AN ECOLOGICALLY-SUSTAINABLE SURFACE WATER WITHDRAWAL FRAMEWORK FOR CROPLAND IRRIGATION –

A CASE STUDY IN ALABAMA

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THESIS ABSTRACT

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Agricultural production in the State of Alabama, USA, mostly depends on natural rainfall. Because of this and also because of low and uncertain precipitation levels during growing seasons, agricultural production in Alabama is high vulnerable, especially during drought years. On the contrary, Alabama receives plenty of rain during winter months. Recently, the state agencies, researchers, and extension personnel in Alabama have been evaluating the feasibility of surface water withdrawal from stream during winter months and storing it for irrigation use in the growing period. A modeling study using the SWAT (Soil and Water Assessment Tool) model was completed for a Southwest Alabama watershed to estimate the quantity of water that could be withdrawn in an ecologically-sustainable manner from streams during winter high flow periods. The model was calibrated and validated separately using base flow, surface runoff, and total stream flow. The streamflows generated by the model at several locations within the watershed were then used to examine how much water can be withdrawn from streams of various orders (1^{st}, 2^{nd} and 3^{rd} order) while satisfying the criteria for ecologically-sustainable stream flows. Although there was a considerable year-to-year variability in the amount of water that can be withdrawn, a sixteen year average simulation showed that 1^{st}, 2^{nd}, and 3^{rd} order streams can irrigate about 11.6 %, 10.3%, and 10.6% of their drainage areas, respectively, per year. The percentage of drainage area that could be irrigated was found to be not a function of the order of the stream.

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CHAPTER I

INTRODUCTION

Water is becoming an increasingly scarce commodity in the United States and also in other parts of the world. Due to increasing population, there is an ever increasing need for increased crop production. At the turn of the 20th Century, most of the food and fiber production in the U.S. was carried out under a rain-fed agricultural system in the East and Mid-West (McNider et al., 2005). By 1950, this rain-fed agricultural system went through a dramatic transformation, changing from rain-fed system in the East to desert-irrigated system in the West and High Plains, as the water projects built during the 1920 – 1940 period became operational (Riesner, 1986; McNider et al., 2005). Because of this, since 1970s a substantial portion of agricultural production in the U.S. is located in the arid western region.

However, in spite of substantial irrigation infrastructure in the west, sustainable agriculture is not possible because of insufficient annual precipitation and increased water demand by the ever increasing urban centers. For example, in the High Plains, reduced groundwater levels have increased pumping costs and have forced a 30% drop in irrigated area of the Ogallala Aquifer region (De Villier, 2000). In California, the water conflict between the urban stakeholders of Los Angeles and the agricultural producers is widely known.

On the contrary, humid southern state of Alabama is blessed with plenty of annual precipitation. However, agricultural production in Alabama has declined considerably in the past few decades. The decline in Alabama farm land almost inversely mirrors agricultural increases in California as water projects came on-line. The reason for such a considerable decline in farm land and agricultural production is that agricultural production in Alabama was (and still is) mostly rain-fed. Alabama farmers could not compete with irrigated agricultural production in the west. The average annual precipitation of Alabama ranges from as low as 50 inches in the southeastern part of the state to as high as 68 inches in the southwestern part (Dougherty et al., 2007). However, most of the precipitation falls in non-growing season during winter months. For example, in Belle Mina in Northern Alabama, which normally receives about 1350 mm (53 in) of rain annually, only about 560 mm (22 in) of rainfall occurs during May – October growing season (Dougherty et al., 2007). In addition to great inter-annual variability in precipitation, Alabama often experiences severe droughts. The inability to supply water during critical crop growing periods results in significant production losses, as a consequent of which, over the years, Alabama farmers have planted reduced acreages in row crops. Therefore, to sustain agricultural production and to reduce drought risks, Alabama farmers would have to rely on irrigation during growing season.

Alabama farmers are becoming increasingly aware of irrigation as a tool for increasing production (ACES, 1994). Irrigation can help Alabama farmers achieve high yields and quality demanded in today's markets to be competitive. However, lack of adequate irrigation facility is a big hindrance in increasing the agricultural productivity

(ACES, 1994). Furthermore, since in Alabama most of the crops are grown during the summer season when surface water sources do not have sufficient flow (also, groundwater sources are either inadequate or impractical for irrigation, ACES, 1994), enhanced withdrawal during summer months would lead to detrimental environmental impact on streams.

A practical approach for solving this irrigation problem could be **"**water harvesting**."** **"**Water harvesting" is the process of withdrawal and storage of surface water in reservoirs during off-season (i.e., winter months) when precipitation and stream flows are generally high and utilizing it for irrigation during growing crops in summer months. Rochester et al. (1996) have reported on the feasibility of storing winter-pumped water in off-stream reservoirs for use in the growing season. Since different crops have different water needs, each irrigation system should be designed to provide adequate water for the crop to be irrigated. In Alabama, the average minimum water required is about 4570 m^3 (about 3.7 ac-ft) for one irrigated hectare area (Larry Curtis, 2008; personal communication). Except in extreme drought years, this quantity of water is sufficient for most crops in Alabama (ACES, 1994).

While surface water withdrawal during winter months appears to be feasible, ad hoc and excessive water withdrawal would lead to adverse impacts on streams that may not be ecologically sustainable. Hence, water withdrawal during winter months needs to be done in such a way that it satisfies a set of agreed upon ecological sustainability criteria (agreed upon by the federal, state and local agencies) and reduces environmental impacts. The challenge would be to develop such criteria.

Once these criteria are established, a distributed parameter, physically-based hydrologic simulation model, such as Soil and Water Assessment Tool (SWAT), can be used to simulate flows at various points along a stream to develop a water withdrawal prescription. Hydrologic simulation models can provide the basis of information for multitude of decisions regarding the development and management of water resources (Singh and Woolhiser, 2002).

This research was initiated to address two important questions associated with surface water withdrawal for irrigation:

1. How much water can we sustainably withdraw?
2. Will the percentage of watershed that can be sustainably irrigated through surface water withdrawal depend on the size of the stream?

One added benefit of this study was that this study provided an approach for sustainable water withdrawal for any type of beneficial use.

CHAPTER II

LITERATURE REVIEW

With the increase in population, there is an ever increasing need for increased crop production. Low risk, increased crop production cannot be economically sustained without irrigation in Alabama (and many parts of the world) because of inter-annual variability in precipitation. Better irrigation infrastructure can help farmers achieve high yields and quality demanded in today's markets to be competitive. However, lack of adequate irrigation facilities is a big hindrance in increasing agricultural productivity in Alabama (ACES, 1994) and in many parts of the world.

However, with increased irrigation there is a need to better manage land and water resources for ecological sustainability. Water for irrigation can be obtained from surface water sources or from groundwater. Withdrawal of water from surface water bodies, if not done appropriately, can lead to flow and habitat degradation, which would ultimately lead to impairment of biological integrity of the surface water bodies. Excessive withdrawal of water from groundwater can also lead to depletion of groundwater table. In addition to flow related degradations, increased irrigation infrastructure will lead to expansion of cropland areas within a watershed, which can lead to water quality degradations if the irrigation is not managed properly and the appropriate BMPs are not applied.

Use of Watershed Models for Irrigation Planning

A number of studies have been attempted to use watershed models for making irrigation planning decisions. For example, Singh et al. (1999) developed an irrigation plan for a small watershed situated in the western part of the Midnapore district of West Bengal, India using MIKE SHE. Hydrologic water balance of the watershed was considered. Irrigation requirement of 490 and 340 mm was calculated for the upstream and downstream ends of the watershed, respectively. The results indicated the applicability of hydrological models for management of water resources for agricultural purposes at a watershed scale.

Gosain et al. (2005) used SWAT model to analyze the effect of introducing canal irrigation on return-flows to the river in Palleru river basin in India. It was estimated that return flows of over 50% will occur in the basin, which is different from the usual thumb-rule of 10-20% assumed in India.

Santhi et al. (2005) configured SWAT as a regional planning tool with a canal irrigation capability for estimating irrigation demand. The tool simulated hydrological processes associated with soil−plant−water interactions and the spatial and temporal variability of the major factors important for regional planning. The tool was applied to the irrigation districts in the Lower Rio Grande Valley in Texas. It was used to analyze the demand and potential water savings of alternative water conservation measures. Results indicated that on-farm management measures might be as beneficial as improving canal conveyance systems.

Wollmuth and Eheart (2000) studied surface water irrigation and riparian management influenced by climate change using SWAT. They assessed the vulnerability of midwestern streams to climate change and, especially, surface supplied irrigation spawned by such climate change.

Geographic Information System-Based Hydrologic/Water Quality Models

Agricultural, urban, forest, and mining nonpoint source (NPS) pollutants continues to impact and degrade surface and groundwater quality. Among the laws that brought NPS pollution to international attention was the U.S. Clean Water Act (CWA) of 1972 and its amendments of 1987. More specifically, Section 319 of the 1987 CWA amendments authorized planning and limited implementation funds to U.S. states for the assessment of NPS problems and development and implementation of programs for their control (Logan, 1990). Furthermore, the U.S. Environmental Protection Agency (USEPA), the federal agency that administers the CWA, required states to develop a list of high priority or critical water bodies (called 303(d) list) on a watershed-by-watershed basis to the maximum practicable extent and to develop Total Maximum Daily Loads (TMDLs) for pollutants in these waters. A TMDL is defined as the maximum amount of pollutant that a waterbody can receive and still meet the water quality standards. TMDLs include both point source and NPS discharges that arise from a watershed or the environs of a watercourse (Ward and Benaman, 1999). The CAW requires development of TMDLs for all waters on the 303(d) list by developing restoration scenarios. The creation of this list is authorized by section 303(d) of the CWA. The ultimate goal of a TMDL development and implementation can be stated as removal of the waterbodies from the 303(d) list by attaining water quality standards. Eventually, the list of impaired waterbodies and established TMDLs by states, territories and authorized tribes must be approved by USEPA.

These requirements made by USEPA lead to the assessment of NPS water quality problems and identification of critical contributing areas in several states. The CWA also required states to develop management plans to remediate NPS pollution problems. With limited resources available (in terms of time, labor, and money), it is imperative that control and implementation programs focus on critical contributing areas and adequately consider the impacts of alternative management, land use, and conservation approaches (e.g. conservation tillage, contour cropping, strip cropping, fertilizer management, etc.) on NPS pollution. Evaluating NPS pollutant reduction effectiveness of alternative management, land use, and conservation practices at a watershed scale through experiments and monitoring systems is not feasible because of the enormous cost, time, and labor involved. Modeling studies based on experimental data are often the only viable means of providing timely inputs to management decisions with the least cost. Therefore, modeling NPS pollutant fate and transport processes at a watershed scale is fundamental to addressing contamination of surface and ground waters. Watershed scale NPS models are currently used for a variety of purposes, including designing soil conservation practices, water table management, prevention of chemical pollution of surface waterbodies and groundwater, protection of aquatic biota and development of TMDLs. In the years ahead, worldwide, the watershed models will play an increasing important role in managing NPS pollutants.

Models, in general, and watershed model, in particular, can be characterized as mechanistic or empirical, stochastic or deterministic, linear or nonlinear, event or continuous simulation, and lumped or distributed parameter model (Haan, et al., 1982).

Truly mechanistic models are those in which governing physical, chemical, and biological laws and the model structure are well-known and can be described by mathematical equations. Empirical models are used when model structure and governing laws are unknown or the mechanistic model is so complicated that simplification of model behavior is needed. In reality, most current watershed-scale models have mechanistic and empirical components. Further, most make an attempt to model physical, chemical, and biological processes that occur on land or in waterbodies (e.g., streams, ponds, lakes, or reservoirs). These models are best described as process-based models. If any of the variables in a process-based model are regarded as random variables having a probability distribution function, the model is called a stochastic model. However, if all of the variables are free from random variations, then the model is a deterministic model. Although most current day models are deterministic models, since many of the input variables, model parameters, and the processes modeled are stochastic in nature, stochasticity is introduced through model uncertainty analysis.

Since watershed-scale models have mostly nonlinear components, based on the mathematical properties of the operator function they can best be regarded as nonlinear models. Linear models, such as the unit hydrograph theory, are based on two simple principles: principle of proportionality and principle of superposition. The former can be stated as; if $f(x)$ is a solution of a system, then $c.f(x)$ is also a solution of the same system with c being a constant. The latter principle implies that if $f_1(x)$ and $f_2(x)$ are both solutions of the same system, then $f_1(x) + f_2(x)$ is also a solution of the same system.

