Influence of climate variability on the ecologically sustainable water withdrawals from streams for irrigation

by

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Abstract

Alabama (AL) receives a large amount (1270-1727 mm annual average) of rainfall annually. However, much of the rainfall occurs in the non-crop growing season (winter months), and recurring, severe droughts during the crop growing season lead to losses in crop production. In the past two decades, percentage of cropland area irrigated in AL has increased from 42 to 51%. In AL, in addition to using groundwater for irrigation, farmers mostly withdraw water from streams to irrigate crops. However, if water withdrawal from streams is not done in an ecologically-sustainable manner, it can potentially harm stream ecology and reduce the dilution capacity of streams, and therefore impact water quality and aquatic biota. In the southeast United States (U.S.), the quantity of water that can be ecologically-sustainably withdrawn from streams for irrigation depends on El Niño Southern Oscillation (ENSO), a seasonal-to-interannual (SI) climate-variability phenomena. Therefore, it is important to understand how ENSO affects streamflows and therefore, quantity of water that can be sustainably withdrawn from streams for irrigation. The major goals of this study were to: (a) determine how ENSO forecasts can be used to withdraw water sustainably from streams for irrigation and (b) quantify the effect of upstream water withdrawals from streams on the downstream water withdrawals. The study was conducted in the Swan Creek watershed located in Limestone County, AL, U.S. The Soil and Water Assessment Tool (SWAT) model was used to simulate streamflows and develop water withdrawal prescriptions. The results of this study show that La Niña phase of ENSO generated more rainfall from January to March (non-crop growing season), and the El Niño phase generated more rainfall from May to December (except October) (crop growing season). Irrespective of the ENSO phase, the amount of water that can be sustainably withdrawn from streams during non-crop growing season was two times the amount of water that can be withdrawn sustainably from streams during crop growing season. During non-crop growing season, volume of water that can be sustainably withdrawn from streams was greater during La Niña phase relative to El Niño phase. The results indicate that when water withdrawals based on water withdrawal criteria were made at the outlet of each subwatershed with no water withdrawals upstream, on an average, the percentage of subwatershed area than be irrigated using water withdrawn ranged from 1.4% to 10%. This range depended on season (crop growing vs. non-crop growing) in which water was withdrawn and stream order. The water withdrawals in upstream areas affected downstream flows. For example, at the watershed outlet on an average annual basis, volume of water available for withdrawal reduced by 72% when the water withdrawals were made at the outlet of all the subwatersheds upstream of watershed outlet relative to no withdrawals made upstream of watershed outlet. For a pond with an average depth of 2.13 m (7 feet), surface area required (m^2) could be calculated as 0.214 times the area under irrigation (m^2). Overall, results of this study show that ENSO forecasts can be used to withdraw water sustainably from streams for irrigation.

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Chapter 1

Introduction

1.1 Background

In the state of Alabama (AL), United States (U.S.), crop production mostly depends on natural precipitation. Therefore, inadequate precipitation during the crop growing season can affect crop yield. Although AL is blessed with plenty of annual precipitation, most of the precipitation occurs in the non-crop growing months (Dougherty et al. 2007). Due to unavailability of water during critical stages of crop growth, there has been a substantial decrease in crop yield in the past years (Morison et al. 2008). Irrigation has been a successful practice all over the world to battle water scarcity during the crop growing season. Irrigation accounts for 70% of freshwater withdrawals in the world from surface and groundwater sources. Farmers in AL are becoming increasingly vigilant of irrigation as a means to enhance crop production and the area under irrigation has seen an upsurge over a past decade. Subsequently, lack of sufficient flows in streams during the crop growing season and groundwater being inadequate or unfeasible for irrigation are two of the major limitations faced by farmers to expand irrigation operations in AL (ACES 1994).

Natural climate variability has a substantial impact on society, especially water resources and agriculture. El Niño Southern Oscillation (ENSO) influences crop production all over the globe through its influence on weather patterns. In Southeastern US, ENSO has been documented to have substantial effect on climate and water resources (Mo and Schemm, 2008). To determine the impacts of climate variability on water resources, it is important to study the effect of ENSO on watershed level hydrological processes. Irrigation management practices could be tailored to decrease the adverse influence of ENSO on water resources and could help growers make better water management decisions.

