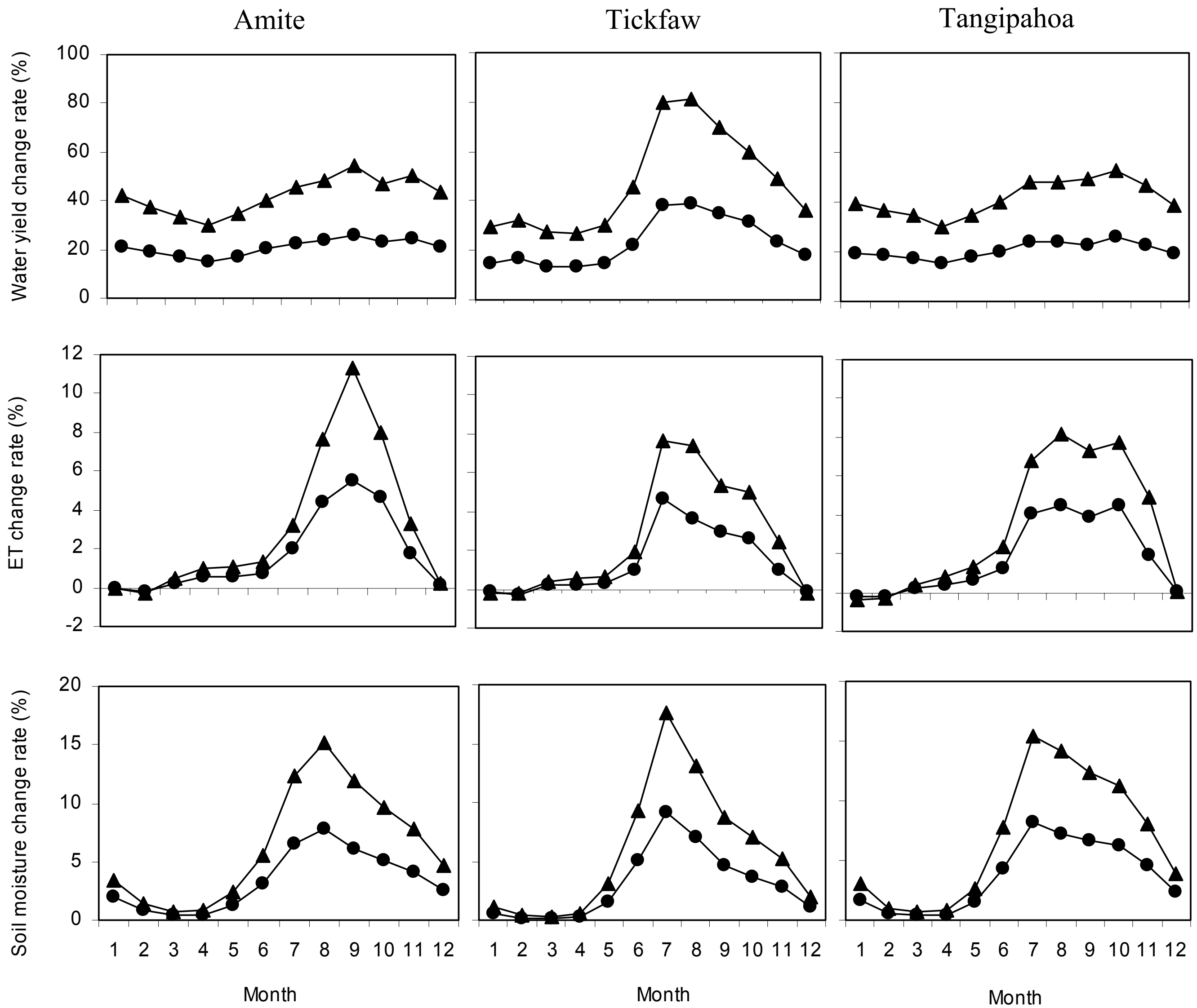


Figure 5.6. Seasonal patterns of change rates in monthly water yield, ET, and soil moisture to 10% increase in precipitation (-•-) and 20% increase in precipitation (-▲-) scenarios in the Amite, Tickfaw, and Tangipahoa river watersheds.