Based on the length of simulation, models can be characterized as event or continuous. An event model represents runoff event occurring over a period of time ranging from hours to several days, while a continuous simulation models can operate over an extended period of time simulating flows and conditions during both runoff periods and non runoff periods. The continuous models keep a continuous account of watershed characteristics. Watershed models can also be characterized as lumped or distributed parameter models. A distributed parameter model directly utilizes the aerial variations in watershed characteristics (e.g., soils, land use, slope, rainfall, etc.); a lumped parameter model cannot do this. Most watershed-scale models, however, are lumped to some extent. Based on the criteria listed above, currently-used popular watershed-scale hydrologic and NPS models can be characterized as nonlinear, process-based, deterministic, distributed parameter, and event or continuous simulation.

Important Components of Watershed Models

Although descriptions of processes vary in different watershed-scale models, most models allow various physical, chemical, and biological processes to be simulated in a watershed. Further, since water balance is the driving force behind accurate prediction of movement of sediment, nutrients, and pesticides, accurate simulation of various components of hydrologic cycle is important for watershed models. The following water balance equation, especially in continuous simulation models, is often used (Neitsch et al., 2005):

$$SW_t = SW_o + \sum_{t=0}^{t} (R_{day,i} - Q_{surf,i} - w_{seep,i} - E_{a,i} - Q_{gw,i})$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

For the simulation of watershed hydrology, hydrologic cycle is usually divided into land phase (red dashed box on Figure 1) and routing phase (blue dashed box on Figure 1). The land phase of the hydrologic cycle transports water, sediment, nutrient, and pesticide loads from land surface to a stream, while the routing phase transports them through stream channels of the watershed to the outlet. Figure 1 presents a schematic of hydrologic processes/water transport pathways simulated in one of the most widely used watershed model, the SWAT model.

To account for aerial variations in watershed characteristics (e.g., soils, land use, slope, and rainfall), a distributed parameter model subdivides the watershed into sub-watersheds, grid cells, or hydrologic response units (HRUs). Runoff is predicted separately in each smaller unit and routed to obtain total runoff for a watershed. The subdivision of watershed increases accuracy and give a more accurate physical description of the hydrologic processes (Neitsch et al., 2005).

As discussed above, water balance is the driving force behind accurate prediction of movement of sediment, nutrients, and pesticides. For example, in many of the watershed-scale models, runoff volume and peak runoff rate are used to simulate erosion and sediment yield. Watershed models also track transport and transformation of various forms of nutrients (nitrogen (N) and phosphorus (P)) in a watershed. In the soil, transformation of N is governed by N cycle, while transformation of P is governed by P cycle. For simulation of point sources, nutrients can be added to the main channel and transported downstream through stream flow. The inorganic and organic forms of nutrients applied can be taken by plants, adsorbed by soils, move to streams and lakes/reservoirs through surface runoff or lateral subsurface flows or percolate to deeper ground water. The movement of pesticides is controlled by its solubility, degradation half-life, and soil organic carbon adsorption coefficient.

The loadings of water, sediment, nutrients, and pesticides from the landscape are routed through the stream network of a watershed. While keeping track of mass flow of pollutants in the stream channel, most watershed models also account for transformation of pollutants in the stream. Many of the sophisticated watershed models also simulate movement and transformation of pollutants in lakes and reservoirs, although not as comprehensively as the reservoir models.

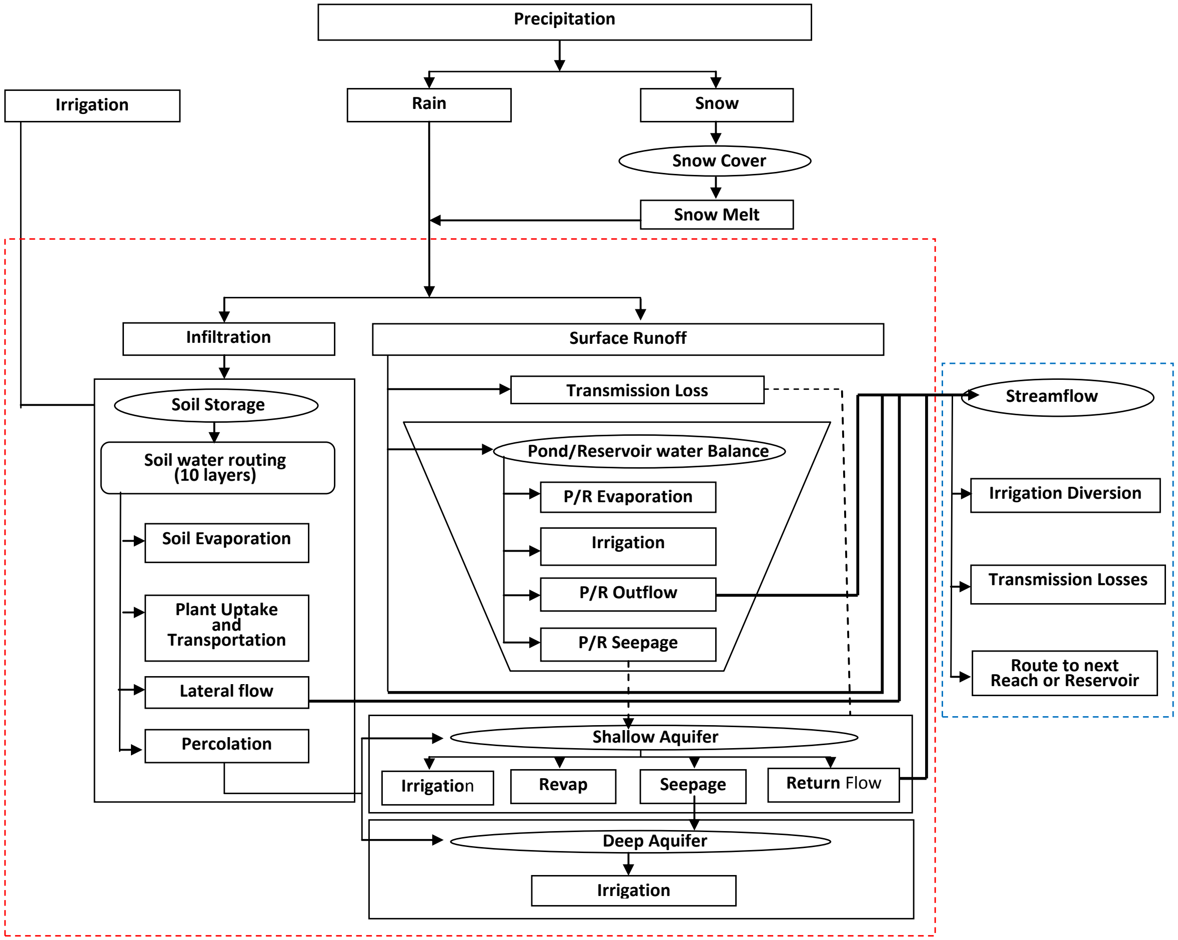

Figure 1: Schematics showing common hydrologic processes/water movement pathways simulated in watershed-scale NPS models (redrawn after Neitsch et al., 2005).

Examples of Commonly Used Watershed Models

Currently, a number of NPS models exist which are designed to address specific problem domains. Some of the more widely used watershed-scale NPS models are described in this section.

SWAT, Soil and Water Assessment Tool (Neitsch et al., 2002)

The SWAT model is a modified version of the SWRRB and ROTO models for application to large, complex rural basins and uses new routing structures. SWRRBWQ was a continuous simulation, daily time step computer model developed to simulate hydrologic and nutrient transport processes in rural basins. It was designed to predict the effect of management decisions on water, sediment, nutrient, and pesticide yields at the sub-basin or basin outlet. In SWRRBWQ a basin could be divided into a maximum of 10 sub-basins to account for differences in soils, land use, crops, topography, vegetation, or weather. SWRRBWQ also had a water quality component that tracked the fate of pesticides and P from their initial application on the land to their final deposition in a lake. SWRRBWQ could be used to model the effect of farm-level management systems such as crop rotations, tillage, planting date, irrigation scheduling, and fertilizer and pesticide application rates and timing. Modified Universal Soil Loss Equation (MUSLE) was used for sediment yield. Nutrient, pesticide, and sediment yields at the basin outlet were determined after accounting for channel transmission losses and deposition in the sub-basins.

SWAT is an extended and improved version of SWRRB, running simultaneously in several hundred sub-basins to predict the effects of management practice on sediment and chemical yields from large river basins. SWAT has the ability of simulating surface flow, subsurface flow, sediment, nutrients, pesticides, and bacteria in addition to various best management practices (BMPs); for example, agricultural practices, ponds, and tile drains. Management practices are handled within the MUSLE. SCS curve numbers can also be varied throughout the year to take into account variations in the management conditions. SWAT divides the watershed into HRUs that has uniform properties. Edge-of filter strips may be defined in an HRU. The filter strip trapping efficiency for sediment is calculated empirically as a function of the width of the filter strip. When calculating sediment movement through a water body, SWAT assumes the system is completely mixed. Settling occurs only when the sediment concentration in the water body exceeds the equilibrium sediment concentration specified by the user. The sediment concentration at the end of a day is determined based on an exponential decay function. SWAT also simulates the buildup and wash-off mechanisms similar to SWMM (Storm Water Management Model). SWAT has its own GIS interfaces that utilize Environmental Systems Research Institute's (ESRI) ArcView 3.X and ArcGIS. SWAT is also linked to the water quality model QUAL2E for in-stream nutrient processes.

AGNPS and AnnAGNPS Pollutant Loading Model (Young et al., 1987 and Bingner and Theurer, 2003)

AnnAGNPS, developed by the USDA-ARS at the National Sedimentation Laboratory, Oxford, Mississippi, is a batch-process, continuous simulation, distributed parameter, watershed scale pollutant loading computer model developed in ANSI FORTRAN 90. This model is mainly an expansion of the capabilities in the single-event model AGNPS.

AGNPS, a watershed scale, distributed parameter, event-based model, was designed to simulate runoff, sediment, and nutrient transport. Square cell representation was used in AGNPS to represent field boundaries. AGNPS used the USDA SCS runoff curve number and unit hydrograph method for calculating flow volume and peak flow, respectively. The modified USLE was used for erosion, and a simple correlation of extraction coefficients was used for nutrient and sediment. Capabilities were also provided in AGNPS to simulate gully, wastewater treatment plants, and feedlot point source pollution as well as a number of agricultural practices. Flow, sediment, and nutrients could be calculated in every cell within a watershed.

AnnAGNPS divides a watershed into homogeneous land areas with respect to soil type, land use, and land management. The areas can be of any size and any shape, including hydrologically-based and square grids. AnnAGNPS simulates movement of surface water, sediment, N, P, and pesticides leaving the land areas as well as their travel through the watershed. Portions of water, sediment, N, P, and pesticides reach the watershed outlet while the remainder is deposited within the watershed. Calculations are done on a daily time step and pollutant loads generated from land areas are routed through the stream systems on a daily-basis.

AnnAGNPS is suitable for evaluation of long-term NPS pollution from agricultural watersheds. AnnAGNPS is also suitable for comparing the effects of alternative cropping and tillage systems, fertilizer, pesticide, and irrigation application rates, and feedlot management systems on levels of NPS pollutants. AnnAGNPS is capable of simulating point source loads too. AnnAGNPS generates both event and source accounting outputs. Source accounting indicates the fraction of a pollutant loading at the watershed outlet or at a particular reach coming from user identified source location. Output generated by AnnAGNPS is: water, sediment, nutrients, and pesticides at the user-defined watershed source location (specific cell, reach, feedlots, point sources, and gullies).

AnnAGNPS uses the SCS curve number method for determining runoff volume and peak discharge is calculated using a procedure similar to TR-55 method. The sheet and rill erosion model is based upon RUSLE. RUSLE is an erosion model that predicts longtime average annual loss of sediment resulting from raindrop splash and runoff from specific field slopes in specified cropping and management systems. HUSLE is used to determine the delivery ratio for the sheet and rill erosion for each cell to its receiving reach. The delivery ratio for the individual particle-size classes is proportioned according to their respective fall velocities. The resulting sediment is called the sediment yield to the stream system. Sediment reach routing by particle size class is based upon a modified Einstein deposition equation using the Bagnold suspended sediment formula for the transport capacity. If the upstream sediment load is greater than the transport capacity for the respective particle size class, then degradation is assumed.