Crop production can be increased by water harvesting from streams during high seasonal streamflows with storage in the on-farm reservoirs or ponds with later use during limited precipitation or critical crop growth stages. While water withdrawals from streams during the non-crop growing season seems feasible, water withdrawals should be done sustainably. Excessive water withdrawals from streams and rivers can affect in-stream habitat and biota at times of low flow. Therefore, water withdrawals from streams must comply with the norms of federal and state agencies which would leave a minimal impact on water resources.

A watershed hydrological model such as Soil and Water Management Tool (SWAT) can be used to study the effect of management practices on watershed level hydrological processes. SWAT model has a capability to model streamflows at different points in the watershed on a long-term scale. Therefore, use of SWAT model to simulate streamflows as a function of ENSO phases can help to quantify the amount of water available for irrigation from streams in different ENSO phases.

1.2 Research Objective

The major goal of this study was to understand the effect of ENSO on streamflows and determine the amount of watershed area that can be irrigated using water withdrawn from streams in an ecological sustainable manner. The major objectives of the study are listed below:

1. To demonstrate an innovative approach to rainwater harvesting for irrigation based on ENSO forecasts.
2. To quantify the effect of ENSO based upstream water withdrawals for irrigation on the downstream water withdrawals.

1.3 Thesis Outline

In this thesis, each objective mentioned is the focus of a separate chapter and each chapter is written as a separate manuscript.

Chapter 2 focus to quantify the effect of ENSO on temperature, precipitation, streamflow and water withdrawal. It aims to develop water withdrawal prescriptions based on ENSO forecasts. Furthermore, the percentage of area irrigated, and the size of pond required to store the water withdrawn is quantified in the chapter.

In chapter 3, the main focus is to quantify the effect of water withdrawals from streams in the upstream areas of the watershed on downstream streamflows. Additionally, as a function of crop growing (Apr.-Sep.) and non-crop growing seasons (Dec.-Mar.), we quantified the effect of ENSO on temperature, precipitation, streamflows and water withdrawals. The effect of upstream water withdrawals was quantified for three scenarios i.e. with no water withdrawals upstream of the withdrawal point, simultaneous water withdrawals from all upstream reaches, and withdrawal only from 2nd order streams. Finally, the pond sizes were determined to store water withdrawn from streams as a function of area under irrigation.

In chapter 4, conclusions of this study and recommendations for the future work are discussed.

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Chapter 2

An innovative approach to rainwater harvesting for irrigation based on ENSO forecasts

Abstract

Alabama (AL) receives a large amount (1270-1727 mm) of rainfall annually. However, much of the rainfall occurs in the non-growing season (winter months), and recurring, severe droughts during the crop growing season lead to losses in crop production. In AL, in addition to using groundwater for irrigation, farmers withdraw water from streams to irrigate crops. However, if water withdrawal from streams is not done in an ecologically-sustainable manner, it can potentially harm stream ecology and reduce the dilution capacity of streams, impacting water quality and aquatic biota. In the southeast United States (U.S.), the quantity of water that can be ecologically-sustainably withdrawn for irrigation and other uses depends on El Niño Southern Oscillation (ENSO), a seasonal-to-interannual (SI) climate-variability phenomena. The objectives of this study were to: (a) quantify the relationship between ENSO and precipitation, ENSO and temperature, and ENSO and streamflow; (b) develop surface water withdrawal prescriptions for irrigation without disturbing the ecological integrity of streamflow; (c) quantify the area of a watershed that can be irrigated via surface water withdrawals from different order streams; and (d) determine optimum pond size for the storage of withdrawn water from streams for irrigation. The study was conducted in the Swan Creek watershed located in Limestone County of north AL, U.S. The Soil and Water Assessment Tool (SWAT) model was used to simulate streamflows and

develop water withdrawal prescriptions. The La Niña phase of rainfall from May to December (except October). The results of this study indicate that percentage area irrigated upstream of withdrawal point was not the function of stream order. During a La Niña phase 14% to 55% more water can be sustainably withdrawn from streams than the El Niño phase from January to March. Furthermore, irrespective of the ENSO phase, about 8% more water could be withdrawn during the non-crop growing months than the crop growing months. Based on the water withdrawal criteria, about 16% of the watershed cropland area can be irrigated if the withdrawals were made throughout the year, 9% if stream water was withdrawn in non-crop growing season months and 5% if stream water was withdrawn in the growing season. If farmers plan water withdrawal in accordance with the ENSO phase, it would not only provide them ample volume of water for irrigation during the growing season but would also help to maintain stream water quality and aquatic biota.