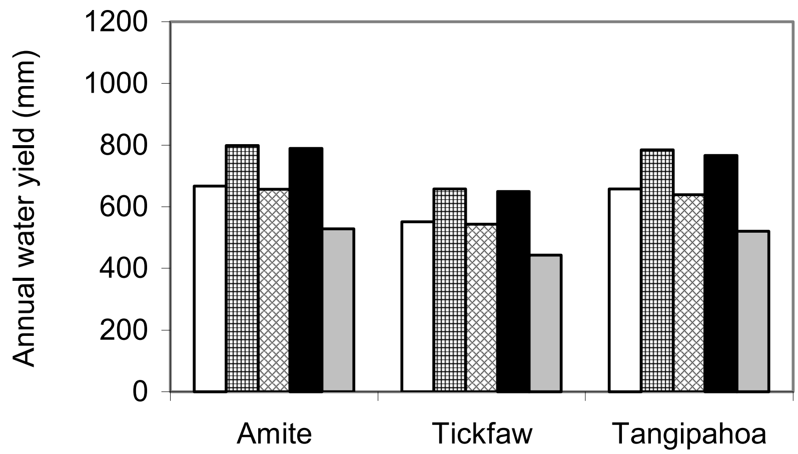
5.3.3 Combined Effects of Temperature and Precipitation

The simulation showed that under Scenario 5 (+1.6 ºC and +10%), annual average water yield increased to 788.8 mm, and that under Scnario 6 (+1.6 ºC and -10%), annual average water yield decreased to 528.4 mm in the Amite River watershed. Under the same climate change scenarios and in the same order, annual average water yield increased to 649.6 mm and decreased to 443 mm from the baseline 551.6 mm in the Tickfaw River watershed and increased to 766.1 mm and decreased to 519.9 mm from the baseline 657.3 mm in the Tangipahoa River watershed (Figure 5.7). Under Scenario 5, the increased rates in annual water yield ranged from 16.6% to 18.4 %, while under Scenario 6 the decreased rates ranged from 19.7% to 20.9% in the three watersheds. Annual ET showed the similar pattern as the water yields, i.e., annual ET increased under Scenario 5, but decreased under Scenario 6 in all the three watersheds, with a percentage change rate ranging from -1.8 to 4.2% (Table 5.5).

Seasonal changes of monthly water yield, ET, and soil moisture were found under both Scenarios 5 (+1.6 ºC and +10%) and 6 (+1.6 ºC and -10%). The largest increase rates in monthly water yield under Scenario 5 occurred from August to November, while the largest decrease rates in monthly water yield under Scenarios 6 occurred from June to July. Under both scenarios, monthly ET showed the largest increase rates in April. Soil moisture increased under Scenario 5, with the largest rates from August to November, while soil moisture deceased in Scenario 6, with the largest rates occurring in June and July (Figure 5.8).

5.3.4 Hydrologic Impacts of Extreme Storm Events

The simulation results from this study showed that annual water yield in the Amite River watershed could increase by 42.8%, from 660.4 mm to 951.6 mm, in response to an