Mass balance of N, P, and organic carbon is computed for each cell on a daily basis. Uptake of N and P by plants, application of fertilizers, residue decomposition, and downward movement of N and P are the major components considered in AnnAGNPS. The output from each field includes sediment N, dissolved N, sediment P, dissolved P, sediment organic carbon, and dissolved organic carbon. AnnAGNPS partitions N and P into organic and mineral parts, and a separate mass balance is computed for each. The N and organic carbon cycles represented in AnnAGNPS are simplifications that track only major N transformations of mineralization from humified soil organic matter and plant residues, crop residue decay, and fertilizer and plant uptake. A simple crop growth stage index is used to model plant uptake of N and P.

Runoff, evapotranspiration, and percolation are considered to affect soil moisture. Runoff is calculated using the SCS curve number method and potential evapotranspiration is calculated using the Penman equation. Actual evapotranspiration is estimated as a function of potential evapotranspiration and available soil moisture content. Percolation is assumed to occur at the rate of the hydraulic conductivity corresponding to the soil moisture content using the Brooks-Corey equation.

AnnAGNPS also includes a winter routing for snow, snowmelt, and frozen soil by maintaining a daily thermal energy balance to track the soil and snow pack temperatures. Rainfall is supplemented by snowmelt. The depth of the upper most frozen soil layer is used to adjust the curve number and soil erodibility for potential sheet and rill erosion. Several GIS interfaces using ArcView 3.X and ArcGIS have been developed for the AGNPS and AnnAGNPS models.

HSPF, Hydrologic Simulation Program-Fortran (Bicknell et al., 2001)

HSPF performs long-term simulations of the hydrologic and associated water quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. HSPF is supported by both USEPA and U.S. Geological Survey (USGS). It is incorporated into the BASINS and WMS modeling systems (described later) and is extensively used for TMDL studies. The model contains hundreds of process algorithms developed from theory, laboratory experiments, and empirical relations from instrumented watersheds. There are three basic modules, PERLND, a watershed loading model for pervious surfaces, IMPLND, a watershed loading model for impervious surfaces, and, RCHRES, a one-dimensional receiving water model for simulation of in-stream transport and transformation processes. HSPF is based on the Stanford Watershed Model, ARM (Agricultural Runoff Management), and NPS (NonPoint Source) models. It uses simple storage based equations for flow routing. Flows in streams are one-dimensional. It is one of the few comprehensive models of watershed hydrology and water quality that allows the integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions. HSPF uses continuous rainfall and other meteorologic records to compute streamflow hydrographs and pollutographs. HSPF simulates interception soil moisture, surface runoff, interflow, baseflow, snowpack depth and water content, snowmelt, evapotranspiration, ground-water recharge, dissolved oxygen, biochemical oxygen demand (BOD), temperature, pesticides, conservatives, fecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia, nitrite-nitrate, organic N, orthophosphate, organic P, phytoplankton, and zooplankton. Program can simulate one or many pervious or impervious unit areas discharging to one or many river reaches or reservoirs. Frequency-duration analysis can be done for any time series. Any time step from 1 minute to 1 day that is divided equally within 1 day can be used. Any period from a few minutes to hundreds of years may be simulated. HSPF is generally used to assess the effects of land use change, reservoir operations, point or NPS treatment alternatives, flow diversions, etc. Programs, available separately, support data pre- and post-processing for statistical and graphical analysis of data saved to the Watershed Data Management (WDM) file. The major application of the HSPF model is the Chesapeake Bay Project.

KINEROS-2, KINematic EROSion model (Woolhiser et al., 1990)

This is the improved version of KINEROS (Woolhiser et al., 1990) model. It is event based since it lacks a true soil moisture redistribution formulation for long rainfall hiatus and, more importantly, it does not consider evapotranspiration (ET) losses. This model is primarily useful for predicting surface runoff and erosion over small agricultural and urban watersheds. Smith et al. (1995) suggest watershed size smaller than 1000 ha for best results. Runoff is calculated based on the Hortonian approach using a modified version of Smith-Parlange (Smith and Parlange 1978) infiltration model. KINEROS-2 requires the watershed to be divided into homogeneous overland flow planes and channel segments, and routs water movement over these elements in a cascading fashion. Mass balance and the kinematic wave approximations to the Saint-Venant equations are solved with implicit finite difference numerical scheme in a 1-D framework. KINEROS-2 accounts for erosion resulting from raindrop energy and by flowing water separately. A mass balance equation is solved to describe sediment dynamics at any point along a surface flow path. Erosion is based on maximum transport capacity determined by Engelund-Hansen equation (1967). The rate of sediment transfer between soil and water is defined with a first order uptake rate. KINEROS-2 can be used under the AGWA system (described later) which provides a GIS interface for data preparation and visualization of results.

MIKE SHE (Danish Hydraulic Institute (DHI))

MIKE SHE is an integrated hydrological modeling system for simulating surface and groundwater flows. The user-friendly tools provided by MIKE SHE can simulate the entire land phase of the hydrologic cycle and allows components to be used independently and customized to local needs. MIKE SHE emerged from System Hydrologique European (SHE) as developed and extensively applied since 1977 onwards by a consortium of three European organizations: the Institute of Hydrology (the United Kingdom), SOGREAH (France) and DHI Water.Environment.Health (Denmark). Since then DHI has continuously put effort in development and research on MIKE SHE. MIKE SHE can be used for the analysis, planning and management of a wide range of water resources and environmental problems related to surface water and groundwater. Examples include surface water impact from groundwater withdrawal, conjunctive use of groundwater and surface water, wetland management and restoration, river basin management and planning, environmental impact assessments, aquifer vulnerability mapping with dynamic recharge and surface water boundaries, groundwater management, floodplain studies, impact studies for changes in land use, climate, and agricultural practices.

MIKE SHE is a watershed model and is distributed parameter and physically-based. It has the capability of handling both single events and continuous simulations. Watershed is divided into square grid cells. Overland flow routing is based on 2-D diffusive wave equations, whereas options vary for channel flow from simple Muskingum routing to the Higher Order Dynamic Wave formulation of the Saint-Venant equations. Ground water flow is solved with 3-D full Richards' equation. Stream-ground water interactions are considered. In general, depending on the size of the watershed, simulations can be computationally very intensive. MIKE SHE can be used in combination with MIKE-11 for river hydraulics. This modeling package, however, is proprietary. GIS interface for the MIKE SHE uses ArcView 3.X GIS.

SWMM, Storm Water Management Model (Huber and Dickinson, 1988)

The USEPA's SWMM model is a comprehensive computer model for analysis of quantity and quality problems associated with urban runoff. Both single-event and continuous simulation can be performed on catchments having storm sewers, or combined sewers and natural drainage, for prediction of flows, stages and pollutant concentrations. It is structured in the form of blocks. The principal computational blocks include the Runoff Block for generation of runoff and quality constituents from rainfall (plus simple routing of flow and quality), the Transport Block for kinematic wave routing and for additional dry-weather flow and quality routing, the Storage/Treatment Block for reservoir routing and simulation of treatment and storage quality processes, and the Extended Transport or Extran Block for hydraulic routing of flow (no quality routing) using the complete Saint-Venant equations. Using SWMM, the modeler can simulate all aspects of the urban hydrologic and quality cycles, including rainfall, snowmelt, surface and subsurface runoff, flow routing through the drainage network, storage and treatment. The Rain Block is used for processing of hourly and 15-minute precipitation time series for input to continuous simulation. Although the historical basis of the model was for analysis of urban runoff quality problems, the model often is used just for hydrologic and hydraulic analysis. The model is designed for use by engineers and scientists experienced in urban hydrologic and water quality processes. An engineering background is necessary to appreciate most methods being used and to verify that the model results are reasonable. SWMM Version 4 is microcomputer based (DOS-compatible), although the Fortran code may be compiled on any machine. For hydrologic simulation in the Runoff Block, data requirements include area, imperviousness, slope, roughness, width (a shape factor), depression storage, and infiltration parameters for either the Horton or Green-Ampt equations for up to 100 subcatchments (number of subcatchments, pipes, etc. are variable depending on the compilation). Flow routing can be performed in the Runoff, Transport and Extran Blocks, in increasing order of sophistication. Extran can also simulate dynamic boundary conditions, e.g., tides. Quality processes are initiated in the Runoff Block and include options for constant concentration, regression of load vs. flow, and buildup wash-off, with the latter requiring the most data. Additional options include street cleaning, erosion, and quality contributions from precipitation, catchbasins, adsorption, and base flow. USEPA Nationwide Urban Runoff Program data are often used as starting values for quality computations. SWMM interfacing requirements are clearly defined. For example, output may be directed to the EPA WASP receiving water model. Basic SWMM output consists of hydrographs and pollutographs (concentration vs. time) at any desired location in the drainage system. Depths and velocities are also available as are summary statistics on surcharging, volumes, continuity and other quantity parameters. Additional quality output includes loads, source identification, continuity, residuals (e.g., sludge), and other parameters. GIS linkage is available. The model performs best in urbanized areas with impervious drainage, although it has been widely used elsewhere. Technical limitations include lack of subsurface quality routing (a constant concentration is used), no interaction of quality processes (apart from adsorption), difficulty in simulation of wetlands quality processes (except as can be represented as storage processes), and a weak scour deposition routine in the Transport Block. The current edition, version 5.0 (Rossman, 2008), is a complete re-write of the previous release and uses Windows to provide an integrated environment for editing study area input data, running hydrologic, hydraulic, and water quality simulations, and viewing the results in a variety of formats. These include color-coded drainage area and conveyance system maps, time series graphs and tables, profile plots, and statistical frequency analyses. Although a Windows-based graphical interface is present for this model, it has not been integrated with a GIS. SWMM has been used in scores of U.S. cities as well as extensively in Canada, Europe, Australia and elsewhere.

CHAPTER III

DETAILS OF MODELING TOOLS

In the past, a number of lumped hydrological models have been developed (Crawford and Lindsey, 1963; Sittner et al., 1969). Parameters of such models do not have a direct physical meaning and cannot be derived with ease from the measured properties of the watershed. These limitations have led to the development of physically-based catchment models (Refsgaard and Storm, 1995; Arnold et al., 1998). Parameters of these models are linked to the properties of the catchment via soil, land use, and topography. Soil and Water Assessment Tool (SWAT) used in this study is a physically-based catchment model.

SWAT Model Description

SWAT was developed by Dr. Jeff Arnold for the United States Department of Agriculture-Agriculture Research Service (USDA-ARS). SWAT is a watershed-scale, physically-based, continuous simulation model, which is capable of simulating landscape hydrologic and contaminant transport and transformation processes at a high spatial resolution (Santhi et al., 2006). The entire watershed can be divided into sub-watersheds, which can be further discretized into unique combination of land use, soils, and slopes called Hydrologic Response Units (HRUs). Subbasins can be divided into a single HRU or multiple HRUs based on threshold percentages used for the selection of land use and soil (Arnold et., 1998). Major components of the model include weather, surface runoff, return flow, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, water transfer, soil temperature, erosion and agricultural management practices (Kalin and Hantush, 2006; Santhi et al., 2006). Since this project focused on surface water withdrawal, additional details on the hydrologic components of the SWAT model is provided below.

Hydrologic Components of the SWAT Model

Accurate simulation of hydrology is the backbone of SWAT model. In SWAT, simulation of hydrology of a watershed is done in two separate components: (1) the land phase of the hydrologic cycle that controls the amount of water, sediment, nutrient, and pesticide loadings to the reach in each subwatershed, and (2) the routing phase of the hydrologic cycle that moves the water, sediment, nutrients, and pesticides through the stream network to the watershed outlet.

The land phase of the hydrologic cycle, as described in the SWAT theoretical document version 2000 (Neitsch et al., 2002), is based on the following water balance equation that keeps track of daily soil water content, precipitation, surface runoff, evapotranspiration, water entering the vadose zone, and return flow:

$$SW_t = SW_o + \sum_{t=0}^{t} (R_{day,i} - Q_{surf,i} - w_{seep,i} - E_{a,i} - Q_{gw,i}) \qquad (1)$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

Although not important for our study area, the mass balance equation for snow is given as

$$SNO_t = SNO_0 + R_{day} - E_{Sub} - SNO_{mlt} \tag{2}$$

where, SNO_t= water content in the pack of snow at the end of a day (mm); SNO_0= initial water content in the pack of snow (mm); R_{day} = amount of precipitation on a given day (mm); E_{sub}= amount of sublimation taken place on a given day (mm); and SNO_{mlt} = amount of snowmelt on a given day (mm).