2.1 Introduction

Climate variability plays a vital role in the world's science and policy-making decisions due to its significant influence on water resources (Sharma and Gosain 2010). In the southeastern United States (U.S.), climate variability is mainly affected by El Niño Southern Oscillation (ENSO), a seasonal-to-interannual climate variability phenomenon. ENSO refers to the periodic warming and cooling of sea surface temperatures (SST) in the central and eastern equatorial Pacific regions west of Peru. Ocean dynamics alter SST, changing the atmospheric heating which changes the precipitation patterns over the globe. Walker (1923) was one of the first to investigate the linkages between ENSO and large-scale precipitation patterns along with documentation and prediction of variations in the Indian monsoon rainfall. ENSO has been shown to have anticipated impacts on stream flow, precipitation, monsoon occurrence, and flood frequency in different regions around the world (Kulkarni 2000; Chiew et al. 1998; Piechota & Dracup 1999). For example, Almanaseer and Sankarasubramanian (2012) reported that ENSO influences precipitation, temperature, streamflow, and groundwater throughout the winter season over the southeastern U.S. Schmidt et al. (2001) also recorded strong linkages between ENSO and precipitation in the southeastern US, especially during the winter season.

El Niño and La Niña are reverse phases of ENSO. These phases refer to the large-scale ocean-atmosphere climate interaction linked to periodic warming or cooling of SST over the central and east-central equatorial Pacific. For the Niño 3.4 index, El Niño and La Niña events are defined based on the three-month running mean of SST anomalies in the Niño 3.4 region (i.e., region between 5ºN to 5ºS and 170ºW to 120ºW) exceeding positive (for El Niño) or negative (for La Niña) 0.5ºC, respectively, for at least five consecutive months (Hansen et al. 1998). In the southeastern U.S., ENSO may result in bringing suitable precipitation in a year while generating extremes of too much or too little precipitation in others. For example, the drought in 2007 caused by La Niña resulted in water shortages which invoked the first importing of water in 100 years and causing catastrophic impacts on crop production, subsequently resulting in an estimated economic loss of $1.3 billion in southeastern U.S. (Manuel 2008). Therefore, it is crucial to understand and quantify the impacts of ENSO on water resources. While little can be done about the occurrence of the events, the impacts of ENSO on agriculture and water resources can be reduced through proper planning and awareness.

In AL, most of the crop production is rain-fed because the state receives a large amount of annual precipitation ranging from 1,270 mm in the Northeast to 1,727 mm in Southwest of the state (Dougherty et al. 2007). However, 59% of the rainfall (determined by averaging precipitation from 1961-1990) occurs in the non-crop growing season (i.e., winter months) (Rochester et al.

1996). Therefore, farmers rely on irrigation to meet crop water demands during the crop growing season (i.e., summer months). Complementing irrigation with natural rainfall has helped farmers to increase crop productivity (Cull et al. 1981). Therefore, farmers are increasingly adopting irrigation to maximize crop yield. For example, in AL, the area under irrigation has increased by 42% from 1997 to 2012 (Templeton et al. 2014). To irrigate crops, farmers use groundwater and/or withdraw water from streams (ADECA 2010). When stream water is used for irrigation, it is essential to withdraw water from streams sustainably. This is because excessive water withdrawals from streams and rivers can affect in-stream habitat and biota at times of low flows (USFWS and USEPA 1999). Reduction in current velocity is lethal to river biota, many or most of which depend on running water to deliver food and maintain oxygen and temperature levels (USFWS and USEPA 1999). Furthermore, low flows reduce the assimilative capacity of streams, and, therefore, maintaining sufficient levels of flow in streams is necessary for dilution of pollutants (Farhadian et al. 2014).