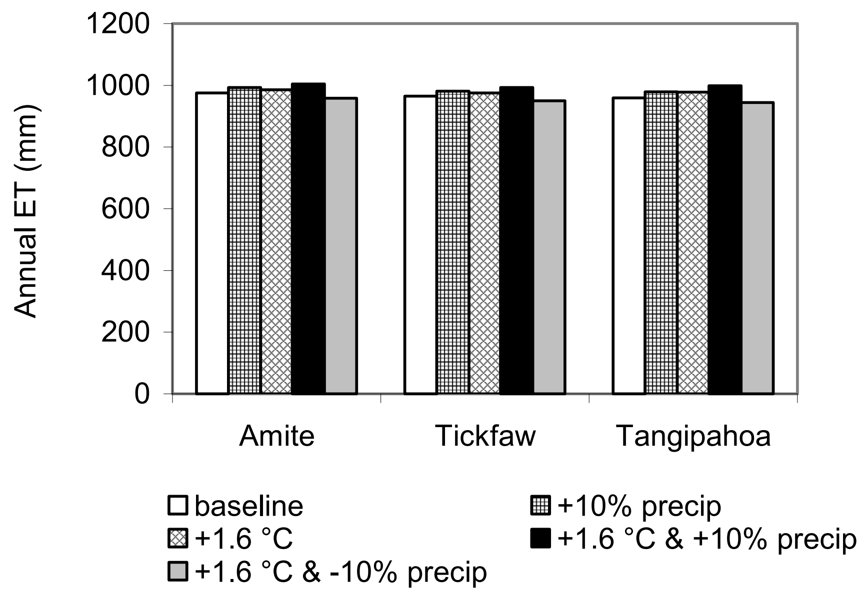


Figure 5.7. Comparison of long-term annual average of water yield and ET in the baseline, a 10% increase in precipitation (Scenario 2), a 1.6 °C increase in air temperature (Scenario 1), a 1.6 °C increase in air temperature plus a 10% increase in precipitation (Scenario 5), and a 1.6 °C increase in air temperature plus a 10% decrease in precipitation (Scenario 6) in the Amite, Tickfaw, and Tangipahoa river watersheds.

Table 5.5. Change rates of ten-year annual average water yield and ET to 1.6 °C annual air temperature increase, 10% annual precipitation increase, 1.6 °C increase in air temperature plus 10% increase in precipitation, and 1.6 °C increase in air temperature plus 10% decrease in precipitation scenarios in the Amite, Tickfaw, and Tangipahoa river watersheds.

Watershed	Scenarios	Rate[a] (%)	Rate[b] (%)
Amite			
	baseline	-	-
	+1.6°C	-1.4	1.1
	+10%	19.9	1.8
	+1.6 °C & + 10%	18.4	3.0
	+1.6 °C & – 10%	-20.7	-1.8
Tickfaw			
	baseline	-	-
	+1.6°C	-1.5	1.1
	+10%	19.3	1.8
	+1.6 °C & + 10%	17.8	2.9
	+1.6 °C & – 10%	-19.7	-1.6
Tangipahoa			
	baseline		
	+1.6°C	-2.7	1.9
	+10%	19.4	2.1
	+1.6 °C & + 10%	16.6	4.2
	+1.6 °C & – 10%	-20.9	-1.5

[a]Change rate for annual water yield, see Eq.5.1.
[b]Change rate for annual evapotranspiration (ET), see Eq.5.1.