For computing surface runoff from each HRU, SWAT uses USDA Soil Conservation Service (SCS) curve number method (USDA, 1972) or the Green and Ampt infiltration equation (Green and Ampt, 1911). SCS curve number method is the most common method used by the SWAT model and is give by

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \tag{3}$$

where, Q_{surf} in the amount of surface runoff generated (mm); S = retention parameter (mm). In this equation, the initial abstractions (surface storage, interception, and infiltration prior to runoff) is estimated as 0.2S. The retention parameter (S) is given as

$$S = 25.4\left(\frac{1,000}{CN} - 10\right) \tag{4}$$

where, CN = curve number on the given day, which depends on land use, soil permeability, and antecedent soil water conditions.

Evapotranspiration (ET) is the process of water removal from the earth's surface as water vapor, evaporation from plant canopy, transpiration, sublimation, and evaporation from the soil (Kalin and Hantush, 2006). In SWAT, actual ET is calculated from potential evapotranspiration (PET). PET is estimated in SWAT using three methods: (1) Penman-Monteith method (Monteith, 1965), (2) Priestly-Taylor method (Priestley and Taylor, 1972), and (3) Hargreaves method (Hargreaves et al., 1985). Penman-Monteith method was used in this study.

Surface runoff which enters the main channel is calculated using the following equation:

$$Q_{ch,i} = (Q_{surf,i} + Q_{stor,i-1})\cdot\left(1 - e^{-surlag/t_{conc}}\right) \tag{5}$$

where, $Q_{ch,i}$ = amount of surface runoff that enters the main channel on day i (mm); $Q_{surf,i}$= amount of surface runoff generated within the sub basin on day i (mm); $Q_{stor,i-1}$ = surface runoff stored or lagged from day i-1(mm); *surlag* = surface runoff lag coefficient; and t_{conc} = time of concentration of the subbasin (hr).

In SWAT, water is routed through the channels and reservoirs of the subbasin to the outlet of the sub basin using Muskingum or variable storage methods (Williams, 1969) on a daily time step. The former was used in this study.

Groundwater component in SWAT is modeled by two aquifer system consisting of shallow (unconfined) and deep aquifer (confined). Water balance for shallow aquifer is defined as:

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg,i} - Q_{gw,i} - w_{revap,i} - w_{deep,i} - w_{pump,sh,i} \tag{6}$$

where, $aq_{sh,i}$= amount of water stored in shallow aquifer on day i (mm); $aq_{sh,i-1}$ = amount of water stored in shallow aquifer on day i-1 (mm); $w_{rchrg,i}$= amount of recharge water entering the aquifer on day i (mm); $Q_{gw,i}$= discharge from ground water, or base flow contribution to the main channel on day i (mm); $w_{revap,i}$= amount of water moving through the soil zone as a result of water deficiencies on day i (mm); $w_{deep,i}$ = amount of water that percolates from the shallow aquifer into the deep aquifer on day i (mm); $w_{pump,sh,i}$ = amount of water that is removed from the shallow aquifer through pumping on day i (mm). Water entering the deep aquifer is thought to be lost from the system.

Criteria Used for Water Withdrawal

Water withdrawal for irrigation from various order streams in the watershed would lead to ecological impacts on streams. Hence, water withdrawal needs to be done in such a way that it leaves minimal impact on in-stream flows. This highlights the need for developing in-stream flow criteria. Although developing in-stream flow criteria for the sustainability of a stream have been much discussed, relatively little work has been done to develop numeric criteria. Ideally, ecological sustainability criteria should be agreed upon by the federal, state and local agencies and should leave minimal impact on a stream. Since numeric in-stream flow criteria are generally not available for most of the watershed, especially in Alabama, criteria selected for this study (Table 1) is borrowed from Richter et al. (2003) and (USFWS and EPA, 1999). These are the criteria agreed upon by U.S. Environmental Protection Agency (USEPA) and U.S. Fish and Wildlife Services (USFWS) for the Apalachicola-Chattahoochee-Flint (ACF) river basin in Alabama, Florida, and Georgia. Since ACF basin is close to the study watershed, the criteria developed for ACF were used in this study. The criteria listed in Table 1 are fairly comprehensive and ensure that not only low flows, but also average flows and high flows are preserved. The criteria for maintaining sustainable low flows were monthly 1-day minima and annual low-flow duration, while the criteria for maintaining sustainable high flows were annual 1-day maxima and annual high-flow duration. More detail on computation of these criteria can be found in USFWS and EPA (1999).

As discussed in the introduction section, while different crops have different water needs, in Alabama, the minimum water required is about 3.7 ac-ft (about 4570 m^3) for one irrigated hectare area (Larry Curtis, 2008; personal communication). Except for extreme drought years, this quantity of water is thought to be sufficient for most crops in Alabama (ACES, 1994).

Table 1: List of criteria used for maintaining sustainable flow.

Flow parameter	**Guidelines for maintaining flows**
Monthly 1-day minima	Exceed the minimum in all years Exceed the 25th percentile in 3 out of 4 years Exceed the median in half of the years
Annual low-flow duration	Do not exceed the maximum in all years Do not exceed the 75th percentile in 3 out of 4 years
Monthly average flow	Maintain the monthly mean flow within the range of the 25th and 75th percentile values in half of the years
Annual 1-day maxima	Exceed the minimum in all years Exceed the 25th percentile in 3 out of 4 years Exceed the median in half of the years
Annual high flow duration	Exceed the minimum in all years Exceed the 25th percentile in 3 out of 4 years Exceed the median in half of the years

CHAPTER IV

RESEARCH PROCEDURE

Study Area

The Big Creek watershed, a sub-watershed of the Converse Lake watershed, encompassing approximately 8158 hectare (about 31.5 mile^2) area in the Mobile County in southwest Alabama was selected for this study (Figure 2). The selection was based on the availability of data for SWAT modeling. Lake Converse is the primary source of drinking water for the City of Mobile. A USGS stream gauge (02479945) is located at the outlet of the watershed. Mean annual precipitation in the watershed is about 66 inches. Elevation in the watershed ranges from a maximum of 100 m to a minimum of 34 meters at the watershed outlet. The land use in the watershed is mixed with 47.8% evergreen forest, 27.2% rangeland grasses, 10.7% pasture, 10.4% forested wetlands, and 3.9% agricultural land. Pasture and agricultural land are properly managed land used for grazing and growing row crops. The land use in the watershed has remained stable in the last 15 years. The soils in the watershed comprise mainly of Troup-Bennadale (52.96%), Troup-Heidel (19.77%), Heidel (7.78%), Troup (2.29%), Bama (2.9%), and Notcher (14.3%). The coastal plain geology dominates in the watershed.

Management practices used for pasture and agricultural area were bahiagrass and peanut-cotton rotation, respectively. Actual crop rotation in a watershed varies from year to year and accurate crop rotation information is usually not available for modeling purposes for most watersheds. Therefore, on the basis of statewide BMP database prepared by Butler and Srivastava (2007), peanut-cotton rotation was selected for modeling row crop areas.

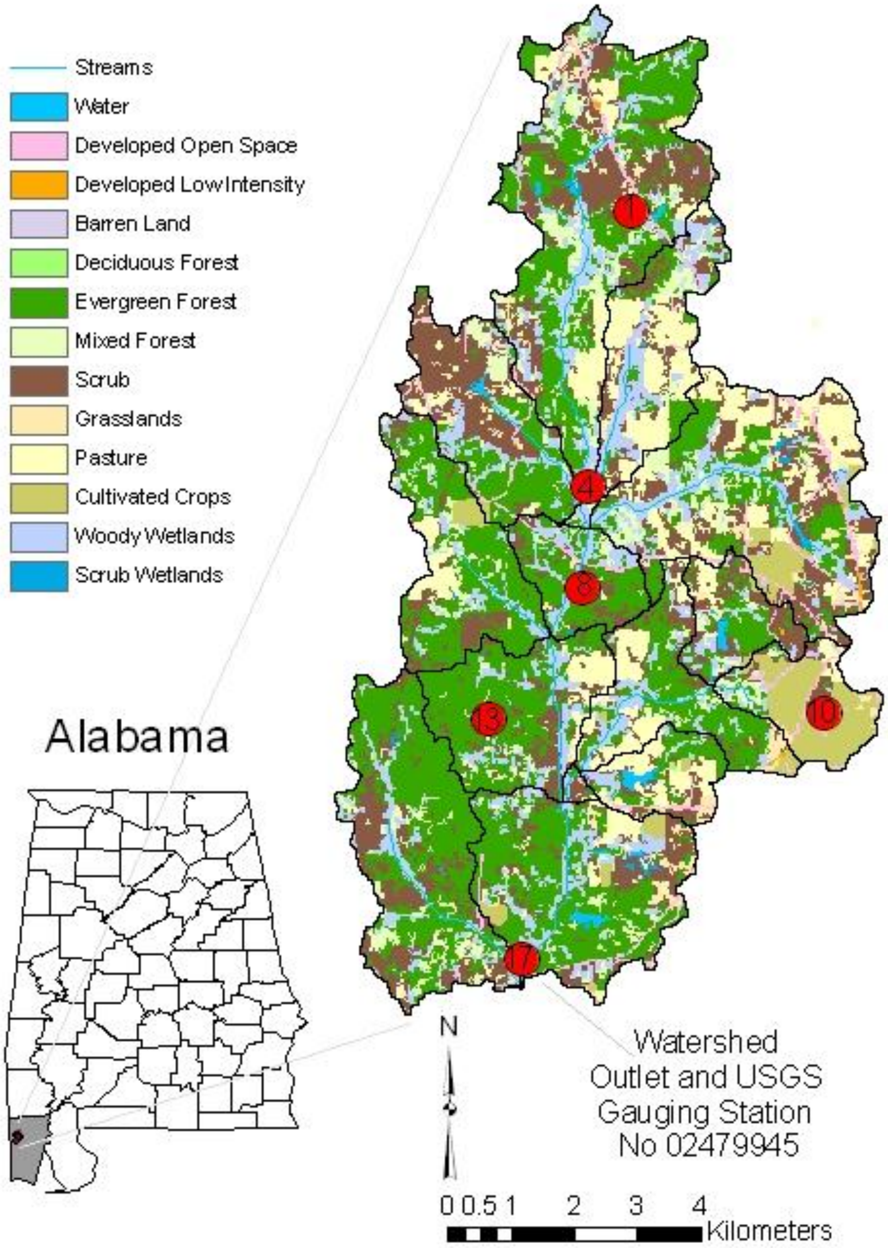

Figure 2: Landuse distribution and the locations of USGS gauging station in the SWAT delineated Big Creek watershed. Also shown are the subbasins evaluated for this study.

Model Input Data Preparation

Basic input data required for SWAT simulation are topography, weather, land use, soil, and management data. Topography data is used to delineate watershed and its multiple subbasins. Topography data was obtained in the form of digital elevation model (DEM) at 30 m resolution from Alabama State Water Program (ACES, 2009). Daily climatic data required include precipitation, wind speed, solar radiation, and relative humidity for each subbasin. In this study, daily precipitation data was obtained from a weather station located near the watershed, while the rest of the climatic inputs were generated internally in SWAT using monthly climate statistics which are based on long-term weather records. Since all other weather stations were too far away to accurately represent conditions within the watershed, true spatial variability of rainfall could not be captured. Spatial variability of rainfall is clearly important, and where appropriate data are available, simulation results can be improved by considering spatial variability of rainfall in modeling exercises. However, especially for small watersheds, lack of multiple weather stations is a common problem, and therefore, this study represents a real world scenario in which SWAT and other similar models are applied. The land use (NLCD 2002) and SSURGO (The Soil Survey and Geographic) soils data were also obtained from Alabama State Water Program (ACES, 2009). As mentioned earlier, the management practice data for pasture and agriculture were obtained from statewide BMP database prepared for the entire State of Alabama by Butler and Srivastava (2007).