Use of ENSO forecasts can help to mitigate the negative impacts of water withdrawal from streams on in-stream habitat and biota (Mondal et al. 2011). Additionally, during the El Niño and La Niña events, climate forecasts of precipitation are seen to be more accurate (Goddard et al. 2005). However, in order to use ENSO forecasts for water withdrawal analysis from streams, a relationship between ENSO vs. precipitation and ENSO vs. streamflow should be established. Hydrological models could be used to develop relationships among ENSO, streamflow, and quantity of water that can be sustainably withdrawn from streams for irrigation. The watershed level models such as Soil and Water Assessment Tool (SWAT) are found to be effective in modeling hydrological processes within a watershed (Veith et al. 2008; Nietsch et al. 2009; Arnold et al. 2010; Winchell et al. 2013). Scientists, farmers and the business community recognize climate variability, named as ‘extreme weather events,’ as one of the most anticipated production hazards over the following ten years (WEF 2015). Water may be limited due to increases in water demand and seasonal changes in the precipitation patterns brought upon by the ENSO phases. Rainwater harvesting for irrigation has been improving agricultural productivity in regions where variable precipitation and prolonged dry spells are significant constraints (Pachpute et al. 2009). Irrigation plays a vital role in agricultural production and ensures significant crop yields (Biazin et al. 2012; Unami et al. 2015). However, irrigation is the principal user of water resources and is accountable for around 70% of flow rates withdrawn from the streams. Therefore, the timing and quantity of water withdrawal is important for maintaining stream ecology.

In 1949, the United States Department of Agriculture’s (USDA) Bureau of Agricultural Economics Crop Reporting Districts divided AL into eight climatic zones based on crop grown and climate classification. Climatic zones 1 and 2 comprise north AL while 7 and 8 comprise south AL. Mondal et al. (2011) and Srivastava et al. (2010) developed relationships between ENSO, precipitation, and streamflow for a forested watershed in southern AL, i.e., climatic zone 8 (NCDC, 2019). Hydrological and climatic relationships involving ENSO in south AL do not apply to north AL. Schmidt et al. (2001) also found that for the same ENSO conditions, Florida doesn’t respond as uniformly to ENSO but in a complicated manner with respect to precipitation and streamflow patterns over the state. Similarly, Sharda et al. (2012) suggested that the same phase of ENSO has a diverse effect within AL. Therefore, it is important to develop relationships between ENSO, precipitation, and streamflow and understand the effect of ENSO phase on the volume of water that can be sustainably withdrawn from streams for irrigation in north AL (climatic zone 1). To the best of our knowledge, no studies have been done to quantify the amount of area that can be irrigated using water withdrawn from streams as a function of ENSO phases in agricultural watersheds. Additionally, no past studies have quantified the pond volume required for the storage of withdrawn water from streams for irrigation. Therefore, the objectives of this study were to (a) quantify the relationship between ENSO and precipitation, ENSO and temperature, and ENSO and streamflow in an agricultural watershed; (b) develop surface water withdrawal prescription for irrigation without disturbing the ecological integrity of streamflow; (c) quantify the area of watershed than that can be irrigated via surface water withdrawals from different order streams; and (d) determine optimum pond size for the storage of withdrawn water.

2.2 Methods and Materials

2.2.1 Study Area

The study site was Swan Creek watershed (97 km^2) located in Limestone County, north AL, U.S. (Figure 2.1). The watershed is located in climatic zone 1 of AL. The land use in the study watershed comprises of 22% pastures, 21% agricultural land, 20% deciduous forest, 12% open space, 11% developed low intensity, 3% evergreen forest, and 3% shrubland (USDA 2017). In this watershed, land use has not changed substantially (<4%) within the last 10 years. The elevation in the watershed ranges from 198 m to 248 m with respect to the mean sea level. The dominant soil types in the watershed are Dickson silt loam (26%), Guthrie silt loam (14%), Cookeville silt loam (9%), Lawrence silt loam (8%), Melvin silt loam (8%), Sango silt loam (7%) and Abernathy-Emory silt loams (2%) (USDA 2017). The 68-year (1950-2018) average annual precipitation of the watershed is 1,350 mm (53 in). Soybeans, corn, cotton and winter wheat are the major crops grown in the watershed based on cropland data layer files from 2008-2017 (USDA 2017).