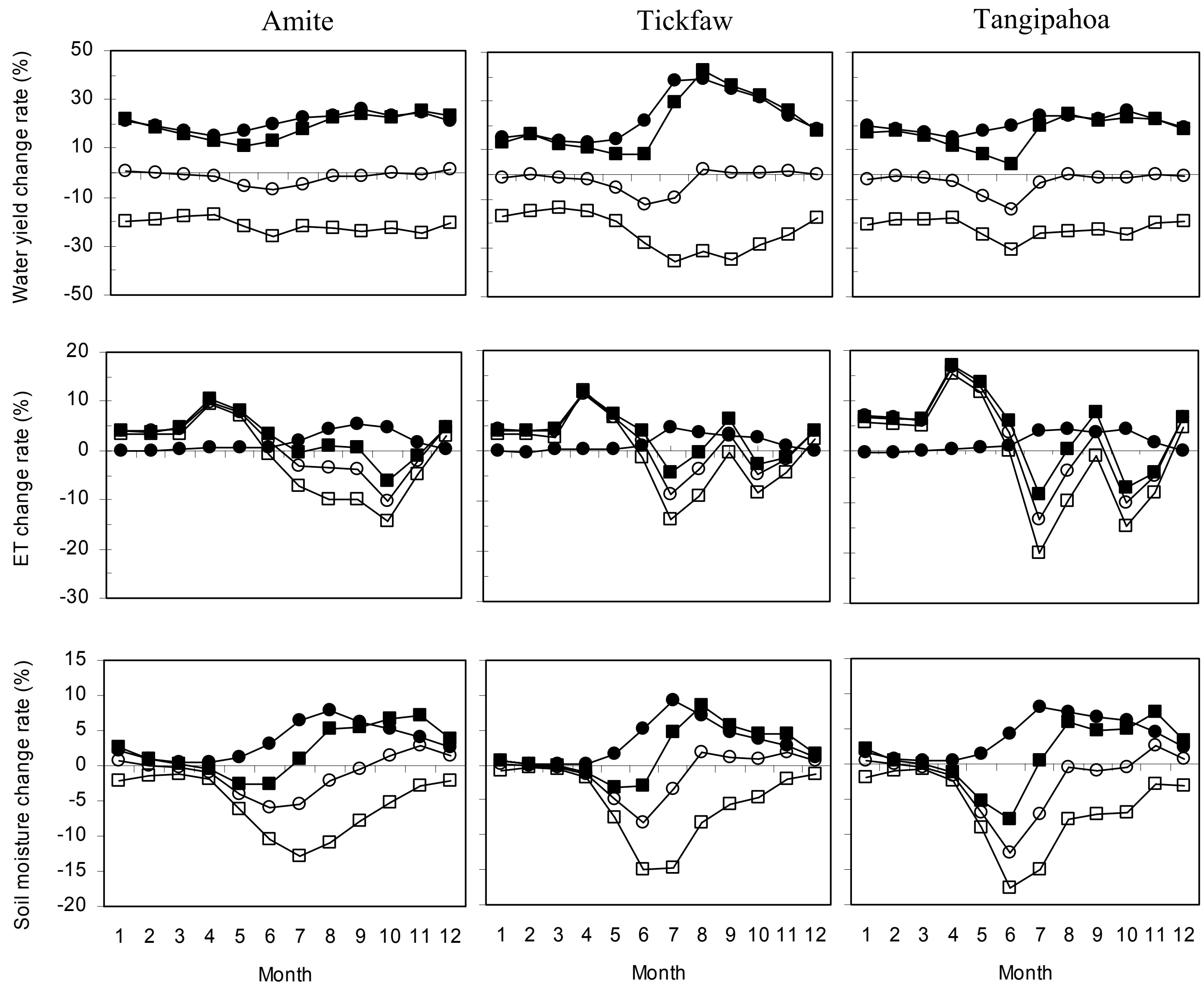


Figure 5.8. Seasonal patterns of change rates in monthly water yield, ET, and soil moisture to 10% increase in precipitation (-•-), 1.6 ºC increase in air temperature (-o-), +1.6 ºC & +10% (-■-), and +1.6 ºC & -10 % (-□-) scenarios in the Amite, Tickfaw, and Tangipahoa river watersheds.

extreme heavy rainfall in spring: a 200% increase in precipitation in April (Scenario 7). The similar effect was also seen in the increased rates of annual water yields in the Tickfaw River watershed and Tangipahoa River watershed (Table 5.6).

The largest response of monthly water yield occurred in April, with an increase rate of 271.3% (Figure 5.9). Monthly ET and soil moisture showed the largest increases in April but less in the remaining months.

Table 5.6. Summary of responses of ten-year annual average of water yield and ET to a 200% precipitation increase scenario in April in the Amite, Tickfaw, and Tangipahoa river watersheds.

Watershed	Scenarios	Water yield (mm)	Rate[a] (%)	ET (mm)	Rate[b] (%)
Amite	baseline	666.4	-	975.6	-
	+200%	951.6	42.8	987.0	1.2
Tickfaw	baseline	551.6	-	964.7	-
	+200%	826.6	49.8	972.4	0.8
Tangipahoa	baseline	657.2	-	958.8	-
	+200%	947.2	44.1	969.5	1.1

[a]Change rate for annual water yield, see Eq.5.1.
[b]Change rate for annual evapotranspiration (ET), see Eq.5.1.

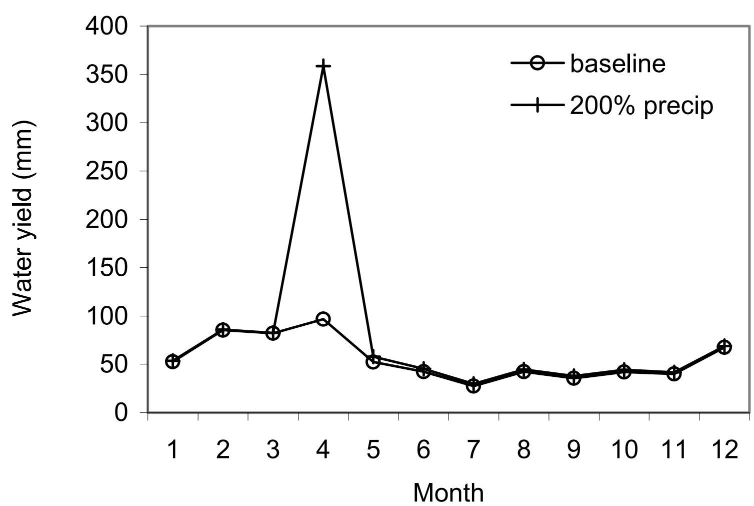


Figure 5.9. A seasonal pattern of monthly water yield in baseline (-o-) and a 200% increase in precipitation in April (-+-) scenario in the Amite River watershed.