SSURGO Soils Data Preparation

The SSURGO soils data was used for model simulation in this study. SSURGO data for the Mobile County was downloaded from Alabama State Water Program website (ACES, 2009). The major soils in the watershed were Troup-Benndel, Troup-Heidel, Heidel, Troup, Bama, and Notcher. The SSURGO data cannot be used directly in ArcSWAT. However, there is a SSURGO Extension Tool (SEA) (Peschel et al., 2003) for AVSWATX which can preprocess SSURGO soil data for the watershed automatically. In this study, ArcSWAT was used for which SEA tool was not designed. Thus, a manual procedure was used. In the manual procedure, the major soils in the watershed (listed above) were first identified using ArcGIS 9.2. Properties of these soils are assessed from the MS Access SSURGO database and entered in the soils database in ArcSWAT manually. Finally, each major soil was linked to its properties in ArcSWAT interface based on their unique map unit symbol (MUSYM).

Base Flow Separation

Total flow in a stream constitutes of two main parts, surface runoff and base flow. The former is a fast contributor to the flow, while the later has a slow response to the flow in the stream (Kalin and Hantush, 2006). SWAT model calculates base flow and surface runoff separately. Hence, for better calibration and validation of the model, it is necessary to separate observed streamflow into base flow and surface runoff so that surface runoff and base flow can be calibrated and validated separately. For this study, base flow was separated based on the method described by Lim et al. (2005) using the WHAT program developed at Purdue University. The digital filter technique incorporated in the WHAT program was used for base flow separation. This method is based on signal analysis and processing which separates high frequency signals from low frequency signals (Lyne and Hollick, 1979). Thus, base flow is separated from direct runoff, because high frequency waves are associated with direct runoff and low frequency waves with base flow (Eckhardt, 2005).

Model Calibration and Validation

"SWAT model was built with state-of-the-art components with an attempt to simulate the processes physically and realistically (Santhi et al., 2001)." However, similar to most current physically-based watershed models, SWAT also has a number of empirical components. Certain variables in SWAT, such as curve number and cover and management factor in modified universal soil loss equation (MUSLE), are not fixed physically (Santhi et al., 2006). Therefore, it needs to be calibrated and validated with observed data before simulating for future scenarios (Kalin and Hantush, 2006).

For this study, the calibration was performed separately for surface runoff and baseflow using monthly flows from 1990 to 2003. Validation was performed using monthly flows from 2004 to 2008. Observed flow data was obtained from the USGS gauging station (02479945) at the outlet of the watershed (also the outlet of subbasin 17) as shown in Figure 1. From the observed flows, surface runoff and base flows were separated using the procedure described earlier.

The streamflow calibration process was completed by varying SWAT hydrologic calibration parameters to match the model-predicted monthly surface runoff and baseflows with the observed surface runoff and baseflows. The parameters calibrated were runoff curve number (CN2), groundwater revap coefficient (GW_REVAP), groundwater delay (GW_DELAY), and threshold depth of water in shallow aquifer required for return flow to occur (GWQMN). Adjustment of these parameters (especially CN2) have been found necessary for calibration and validation of flow in many SWAT studies including Green et al. (2006), Srivastava et al. (2006), and Santhi et al. (2001). The model predictions were evaluated for both calibration and validation periods using two statistical measures described below.

Goodness-of-Fit Statistics Used

Statistical parameters used to evaluate model prediction against observed values were coefficient of determination (R^2) and Nash-Sutcliffe efficiency (E_{NS}), which are defined as:

$$R^2 = \frac{\left[\sum_{i=1}^{N}(O_{obs,i}-\bar{O}_{obs})(O_{sim,i}-\bar{O}_{sim})\right]^2}{\left[\sum_{i=1}^{N}(O_{obs,i}-\bar{O}_{obs})^2\right]\left[\sum_{i=1}^{N}(O_{sim,i}-\bar{O}_{sim})^2\right]} \tag{7}$$

$$E_{NS} = 1.0 - \frac{\left[\sum_{i=1}^{N}(O_{sim,i}-O_{obs,i})^2\right]}{\left[\sum_{i=1}^{N}(O_{obs,i}-\bar{O}_{obs})^2\right]} \tag{8}$$

where, $O_{sim,i}$ and $O_{obs,i}$ are simulated and observed flows, respectively, for the ith observation; N is the number of observations; and $\bar{O}_{sim}$ and $\bar{O}_{obs}$ are average simulated and observed flows, respectively, for the simulation period.

Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) is the measurement of how well the plot of observed and predicted values fit the 1:1 line. R^2value is a measure of strength between observed and simulated values. A lower value for these statistical parameters suggests a poor prediction of the model, while a higher value suggests a good prediction of the model. A value of greater than 0.5 for these parameters is considered acceptable, which was also the criteria used by Santhi et al. (2001).

Water Withdrawal Procedure

For this study, water was withdrawn from streams of different orders (i.e., 1st, 2nd, and 3rd). This was done to study a realistic water withdrawal scenario by farmers or a cooperative body that extracts the water from a stream. A closer look at the water withdrawal criteria used for this study suggests that the criteria are designed to protect low flows, high flows, as well as average flows. The criteria are especially sensitive to flows that drop below 25 percentile and the flows that exceed 95 percentile. Using this observation, the following procedure was adopted for water withdrawal.

When the flow for the day drops below 25th percentile of daily flows for the entire study period, no water is withdrawn from the streams. When the flow is greater than 25th percentile but less than 95th percentile, the water is withdrawn in such a way that the flow does not drop below 25th percentile. When the flow is greater than 95th percentile, about 10 - 15% of total daily flow is withdrawn from the streams. The restriction on water withdrawal from the flows that exceed 95th percentile is based on the practical pumping or diversion constraint. This procedure ensured that the water withdrawal criteria (Table 1) are satisfied and the total yearly water withdrawals are maximized, thus optimizing the entire water withdrawal procedure. The flows were withdrawn only during winter months from (December to April) and the rest of the year was left untouched.

CHAPTER V

RESULTS AND DISCUSSION

Calibration and Validation

Monthly observed and simulated flows at the watershed outlet (Figure 3) were used for SWAT calibration and validation. Date from July 1, 1990 to December 31, 2003 was used for calibration and January 1, 2004 to November 30, 2008 was used for validation. The parameters calibrated and their final values are shown in Table 1. Figures 4, 5, and 6 show calibrated monthly surface runoff, baseflows, and total streamflows, respectively. The graphical results suggest that SWAT accurately predicted monthly surface runoff during the calibration period. The measured monthly average surface runoff of 0.59 m^3/s was slightly higher than the predicted runoff of 0.46 m^3/s over the entire calibration period. This suggests that SWAT slightly under-predicted surface runoff for the calibration period. However, temporal trend of SWAT generated surface runoff closely followed observed surface runoff (Figure 4). This was further confirmed by high statistical parameter values with R^2 0.66 and E_{NS} 0.53.

Graphical comparison of baseflows for the calibration period (Figure 5) and statistical parameters, with R^2 0.76 and E_{NS} 0.69 suggest that the baseflows were adequately simulated by the SWAT model. The estimated monthly average baseflow of 1.11 m^3/s was slightly lower than the predicted baseflow of 1.18 m^3/s over the entire calibration period. Since both surface runoff and baseflows were adequately simulated by the SWAT model, the R^2 and E_{NS} of 0.67 and 0.55 for the total streamflows were also high for the calibration period. The graphical comparison (Figure 6) indicated no significant over prediction or under prediction over this simulation period. This was further confirmed by the graphical comparison of the daily flows for the years 1995 and 1996 (Figure 7).

Table 2: Calibrated SWAT parameters and their final values.

Variable* Name	**Model Process**	**Final Value**	**HRU for which values were changed**
CN2	Flow	55	FRSE-Notcher
		55	FRSE-Bama
		55	FRSE-Heidel
		35	FRSE-Troup Benndel
		35	FRSE-Troup Heidel
GW_REVAP	Flow	0.3	All HRU’s
GW_DELAY	Flow	60	All HRU’s
GWQMN	Flow	0	All HRU’s

* CN2 = Curve number for antecedent moisture condition 2; GW_REVAP = Groundwater “revap” coefficient; GW_DELAY = Groundwater delay time (days); GWQMN = Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O).

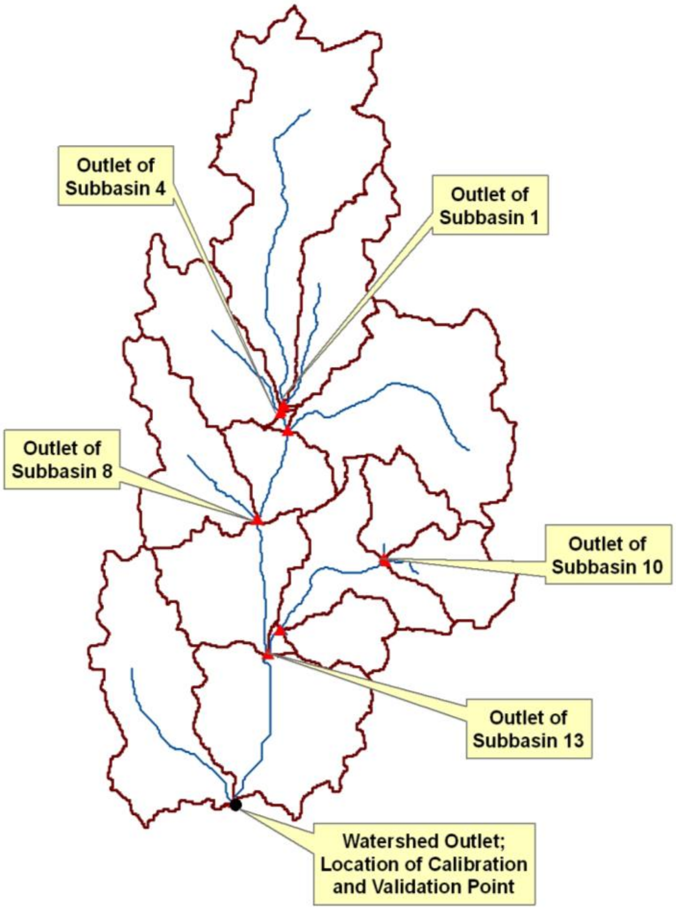

Figure 3: Watershed outlet location used for calibration and validation of the SWAT model. Also shown are the withdrawal points used.

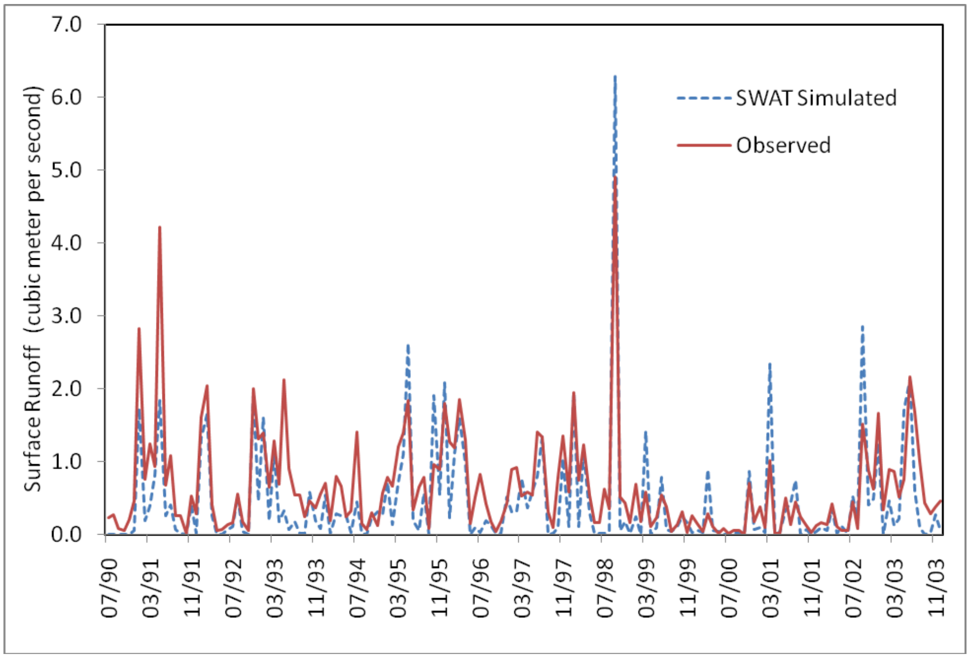

Figure 4: Observed and SWAT simulated monthly surface runoff for the calibration period (July, 1990 – December, 2003).