2.2.2 Soil and Water Assessment Tool

The SWAT (Soil and Water Assessment Tool) model is a continuous-time, semi-distributed, process-based river basin model which was developed to quantify the impacts of alternative management decisions on water resources and nonpoint-source pollution (Arnold et al. 2012). In SWAT, a watershed is divided into various sub-watersheds, which are further subdivided into hydrologic response units (HRUs) that consist of similar land use, management, topographical, and soil characteristics within a sub-watershed. SWAT simulates hydrological and water quality processes at a daily time step. Hydrologic processes simulated in the SWAT model include canopy storage, surface runoff, infiltration, evapotranspiration (ET), lateral flow, tile drainage, redistribution of water within the soil profile, consumptive use through pumping (if any), return flow, recharge by seepage from surface water bodies, ponds, and tributary channels (Marek et al. 2016), and streamflow at the sub-watershed and watershed level. Because of the ability of the SWAT model to simulate hydrological processes adequately, it has been successfully used in various studies (Gir et al. 2018; Malhotra et al. 2018; Tegegne and Kim 2018). Therefore, we used the SWAT model in this study. Detailed information regarding the SWAT model can be found in Neitsch et al. (2011). ArcSWAT 2012.10.3.19 version was used in this study.

2.2.3 Data Input

Data required to simulate hydrological processes in the SWAT model includes topography, weather, land use, soil, and management practices. Topography data (i.e., 10 m digital elevation model (DEM) used for the delineation of the watershed and sub-watershed boundaries were obtained from National Geospatial Gateway (USDA 2017) (https://datagateway.nrcs.usda.gov/). The Soil Survey and Geographic (SSURGO) data was used to obtain relevant soil properties.

To incorporate crop rotations into the SWAT model, we used Cropland data layers (USDA 2017). Cropland data layers were combined for the years 2008-2017 into a single file. This combined file provided pixel level information regarding the types of crop grown within this watershed from 2008-2017, which was then used to generate crop rotations (Figure 2.2). Thirty-four different sets of crop rotations, determined for the period 2008-2017, which covered more than 90% of the watershed area were used for the SWAT modeling. This method of incorporating crop rotations within a watershed model helps to accurately represent temporal and spatial crop rotation information within a watershed and, therefore, enhances model performance (Sahajpal et al. 2014). The management practices (e.g., tillage, sowing and harvesting dates, and fertilizer application rates and timing) for the watershed were obtained from the database developed by Butler and Srivastava (2007). The irrigation rates were based on the estimated crop water requirement obtained from the National Engineering Handbook Irrigation Guide (USDA, 2009).

Daily precipitation and temperature data from 1950-2018 were obtained from two NOAA weather stations at Athens, AL and Belle Mina, AL (Figure 2.1). It should be noted that for each subbasin, SWAT makes use of one gage at a time; whichever is nearer to the centroid of each subbasin (Tuo et al. 2016). For unknown climate parameters like solar radiation, relative humidity, and wind speed, we used the SWAT inbuilt weather generator that uses monthly climate statistics from long-term weather records (Saha et al. 2014). The daily measured streamflow data at the outlet of the watershed was obtained from United States Geological Survey (USGS) stream gage for the period June 2009 to June 2018.

2.2.4 Model Calibration and Validation

For this study, we calibrated and validated the model separately for surface runoff and baseflow at the watershed outlet at the daily time step. The period January 1, 2000-December 31, 2008 was used as the model warmup period. The warmup period allows the model to initialize important model variables and processes to reach a dynamic equilibrium. The model warmup period of two-three years for hydrological processes is recommended by the model developers (Daggupati et al. 2015). The model calibration was performed from June 26, 2009-June 26, 2013, and validation from June 27, 2013- June 30, 2018. The observed streamflow was separated into surface runoff and baseflow utilizing the Web-based Hydrograph Analysis Tool (WHAT) program developed at Purdue University (Lim et al. 2005).