5.4 Discussion

5.4.1 Effects of Elevated Air Temperature

This modeling study showed that an elevated air temperature would cause a decrease in annual average water yield in these three coastal watersheds. However, compared to studies conducted on other geographical regions (Frei et al., 2002; Nash and Gleick, 1991; Vankatwijk et al., 1993; Legesse et al., 2003), the change rates in this study were very marginal. This result indicates that the extent of air temperature change impact may differ among different climate zones.

In contrast to annual water yield, an elevated air temperature would lead to an increase in annual ET, although the increase rate was relatively small. As indicated by Savabi and Stockle (2001), in a rainfall-dominated watershed, the magnitude of the response in water yield to an elevated air temperature was most likely affected by sensitivity of ET. This simulation study was done for three coastal watersheds, where the climate can be characterized as subtropical and humid. Under an elevated air temperature, sensitivity of ET in this study area may be attenuated, as compared to those in higher latitude and/or arid regions, resulting in a less sensitivity of water yield. The results from this study imply an essential role of climatic regions in the assessment of climate change on a hydrologic sensitivity.

Although the results from this study agree with Karl and Riebsame (1989)'s conclusion drawn from an assessment of potential climate change on water yield based on 82 river basins across the U.S: variations in air temperature had only minimal impacts on runoff, caution should be paid with respect to different climate regions. The marginal effect of air temperature on annual runoff in Karl and Riebsame's study might be caused by averaging,

which could eliminate the effects of air temperature on runoff within the watersheds with a high hydrologic sensitivity to air temperature.

Although an elevated air temperature showed little effect on annual water yield in the study area, it did affect seasonalities in monthly water yield, ET and soil moisture. The simulation results showed a larger ET increase in April (Figure 5.3), where sufficient soil water was available for evaporation. The change rates of ET decreased and approached to zero in June, apparently due to limited soil water supply. Simultaneously, water yield responded to the faster water loss in soil with the largest decrease rates in June. After June, ET in the climate change scenarios was lower than that in the baseline due to soil moisture deficit. The patterns of monthly ET remained unchanged, even though a slightly higher ET was simulated in September in both the Tickfaw and Tangipahoa River watersheds. The results suggest a complicated hydrologic response of a watershed to an elevated air temperature, which involves both spatial and temporal variations in soil, vegetation, atmosphere, and their interactions as well.

The simulation results showed a temporal shift of monthly ET toward early spring in response to an elevated air temperature in the Amite River watershed. The shift was essentially a result of the increased temperature accompanied with sufficient soil water supply during the early spring. In this coastal region with slow-flowing water and already low dissolved oxygen content, water quality may be even more affected with an elevated air temperature, increased ET, and decreased streamflow during the spring. In addition, decreased freshwater inflow to Lake Pontchartrain can be detrimental to aquatic ecosystem function and productivity, as found in other regions (Neill et al., 2004; Varanou et al., 2002; Quinn and Stroud, 2002; Compagnucci et al., 2001; Mulholland et al., 1997). A variation of hydrologic

sensitivity was found in the three watersheds. The largest annual water yield decrease rates and annual ET increase rates were found in the Tangipahoa River watersheds (Table 5.3). An absolute decrease in annual water yield under the 3.3 ^{o}C temperature increase scenario varied from 8.3 mm to 19 mm, with the highest decrease in the Tangipahoa. The largest decrease rates of monthly water yield (18.9%) and soil water content (16.8%) were also found in the Tangipahoa (Figure 5.3). The variations in hydrologic response to the elevated temperature may have been caused by the heterogeneous nature in soil, land cover, vegetation and topographic features.