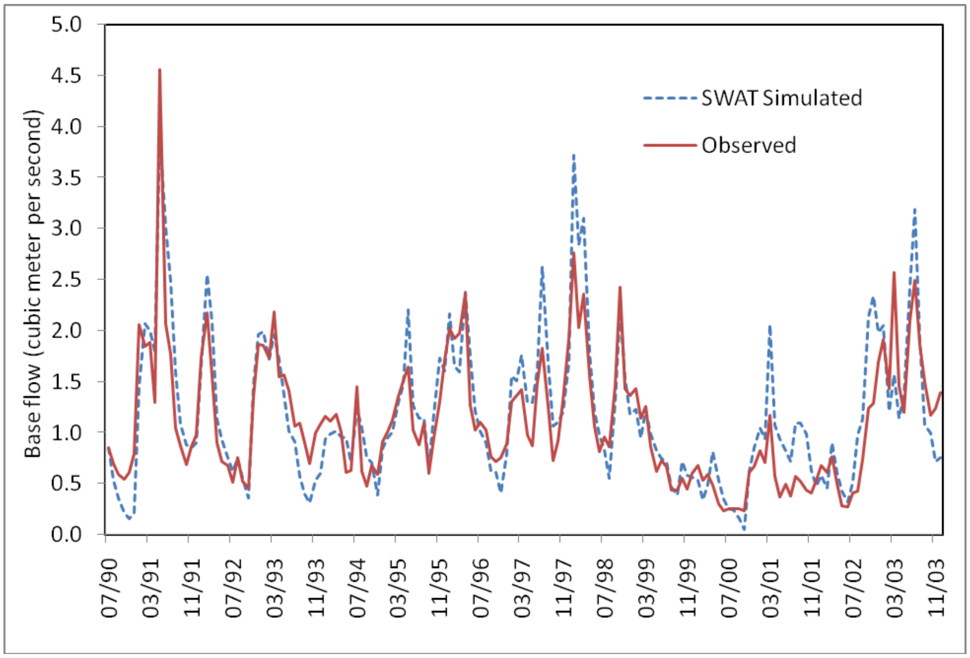

Figure 5: Observed and SWAT simulated monthly base flow for the calibration period (July, 1990 – December, 2003).

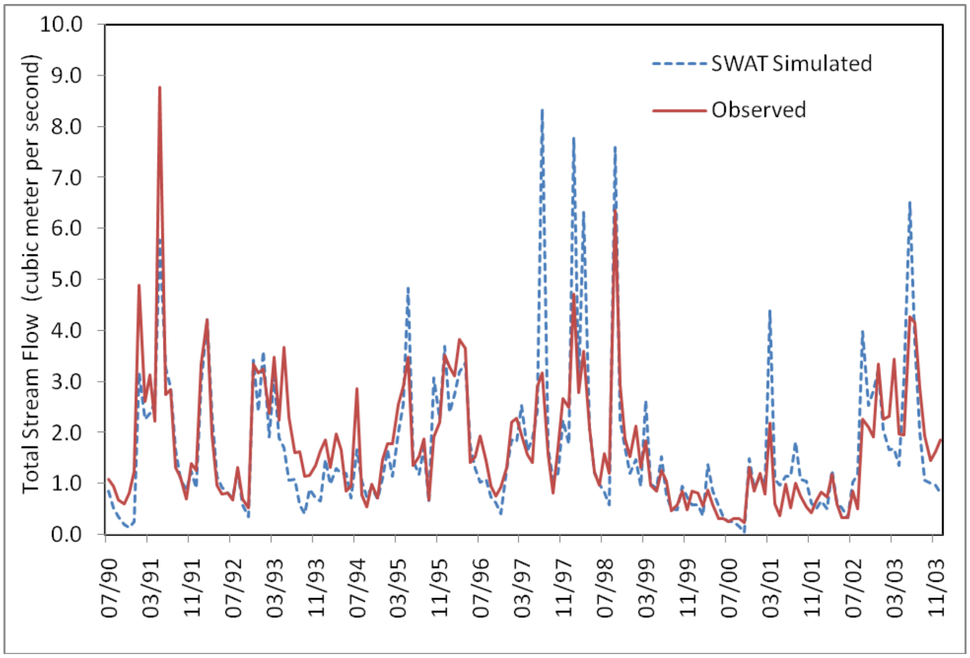

Figure 6: Observed and SWAT simulated monthly total stream flow for the calibration period (July, 1990 – December, 2003).

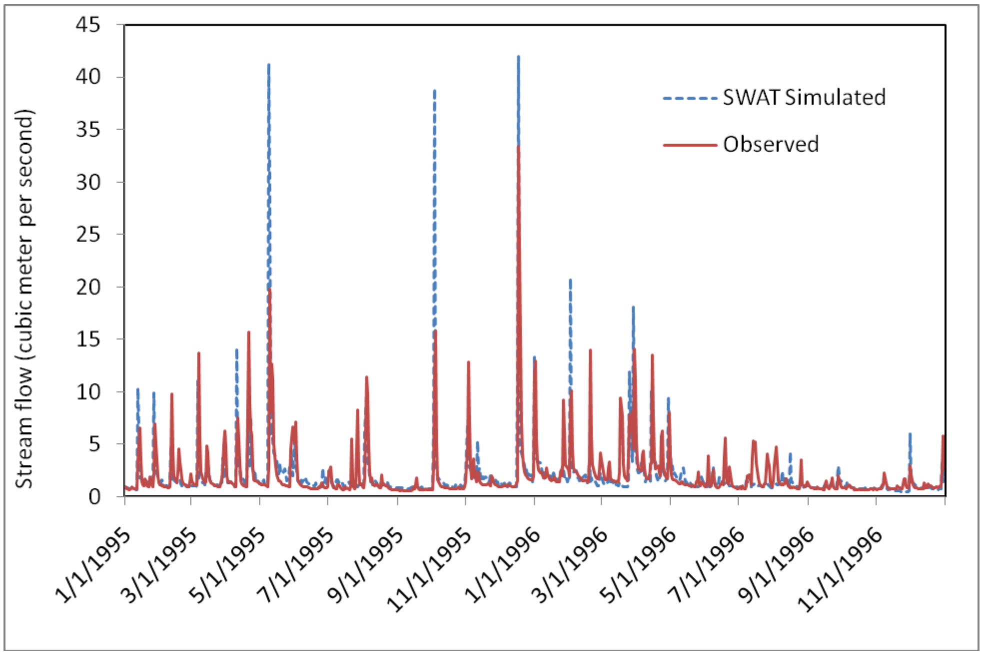

Figure 7: Observed and SWAT simulated daily stream flow for the year 1995 and 1996, shown as an example.

Figures 8, 9, and 10 show validated monthly surface runoff, baseflows, and total streamflows, respectively. The graphical result suggests that SWAT predicted monthly surface runoff were adequate. The estimated monthly average surface runoff of 0.56 m^3/s was slightly higher than the predicted runoff of 0.39 m^3/s over the entire validation. This suggests that SWAT slightly under-predicted surface runoff for the validation period. However, as with the calibration period, temporal trend of SWAT generated surface runoff closely followed observed surface runoff (Figure 8). The statistical parameter values with R^2 was 0.71 and E_{NS} 0.52.

Graphical comparison of baseflows for the validation period (Figure 9) and statistical parameters, with R^2 0.62 and E_{NS} 0.53, suggest that the baseflows were adequately simulated by the SWAT model. The estimated monthly average baseflow of 1.02 m^3/s was about the same as the predicted baseflow of 1.03 m^3/s over the entire validation period. Since both surface runoff and baseflows were adequately simulated by the SWAT model, the R^2 and E_{NS} of 0.66 and 0.50 for the total streamflows were also high for the validation period. The graphical comparison (Figure 10) indicated no significant over prediction or under prediction. This was further confirmed by the graphical comparison of the daily flows for the years 2005 and 2006 (Figure 11).

Since total streamflow predictions were very good, which were used for water withdrawal, SWAT model was considered to be adequately describing the hydrology of the study watershed.

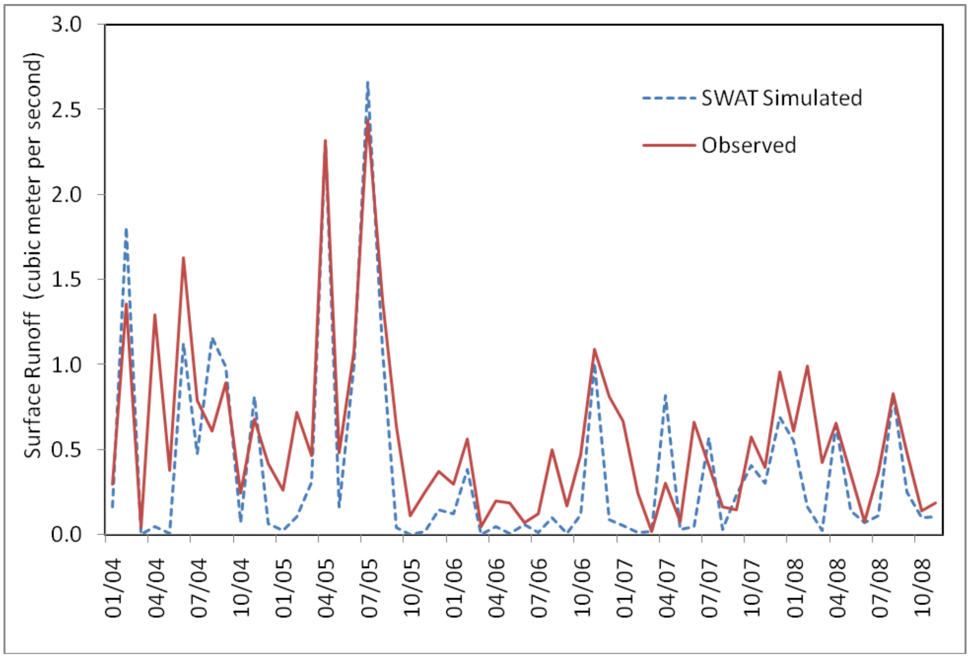

Figure 8: Observed and SWAT simulated monthly surface runoff for the validation period (January 2004 – November, 2008).

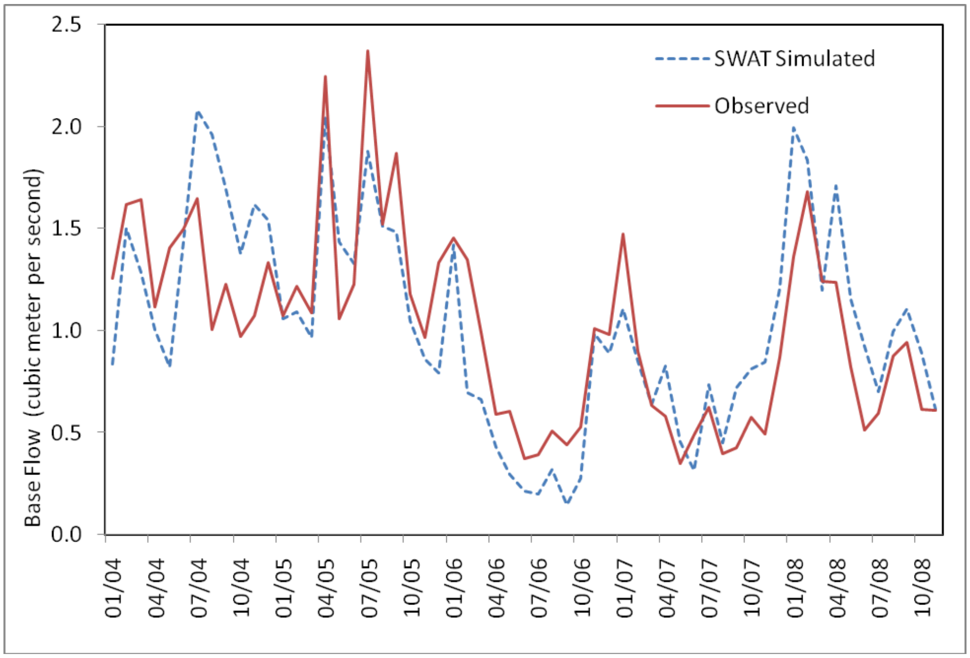

Figure 9: Observed and SWAT simulated monthly baseflows for the validation period (January 2004 – November, 2008).