Calibration was achieved by adjusting the parameters (presented in Table 2.1) to a suitable point to reduce the deviation between simulated and observed daily baseflow and surface runoff. The model performance was evaluated for calibration and validation time periods using three statistical measures, Nash-Sutcliffe efficiency (NSE), Coefficient of determination (R^2) and Percent bias (PBIAS) (Malhotra et al. 2018). The coefficient of determination (R^2) describes the degree of collinearity between simulated and measured data (Moriasi et al. 2007). It was calculated using the following equation:

$$R^2 = \frac{\left[\sum_{i=1}^{n}(O_{obs,i}-\bar{O}_{obs})\,(O_{sim,i}-\bar{O}_{sim})\right]}{\left[\sum_{i=1}^{n}(O_{Obs,i}-\bar{O}_{obs})^2\right]^{0.5}\left[\sum_{i=1}^{n}(O_{sim,i}-\bar{O}_{sim})^2\right]^{0.5}} \tag{1}$$

Where $O_{obs,i}$ and $O_{sim,i}$ are simulated and observed flows, respectively, for the i^{th} observation; n is the number of observations, $\bar{O}_{sim}$ *and* $\bar{O}_{obs}$ are mean simulated and observed flows, respectively, for the simulation period. NSE (equation 2) is a normalized statistics that quantifies the relative magnitude of the residual variance ("noise") relative to the measured data variance (Nash and Sutcliffe, 1970).

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs}-Y_{mean})^2}\right] \tag{2}$$

PBIAS (equation 3) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al. 2002).

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})*100}{\sum_{i=1}^{n}(Y_i^{obs})}\right] \tag{3}$$

where Y_i^{obs} is the i^{th} observation for the component being assessed, Y_i^{sim} is the i^{th} simulated value for the component being assessed, Y^{mean} is the mean of observed data for the component being assessed, and n is the total number of observations.

2.2.5 El Niño Oscillation Index: Niño 3.4

NOAA uses the Oceanic Niño Index (ONI) to forecast ENSO. ENSO data was obtained from the NOAA Climate Prediction Center (CPC) from 1950 to 2018 (NOAA, 2019). Based on the Niño 3.4 index, the three-month running period from January 1950 to June 2018 has been classified as El Niño, La Niña, and Neutral by NOAA. The ENSO phases are also classified into strong, weak or moderate phases based on the ONI values. ONI values above 1.5 indicate strong ENSO events while ONI values between 1 and 1.5 signify moderate ENSO events, and ENSO events with ONI values between 0.5 and 1 are considered weak (Lindsey 2018). The effect of ENSO on precipitation and temperature was analyzed using the observed data. ENSO effect on streamflow as a result of water withdrawal from streams for irrigation was quantified using the simulated streamflow data (output from calibrated and validated SWAT model).

2.2.6 Ecologically sustainable water withdrawal criteria

The ecologically sustainable water withdrawal criteria adapted in this study were borrowed from Richter et al. (2003) and USFWS and USEPA (1999). United States Environmental Protection Agency and United States Fish and Wildlife Service agreed upon these criteria for the

Apalachicola- Chattahoochee-Flint (ACF) River basin in AL, Florida, and Georgia. These criteria (Table 2.2) define threshold limits for specific flow characteristics that should not be surpassed (Richter et al. 2003). These guidelines represent an initial articulation of ecosystem flow to maintain biodiversity in the basin and have helped federal environmental agencies assess the potential impacts of any proposed water allocation formula on the ecological integrity of the ACF basin. Numerical values for the minimum and maximum flows which would be withdrawn from the streams were determined for different low and high flow scenarios using the detailed methodology presented in USFWS and USEPA (1999). These criteria are relatively comprehensive and ensure that not only low flows, but also average flows and high flows are preserved within a watershed. Since our watershed is located in AL, we used these guidelines in our study.