5.4.2 Effects of Precipitation Changes

This study showed that, unlike temperature changes, an increase in precipitation will have profound impacts on annual water yield in the coastal watershed. A similar response of water yield to the precipitation change has been also found in other modeling studies (Karl and Riebsame, 1989; Ceballos and Schnabel, 1998; Chiew et al., 1995; Stone et al., 2001; Duell, 1994; Jha et al., 2004).

This study showed, on average, annual average water yield increased by approximately 1.96% for every 1% increase in annual precipitation within the range from a 10% to a 20% annual precipitation increase in the study area. This result is in agreement with the result reported by Sankarasubramanian and Vogel (2003). Using a national database of climate and streamflow for 1337 watersheds across the U.S., the authors found that every 1% change in precipitation resulted in a 1.5-2.5% change in watershed runoff, depending upon the degree of buffering by storage processes and other factors. In contrast to the significant role of climatic regions in the impacts of air temperature on annual water yield, the effects of precipitation on water yield seem to be less dependent on geographical regions. In other

words, the proportional increase rate in annual water yield caused by precipitation in this study area can be also found in other regions. For instance, a study conducted in the Upper Mississippi River basin (Jha et al., 2004) found a 50% increase in total water yield in response to a 21% increase in precipitation. Another study conducted in the Upper Wind River Basin, Wyoming (Stonefelt et al., 2004) found a 18.5% increase in annual water yield in response to a 10% increase in annual precipitation.

In this study, seasonal changes of monthly water yield, ET, and soil moisture in response to a 10% and a 20% increase in precipitation were apparent. The greater increase rates were seen during the period from July to October, which may have important implications for water quality and biological processed in the Lake Pontchartrain estuary.

During the spring months, ET and soil moisture did not show a significant change in response to the 10% and 20% increase of precipitation. This is mainly because soils are saturated or near saturated in the season and much of the increased precipitation runs over towards streams. additionally, monthly water yield, ET and soil moisture in the watersheds increased significantly during summer in response to the increased precipitation. Unlike the effect of an elevated air temperature on monthly ET, no impact of an increased precipitation on of the seasonality of monthly ET was found in the watersheds.

No significant difference of annual water yield change rates was found among the three watersheds. While the smallest change rates in monthly water yield were observed in April from all three watersheds, the largest increase rates of monthly water yield were seen in September in the Amite River, August in the Tickfaw River, and October in the Tangipahoa River watersheds. This difference may have been a result of variations in watershed characteristics such as land covers and soil types. The study not only suggests an essential

role of ET in understanding the impacts of an elevated air temperature on hydrologic sensitivity, but also indicates the importance of soil moisture in the explanation of effects of precipitation on hydrologic responses in coastal watersheds.

5.4.3 Effects of Interactions of Temperature and Precipitation

Significant impacts of combined variations in air temperature and precipitation on hydrologic sensitivity in the coastal watersheds were found. The impacts were most likely caused by precipitation rather than air temperature, as discussed before and also suggested by Fontaine et al. (2001). The magnitude of change rates in annual water yield and ET in the combined scenarios, that is, a 1.6 ºC increase in temperature with a 10% increase in precipitation (Scenario 5, +1.6 ºC & +10%) and a 1.6 ºC increase in temperature and a 10% decrease in precipitation (Scenario 6, +1.6 ºC & -10%), were similar to that in the scenario of 10% increase in precipitation (Table 5.5). A substantial seasonality was found in monthly water yield, ET, and soil moisture. While a seasonal pattern of change rates in monthly water yield in a +1.6 ºC & +10% scenario generally followed that in the 10% scenario, a seasonal pattern of ET in both the +1.6 ºC & +10% scenario and the +1.6 ºC & -10% scenario varies similarly as that of the 1.6 ºC scenario (Figure 5.8), with the largest increase rates in April. The results imply a sensitivity of ET to air temperature. Even with a 10% increase in precipitation, ET in Scenario 5 would decrease in summer and fall due to over-depletion of soil moisture in spring. A minimal change in soil moisture in both Scenarios 5 and 6 were found in spring months from February to April. A seasonal pattern and magnitude of soil moisture change rate in Scenario 5 (+1.6 ºC & +10%) indicated an accumulative effect from both impacts of a 1.6 ºC increase in air temperature and of a 10% increase in precipitation.