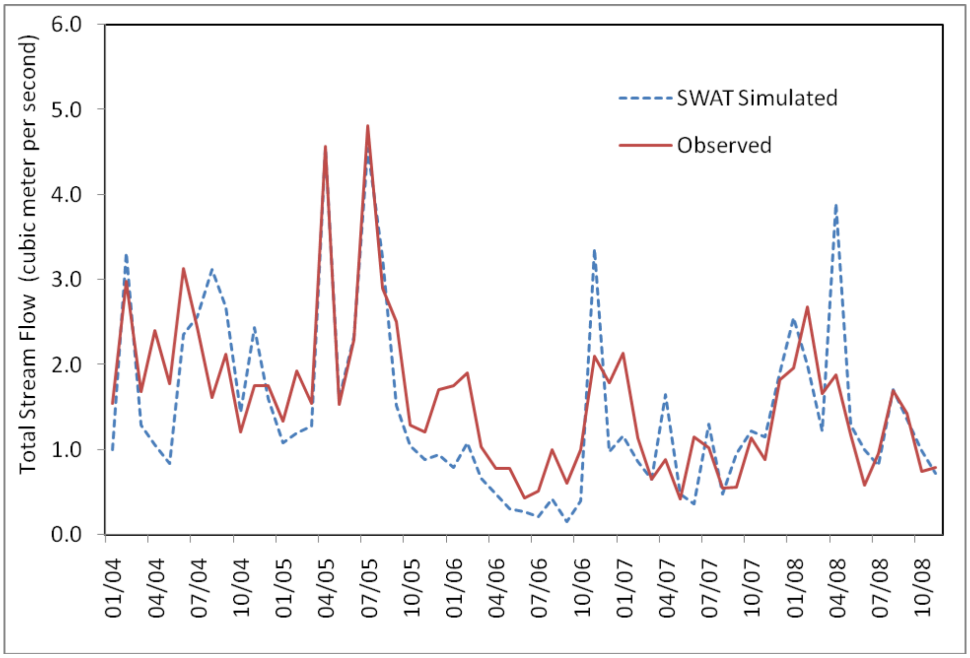

Figure 10: Observed and SWAT simulated monthly total stream flows for the validation period (January 2004 – November, 2008).

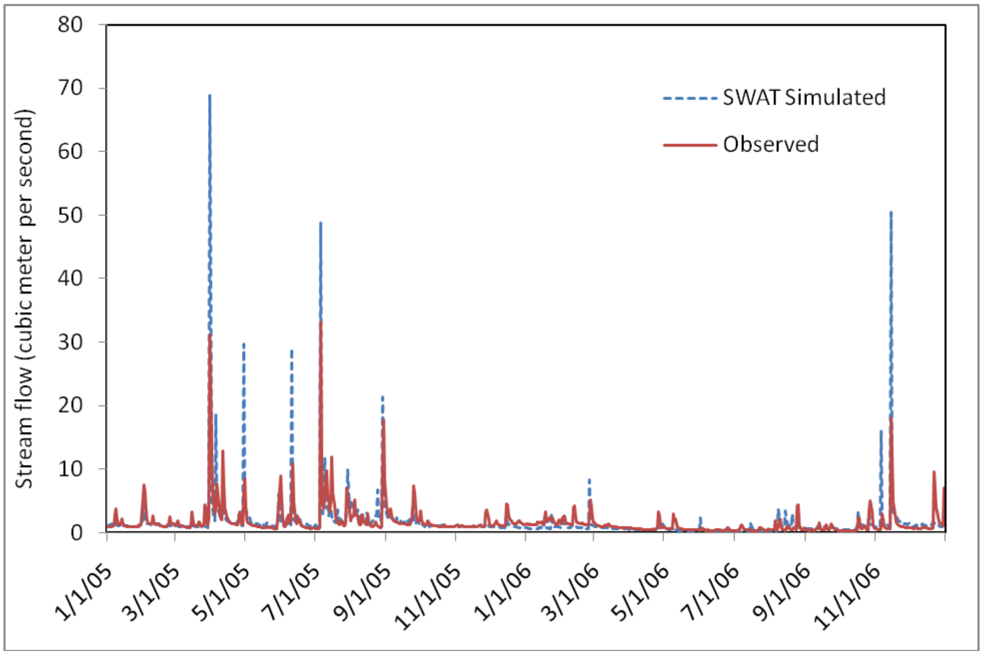

Figure 11: Observed and SWAT simulated daily stream flows for the 2005 and 2006, shown as an example.

Water Withdrawal

Using the procedure described earlier in Chapter IV (Research Procedure), water was withdrawn from two first-order streams in sub-basin 1 and 10; three second-order streams in sub-basins 4, 8, and 13; and one third-order stream in sub-basin 17 (which also drains to the outlet of the watershed). The locations from where the water was withdrawn are shown in Figure 3. Figures 12, 13, and 14 show stream flows before withdrawal, after withdrawal, and water withdrawn on a daily basis for sub-basins 1, 8, and 17, respectively, for the water year 1992, as an example.

As can be noticed from these figures, when the stream flow drops below certain threshold low flow, the water is not withdrawn from the streams. Also, notice that flow is withdrawn only during winter months (Dec – April). When the flows are high (i.e., during major storm events) a certain percentage of high stream flow can be withdrawn. As discussed earlier, in our water withdrawal procedure, only a certain percentage of stream flows was withdrawn when the flows were higher than 95 percentile. It is possible to withdraw more water from these high flows, but there might be some practical limitations to this. Although winter is considered as the wet period in most part of Alabama, it can be seen from these figures that there are periods in these months when no water can be withdrawn. This suggests that a watershed extractor cannot just turn on the pump to withdraw water at a certain constant rate for the entire winter period. The decision for water withdrawal needs to be made on a daily basis by observing the stream flow on a daily basis.

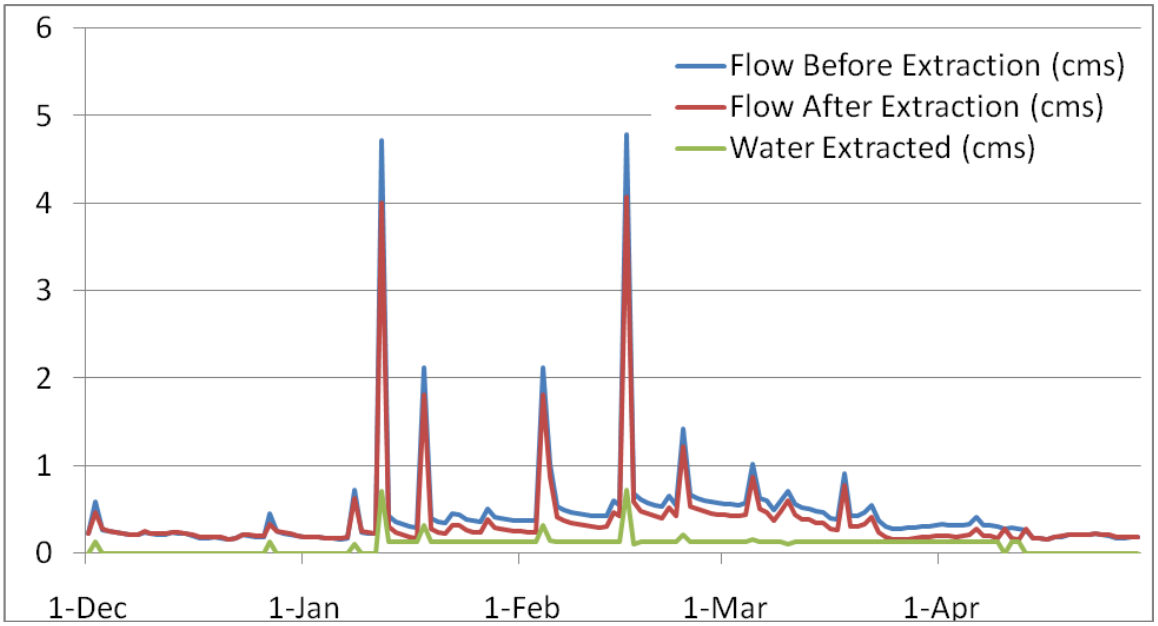

Figure 12: Daily stream flows before and after water extraction, and the water extracted for water year 1992 (Subbasin 1).

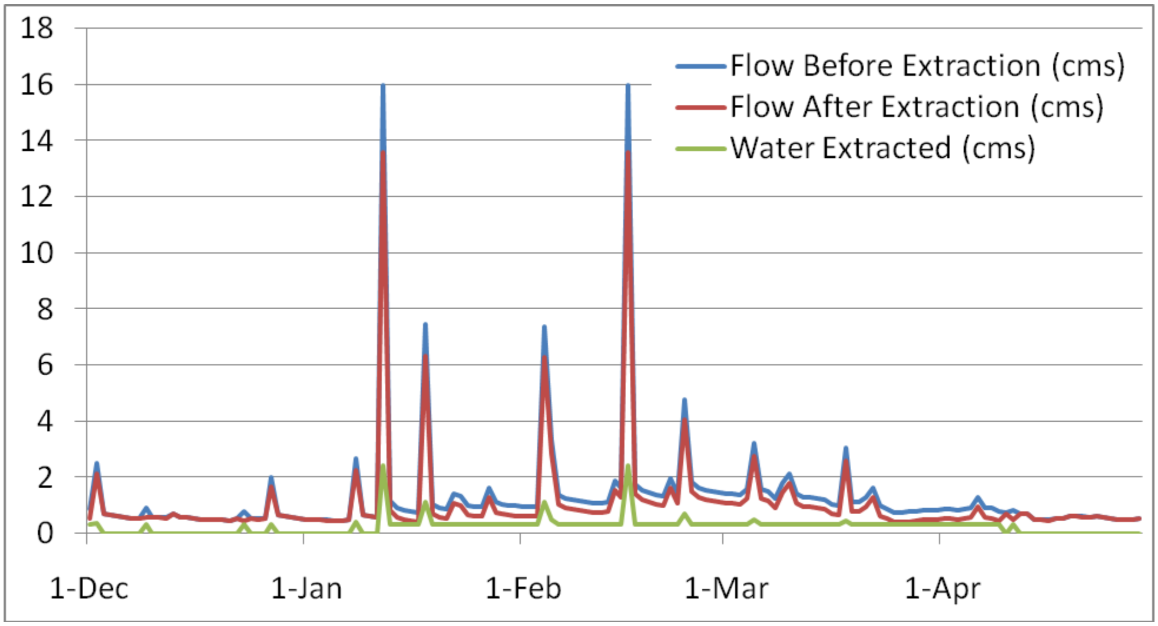

Figure 13: Daily stream flows before and after water extraction, and the water extracted for water year 1992 (Subbasin 8).

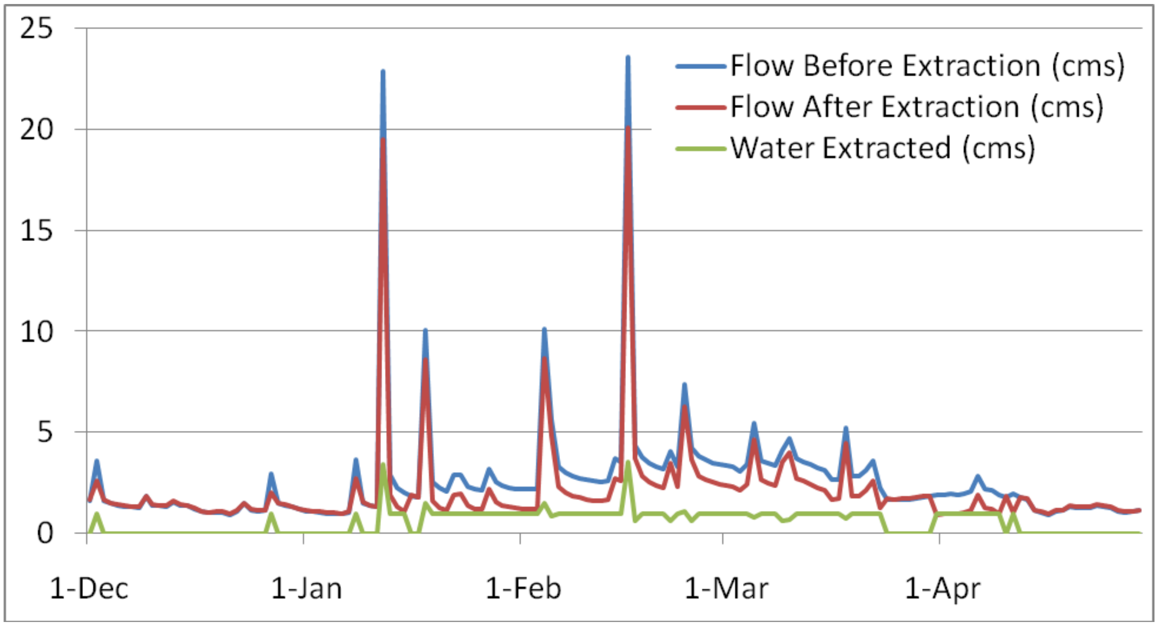

Figure 14: Daily stream flows before and after water extraction, and the water extracted for water year 1992 (Subbasin 17).