2.2.7 Water Withdrawal Procedure

Depending on the location of a field in the watershed, a farmer may have access to a first, second or third order stream. Therefore, we quantified how much area can be irrigated if water was withdrawn from first, second or third order streams. The criteria listed above are mainly sensitive to flows that drop below the 25th percentile and that exceed the 95th percentile. The following procedure was adopted for water withdrawal. Water was not withdrawn from the streams when the flow on a particular day was below the 25th percentile of daily flows of the entire study period (1950-2018). When flow was above the 25th percentile and below the 95th percentile, water was withdrawn in a way that flow doesn’t drop below the 25th percentile. When the flow was higher than the 95th percentile, 20% of the streamflow was withdrawn. This restriction on the water withdrawals for the flows above 95th percentile was due to practical pumping and diversion constraints (Mondal et al. 2011). Three different scenarios (i.e., water withdrawn from streams for the entire year, water withdrawn only in the winter months and water withdrawn in summer months) were performed to quantify the amount of water that can be withdrawn sustainably for irrigation. Although the water requirement for the crops varies, approximately 457 mm (18 in) (i.e., about 4570 m^3 for one irrigated ha area [3.7 ac ft]) has been reported to be adequate for crop growth in AL (ACES 1994). The amount of water withdrawn is assumed to be stored in on-farm storage ponds and is thought to be enough to meet the evaporative loss from the on-farm ponds (Srivastava et at. 2010). We used these criteria to calculate the area of the watershed that can be irrigated using the water withdrawn from streams.

2.2.8 Relationship between El Niño Southern Oscillation and Temperature, Precipitation, Stream Flow, and Water Withdrawn

Each month from 1950 to 2018 was classified as El Niño, La Niña or Neutral based on the Niño 3.4 index. The daily precipitation data for a given month from 1950-2018 were summed up to get monthly precipitation, whereas, daily temperatures were averaged for a given month to get the average monthly temperature. The precipitation and temperature values for each month were then averaged by each ENSO phase (i.e., El Niño, La Niña or Neutral) for the entire study period. Percentage difference was used to find the difference in temperature and precipitation between each ENSO phase for a particular month. For each month of the year, the percentage difference was calculated by finding the difference between La Niña and El Niño average monthly temperature and then diving it by the average monthly temperature of that particular month for the entire study period (equation 4).

$$T_m = \frac{\bar{T}_{La\ Nina,m} - \bar{T}_{El\ Nino,m}}{\bar{T}_m} \tag{4}$$

where T_m is temperature percentage difference (%), T denotes temperature (°C), $\bar{T}$ denotes average temperature, and m denotes month.

The percentage difference was calculated in a similar fashion for precipitation, stream flow, and water withdrawal. To determine if statistically significant differences exist between El Niño and La Niña temperatures, precipitations, stream flows, and water withdrawals, an Analysis of Variance (ANOVA) was conducted using SAS Statistical Software (SAS Institute, Inc., Cary, North Carolina, United States). The statistical results were tested at the significance level of α=0.10.

2.2.9 Pond size for storage of withdrawn water

Farm ponds help provide an adequate quantity of water during crop growth and serve as a reliable practice for assuring optimal crop yields. Water harvested and stored in ponds can be used to irrigate crops, especially during the drought season and during periods of high crop water demand, when the crop water requirement cannot be met by natural rainfall. The area irrigated from a farm pond is regulated by the amount of water available in the pond during the growing season. Pond capacity must be sufficient to adhere to crop requirements and to subdue inevitable water losses due to seepage and evaporation (USDA 1997). The size of the pond is dependent on the area available for pond, the water available for withdrawal, water requirement of the crops grown, rainfall expected in the growing season, and losses due to evaporation and seepage. To determine pond size that would be adequate to store water withdrawn from streams using the ecologically sustainable withdrawal criteria, we followed the guidelines from the USDA-NRCS, Ponds, Planning, Design, Construction Agriculture Handbook Number 590.

$$Surface\ area\ of\ pond = \frac{Capacity\ of\ Pond}{Maximum\ Depth\ of\ pond * 0.4} \tag{5}$$

A pond with a large surface area relative to the volume of water stored becomes low or dried up more easily due to evaporation of more water. It is advised to create a comparatively deep spot in the basin of the pond to secure a steady water supply (Porter 2015). For a typical bowl-shaped pond, the average depth can be estimated as 0.4 times the maximum depth (Swistock 2015). Equation 5 was then used to calculate surface area of the pond. The minimum recommended pond depth in the north AL region is 1.82-2.13 m (6-7 feet) (USDA, 1997). Thus, a deep spot of up to 5.33 m (17.5 feet) could be created in the pond. Therefore, the average depth of pond considered in this study was 2.13 m (7 feet) (5.33*0.4) as recommended by USDA (1997).