This study suggests that annual water yield and monthly water yield in the combined climate change scenarios were mainly determined by the direction and magnitude of precipitation change rather than air temperature change. ET was significantly influenced by the magnitude of air temperature. Though providing a valuable clue to understand hydrologic sensitivity to climate changes in coastal watersheds, the change in soil moisture indicates a combined effect of air temperature and precipitation.

5.4.4 Effects of Extreme Storm Events

This study found a 271.3% increase in monthly water yield in response to a 200% increase in precipitation in April in the Amite River watershed. The large increase of precipitation resulted in a high proportion (92%) of the total increase in annual water yield. ET and soil moisture showed a slight change in the remaining months except in April. The storm events in April apparently increased surface runoff, and the increase implies a higher risk of flooding and vulnerability of soil erosion under such an abrupt climate change scenario. In the Tickfaw and Tangipahoa River watersheds, hydrologic responses to a 200% precipitation increase in April were similar to that in the Amite River watershed; that is, there was a larger response of water yield in April, but less effect in the remaining months and a limited increase of ET and soil moisture in April and few changes in the remaining months.

CHAPTER 6. SUMMARY

With an increasing concern for sustainable water resources management and intensified efforts in coastal ecosystem restoration in Southern Louisiana, seasonal and interannual variability of freshwater inflow and total suspended solids loadings from three watersheds--the Amite, Tickfaw, and Tangipahoa river watersheds--to the Lake Pontchartrain estuarine complex were investigated. Relationships were examined among freshwater inflow, total suspended solids loadings, precipitation, and population density. Using the long-term discharge records (1976-1999), a spatially distributed hydrologic model, the Soil & Water Assessment Tool (SWAT), was evaluated for its applicability in the three lowland coastal watersheds. With calibrated parameters, the model was employed to investigate impacts of elevated air temperature, precipitation change, and extreme storm events on hydrological processes.

The three watersheds produced an annual average freshwater inflow of 5.04 km^3 into Lake Pontchartrain, with the highest contribution from the Amite River watershed. Over 69% of the total annual freshwater inflow occurred from December through May (wet months) and the remaining freshwater inflow occurred from June through November (dry months). A significant increase trend in freshwater inflow was found in the Amite River over the past sixty years, while such an increased pattern was not observed in the Tickfaw and Tangipahoa Rivers. This study also found a twenty-year low flow period from 1954-1973 (0.88 km^3 yr^{-1}) and a twenty-four-year high flow period from 1975-1998 (1.45 km^3 yr^{-1}), coinciding with both the climate variation and population growth in the watersheds. Long-term annual freshwater inflow and annual precipitation were closely related to each other in all the studied

watersheds. Over 80% of the variation in the annual freshwater inflow could be explained by the annual precipitation.

The long-term (1978-2001) annual total suspended solids loadings from the three watersheds was 210,360 tons, of which 66%-71% occurred within the four months from January through April. The annual total suspended solids runoff from the three watersheds ranged from 9.6 tons km^{-2} to 29.3 tons km^{-2}, of which the highest value was found in the Amite River. A significant spatial and temporal variation of total suspended solids loadings was found. Higher loadings and concentration in the Amite River were associated with availability of sediment sources, erodibility of soil, and population density within the watershed comparing to other two watersheds. Annual total suspended solids loadings were not closely related to the annual precipitation. But there was a close relationship between annual total suspended solids loadings and total precipitation from January through April in all three watersheds.

The spatial hydrologic modeling study showed that SWAT can produce reliable estimates of streamflow for the three coastal watersheds. Estimation error in long-term annual average freshwater inflow was below 5.6%. In this study, the most sensitive model parameters for the coastal watersheds were: Manning's roughness coefficient for main channel (CH_N(2)), SCS curve number (CN), soil evaporation compensation factor (ESCO), deep aquifer percolation fraction (RCHRG_DP), ground water delay (GW_DELAY), and maximum canopy storage (CANMX). CH_N(2) showed a great effect on the runoff response time in hydrograph, which implies a critical role of channel routing in hydrologic modeling for lowland watershed with a flat topography. The SWAT model showed excellent performance with a Nash-Sutcliffe model efficiency of 0.935, 0.940 and 0.960 for the

calibration period and of 0.851, 0.811 and 0.867 for the validation period for the three watersheds. In addition to water yield, SWAT produced reasonable estimates of other critical hydrologic components such as ET, groundwater discharge, and soil moisture content in the subwatershed scale. With calibrated parameters, a reliable spatial analysis environment with SWAT was created for a climate change assessment in the three watersheds.