Withdrawal of water from 1st order streams

The reaches of Sub-basins 1 and 10 were selected as representative of 1st order streams. Sub-basin 1 drains an area of 3,457 acres while Sub-basin 10 drains 771 acres. On an average, the amount of water that can be withdrawn from Sub-basin 1 is 0.66 million m^3 per year, while it is 0.19 million m^3 for Sub-basin 10 (Table 3).

The predicted amount of area that can be irrigated within the drainage area of Sub-basin 1 varied from a low of 1.5% to a high of 27.9%, with an average of 10.2% per year over the 16 year study period. A higher percentage of area could be irrigated in years 1992, 1993, 1995, 1996, and 1998 due to the fact that these were extremely wet years compared to the other years (Table 3), especially during winter months. Years

1999-2007 were slightly dry to very dry, hence less than 9% area could be irrigated in these years. Since on an average only 0.66 million m^3 of water can be withdrawn each year from Sub-basin 1, water withdrawal from Sub-basin 1 is not sufficient to irrigate the entire agricultural area of the entire watershed which requires 1.42 million m^3 of water per year.

Sub-basin 10, which was 100% agriculture can irrigate on an average 13% of its drainage area with a low of 2.1% to a high of 27.9 % (Table 3). The irrigated area varies as a function of precipitation during winter months; thus higher percentage of sub-basin can be irrigated in wet years 1992, 1993, 1995, 1996, and 1998 when the stream flows were substantial. Since, Sub-basin 10 is in 100% agricultural, stream flows per unit area of the sub-basin is higher; and that is why, overall, a slightly higher percentage of the sub-basin can be irrigated through water withdrawal.

Table 3: Yearly maximum water extraction from first order streams draining subbasins 1 and 10. Percentage of watershed area that can be irrigated is also shown.

			Subbasin 1			Sub basin 10		
Water Year	Winter Month Precip (mm)	Annual Precip (mm)	Annual Flow Volume (million m^3)	Water With drawn (million m^3)	Percent of Subbasin Irrigated	Annual Flow Volume (million m^3)	Water With drawn (million m^3)	Percent of Subbasin Irrigated
1992	824.3	1653.0	10.3	1.2	18.7	2.3	0.2	15.9
1993	872.2	2122.2	13.5	1.6	24.3	3.4	0.3	20.8
1994	551.2	1508.6	8.2	0.3	4.2	2.0	0.2	13.7
1995	837.8	1743.2	11.2	1.4	21.6	2.6	0.3	18.7
1996	1141.4	2012.9	14.3	1.8	27.9	3.4	0.4	27.9
1997	697.7	1520.5	8.3	0.4	5.6	1.8	0.1	9.5
1998	853.9	1955.6	13.7	1.4	21.5	2.9	0.3	18.6
1999	469.9	1042.0	7.4	0.4	5.5	1.5	0.2	12.3
2000	390.2	911.4	4.4	0.1	1.6	0.4	0.0	2.7
2001	426.5	1327.9	7.4	0.2	3.5	1.3	0.1	7.3
2002	368.2	989.0	4.8	0.1	1.5	0.7	0.0	2.1
2003	565.2	1852.3	10.9	0.5	8.1	2.7	0.2	13.1
2004	516.6	1471.7	8.8	0.4	5.6	2.0	0.2	15.0
2005	722.7	1888.8	12.2	0.6	8.9	2.9	0.2	15.4
2006	359.1	923.3	5.3	0.1	1.7	0.9	0.1	6.3
2007	451.1	1263.6	7.2	0.3	3.9	1.3	0.1	8.8
Average	628.0	1511.6	9.2	0.7	10.2	2.0	0.2	13.0

Withdrawal of water from 2nd order streams

Scenario of water withdrawal from higher order streams was also considered. For this exercise, reaches of the sub-basins 4, 8 and 13 were selected to represent second order streams. Sub-basins 4, 8 and 13 drain an area of 4,723, 9,691 and 12,495 acres, respectively.

Sub-basin 4 could irrigate an upland area varying from 1.7% to 30.3% with an average of 10.2% per year (Table 4). The average amount of water extractable from Sub-basin 4 was 0.89 million m^3 per year. This is closer to the amount of water required to sustain present irrigation needs of the agricultural areas (i.e. 1.42 million m^3) in the entire watershed. This is expected because stream of subbasin 4 is a 2nd order stream and hence it is expected to have much more flow compared to 1st order streams. As it can be noted from Figure 2, since most of the agriculture is located in Sub-basin 10, which is downslope from Sub-basin 4, water withdrawn from Sub-basin 4 can be transported to Sub-basin 10, with little external energy input.

Sub-basin 8 can sustain on an average 10.2% of irrigation within the drainage area that drains to this stream with a minimum of 1.6% and a maximum of 27.7% (Table 4). The average quantity of water that could be withdrawn per year was 1.89 million m^3, which was higher than the quantity of water required to irrigate the present amount of agricultural in the watershed. Again, since Sub-basin 8 is upslope from Sub-basin 10, withdrawn water can be easily transported to Sub-basin 10.

Similar to Sub-basin 8, amount of water that could be withdrawn from Sub-basin 13 is sufficient to irrigate 10.5% of the upland area that drains to the outlet of this sub-basin (Table 4). Average quantity of water extractable per year is 2.43 million m^3 per year

Table 4: Yearly maximum water extraction from second order streams draining subbasins 4, 8 and 13. Percentage of watershed area that can be irrigated is also shown for each year.

	Sub basin 4			Sub basin 8			Sub basin 13		
Year	Annual Flow Volume (million m^3)	Water With drawn (million m^3)	Percent of Subbasin Irrigated	Annual Flow Volume (million m^3)	Water With drawn (million m^3)	Percent of Subbasin Irrigated	Annual Flow Volume (million m^3)	Water With drawn (million m^3)	Percent of Subbasin Irrigated
1992	14.8	1.7	19.4	29.5	3.3	18.5	37.3	4.6	20.1
1993	19.5	2.1	24.3	39.1	4.2	23.5	50.1	6.5	28.0
1994	12.0	0.4	4.9	24.3	1.2	6.6	29.7	0.9	3.8
1995	15.7	1.7	19.6	31.6	3.8	21.3	40.1	5.2	22.3
1996	19.5	2.6	30.3	38.8	5.0	27.7	49.9	7.5	32.4
1997	11.3	0.4	5.0	21.8	0.9	5.3	27.8	0.9	4.0
1998	19.5	1.8	20.2	39.3	3.7	20.8	48.8	5.4	23.4
1999	10.2	0.4	5.1	20.1	1.0	5.6	26.9	1.3	5.5
2000	5.6	0.1	1.7	10.3	0.3	1.6	14.9	0.2	1.0
2001	9.9	0.3	3.4	18.8	0.7	3.7	24.6	0.6	2.5
2002	6.7	0.1	1.6	12.6	0.3	1.6	18.0	0.2	0.8
2003	15.4	0.6	6.5	30.9	1.3	7.1	39.0	1.3	5.5
2004	11.9	0.5	6.0	23.3	1.0	5.7	29.2	1.3	5.5
2005	16.6	0.7	8.5	32.9	1.5	8.6	41.4	2.0	8.5
2006	7.4	0.2	1.9	14.4	0.3	1.9	19.8	0.3	1.2
2007	9.9	0.4	4.1	19.3	0.8	4.4	25.6	0.9	3.7
Average	12.9	0.9	10.2	25.4	1.8	10.2	32.7	2.4	10.5

Withdrawal of water from 3rd order streams

The final scenario where water is withdrawn from a 3rd order stream was considered. This stream flows through Sub-basin 17 and drains to the outlet of the watershed. The area upstream of the outlet of this stream is 20,160 acres. Sub-basin 17 can irrigate a drainage area varying from 1.2% to 32.7%, with an average of 10.6% per year, of the upland area (Table 5).

Table 5: Yearly maximum water extraction from the third order stream draining Subbasin 17 (the watershed outlet). Percentage of watershed area that can be irrigated is also shown for each year.

Sub basin 17				
Year	Annual Precipitation (mm)	Annual Flow Volume (million m^3)	Water Withdrawn (million m^3)	Percentage of Subbasin Irrigated
1992	1653.0	59.8	7.6	20.3
1993	2122.2	80.5	10.1	27.2
1994	1508.6	47.6	1.5	4.0
1995	1743.2	64.5	8.3	22.4
1996	2012.9	80.7	12.2	32.7
1997	1520.5	45.3	1.6	4.4
1998	1955.6	77.7	8.6	23.1
1999	1042.0	43.2	2.0	5.5
2000	911.4	24.3	0.3	0.7
2001	1327.9	40.1	1.0	2.8
2002	989.0	28.9	0.3	0.8
2003	1852.3	62.7	2.0	5.5
2004	1471.7	47.4	2.1	5.7
2005	1888.8	66.9	3.3	9.0
2006	923.3	31.8	0.4	1.2
2007	1263.6	41.1	1.5	3.9
Average	1511.6	52.6	3.9	10.6

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the amount of water that can be extracted for irrigation from 1st, 2nd, and 3rd order streams in the Big Creek watershed located in Mobile County, Alabama, while ensuring ecological sustainable stream flows. Although the percentage of upstream area (upstream of the location from where the water is withdrawn) that can be irrigated varies slightly depending on the order of stream and the land use in the watershed, it can be concluded that on an average this percentage remains stable. In this study, this percentage is estimated to be about 10%, based on 16 years of data. If simulation for a longer time span is conducted, this percentage might change slightly; however, it should not be a function of stream order. This finding is consistent with the well-known fact that the flows are a function of drainage area. This finding is substantial because it suggests that no matter how large a stream is, it can only provide enough water to sustainably irrigate only a certain fixed percentage of the upland area.

It is evident from the results that a completely agricultural watershed might discharge slightly more water, and might provide additional water for irrigation (e.g., Sub-basin 10). However, this increase in percentage is not substantial. In a mixed land use watersheds, this percentage would be fairly fixed and would not change substantially. Another important finding of this study is that there appears to be considerable variability in the amount of water that can be extracted from various streams. It is highly dependent on the amount of precipitation in winter months. In the Southeast, especially in the lower part of Alabama and much of Florida and Georgia, winter precipitation has been linked to ENSO (El Niño Southern Oscillation). Although the ENSO signal in the region is strongest in fall and winter months, some evidence exists that La Niña summers tend to be slightly wetter than normal (Sittel, 1994). This means that it is possible to predict how much water might be available for withdrawal by looking at the ENSO phase. Also, if a wet year is followed by a dry year, the excess amount of water withdrawn from the wet year can be used for irrigation in the dry year. However, it is possible to observe extremely dry years back-to-back and it is not possible to withdraw any water for irrigation, which is the case in some of the years considered in this study. Therefore, it appears the Alabama and other southeastern states should not entirely rely on surface water for irrigation, especially if they want to maintain ecologically-sustainable flows.

Since, currently, only a small percentage of the watershed is used for agriculture and since providing increased irrigation infrastructure would result in land use conversion to agricultural areas, future research should focus on the impact of land use changes (e.g, pasture conversion to cropland and forest conversion to cropland) on the hydrology of the watershed. This will allow better assessment of the amount of water available for withdrawal under various land use while maintaining the flow criteria. Also, since stream flows depend on ENSO, research needs to be conducted to determine if ENSO information can be used to set water withdrawal policies. It is also important to study the availability of water for withdrawal during growing season, especially during high intensity convective storms.

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