The impacts of an elevated air temperature on hydrologic sensitivity in this study area were marginal. Under the scenarios of a 1.6 ^{o}C and a 3.3 ^{o}C increase in air temperature, annual water yield decreased by only 1.4% to 2.9% and annual ET increased by 1.1% to 2.1% in the three watersheds. A seasonal shift of ET toward early spring in the Amite River watershed was found correlated with the elevated air temperature. In general, monthly ET increased in spring and decreased in summer and fall in both scenarios of air temperature change. The largest increase of ET from the baseline occurred in April, while the largest decrease rates in monthly water yield and soil water content were found in June in the three watersheds. The magnitude of the impacts of precipitation change on annual water yield in the study area was greater than those of the elevated air temperature. Annual water yield increased by 19.3% to 19.9% under the scenario with a 10% increase in precipitation, and increased by 38.9% to 40.1% under the scenario with a 20% increase in precipitation. Annual ET increased by a marginal rate (1.8% to 3.8%) under both precipitation change scenarios. Furthermore, the modeling results from this study showed a clear impact of precipitation changes on seasonality of water yield, ET, and soil moisture, with a larger increase rate in summer--a generally dry season with soil moisture deficits, resulting in a considerable increase in streamflow, which may have a positive implication in water quality.

This study has also investigated the combined effects of temperature and precipitation changes on hydrology in the three coastal watersheds. The modeling results showed that annual water yield increased by 16.6% to18.4% under the climate change scenario with a 1.6 ºC temperature increase and a 10% precipitation increase, but decreased by 19.7% to 20.9% under the scenario with a 1.6 ºC temperature increase and a 10% precipitation decrease. The results essentially indicate combined effects of precipitation on water yield and air temperature on evapotranspiration. The temporal variation in monthly soil moisture conditions is a representation of the combined effect.

The impact of a 200% precipitation increase in April on the site hydrology in the three watersheds has been analyzed. The annual water yield showed an increase rate varying from 42.8% to 49.8% under this extreme weather condition. About 92% of the annual change was essentially caused by the water yield change in April. The high flow during spring may have negative implications for the lowland Louisiana, including high flooding risk and excessive sediment and nutrient runoff.

This study has demonstrated that SWAT can be an effective tool in the assessment of hydrologic sensitivity of coastal watersheds to potential climate changes.

The scope of this study did not include a thorough evaluation of the effect of land use change on the freshwater inflow and sediment loadings, although the importance of land use impacts was indirectly assessed through an analysis of population change in the study area. Future research may include complete satellite imagery analyses to determine the land use change over time and their impacts on water yield and water quality in the Lake Pontchartrain drainage basin. Modeling work on hydrologic impacts of potential climate changes may also be conducted for different land use changes and management scenarios in order to assess

interactive effects of climatic variation and anthropogenic activities on hydrologic processes and environmental restoration in coastal Louisiana.

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VITA

Kangsheng Wu was born in Taiyuan, China. He spent his childhood with his grandmother in the countryside. After finishing his high school, he attended Beijing Forestry University in 1981. There he earned his bachelor's degree in forestry and a master's degree in silviculture. In these seven years of study he recognized water as deeply interesting and began his journey studying the relationships among water, soil, vegetation, and atmosphere.

Mr. Wu worked as a research forester in his hometown for about ten years, attempting to discover a better way to cultivate and manage forest plantations through increasing water use efficiency. With much help from his colleagues, he earned two awards for his studies in forest ecophysiology and forest management. In 1998 he came to the United States and worked as a visiting scientist in the State University of New York College of Environmental Science and Forestry for his first year. Then he moved to Louisiana State University in 1999 as a research associate. In 2001, Mr. Wu began his doctoral program in forestry, and at the May 2005 Commencement the degree of Doctor of Philosophy will be confirmed.

He is married to Dongzhi Qi and they have a lovely daughter, Yue Wu.