2.3 Results and Discussion

2.3.1 Calibration and validation of the SWAT model

Based on the NSE and R^2 criteria specified by Ahmad et al. 2011(NSE >0.4 , $R^2>0.5$) and Moriasi et al. 2007 (PBIAS < ±25), the model satisfactorily simulated streamflow at the daily time step for the calibration and validation time periods (Table 2.3). From the graphical comparison of the observed and simulated monthly surface runoff, baseflow and total streamflow, it is apparent that the surface runoff, baseflow, and total flow simulated by the model were representative of the observed surface runoff, baseflow and total flow (Figure 2.3). The statistical values computed for the calibration and validation periods for surface runoff, baseflow, and total streamflow at the monthly time step are presented in Table 2.4. "very good" model calibration and validation results were obtained, as indicated by the NSE and R^2 values for surface runoff, baseflow, and total streamflow (Moriasi et al. 2007). Based on the PBIAS values, the performance rating of the model for the calibration and validation periods was "very good" for baseflow and "satisfactory" for surface runoff and total flow (Moriasi et al. 2007). The average monthly total streamflow predicted by the SWAT at the outlet was 1.93 $m^3 s^{-1}$ as compared to 2.20 m^3s^{-1} for the observed flow whereas the simulated surface runoff compared at 1.14 m^3s^{-1} with the observed 1.39 m^3s^{-1}. The average simulated baseflow of 0.78 m^3 s^{-1} was a close match to the observed baseflow of 0.80 m^3 s^{-1}. Overall, the results show that the SWAT model adequately represented streamflows in this watershed.

2.3.2 Relationship between ENSO and temperature

As mentioned earlier in the manuscript, daily mean temperatures were averaged over month for El Niño and La Niña events and the percentage differences were calculated between La Niña and El Niño temperatures. For the majority of months, daily average temperatures determined for a given month were greater in La Niña phase as compared to El Niño phase (Figure 2.4). The differences were more prominent in the winter months of January and February. La Niña January was found to be 29.8% warmer than El Niño January, while February was 26.9% warmer than El Niño February (Figure 2.5). Similarly, Sarkar et al. (2012) reported that La Niña phase was associated with warmer winters in AL as compared to El Niño and neutral phases. Similar results were found by Kiladis et al. (1989) and Schmidt et al. (2001) in southeastern U.S. Moreover, in climatic zone 1 (north AL), NOAA (2019) reported that on comparison of average temperatures in La Niña phase with average daily temperatures, the average temperature rises during moderate and strong La Niña events were found to be 0.5°C warmer than the average daily temperature during winters. Additionally, for all the winter months (December through February) during strong La Niña seasons, the temperatures were always found to be in the warmest third or middle third tercile. Temperature and soil moisture follow an inverse relationship, i.e., following a dry period, soil moisture decreases and temperature increases (Lakshmi et al. 2003). Thus, with the rise in temperature during La Niña, the water requirement for crops increase. Moreover, studies have shown that ENSO temperatures have effects on irrigation water requirements for the crops (Paz et al. 2007; Meza, 2005; Garcia y Garcia et al. 2010). Therefore, it is inferred that irrigation needs for the crops are greater during La Niña phase than El Niño phase as the temperature is greater during La Niña phase.

2.3.3 Relationship between ENSO and precipitation

As indicated earlier in the manuscript, for the entire study period (1950-2018), daily precipitation data were converted to monthly and then averaged for different ENSO phases for each month. The results show that La Niña phase of ENSO tends to produce wetter winters (January to March) than El Niño winters (Figure 2.6) in north AL. The average precipitation for the months from January to March for La Niña phase per year was found to be 369 mm while the precipitation for same months for El Niño phase per year was found to be 275 mm. Sharda et al. (2012) also reported that the amount of precipitation was greater in the winter months in the climatic zone 1 (north AL) during the La Niña phase compared to the El Niño phase. Similarly, NOAA (2019) found that in north AL, for all the strong La Niña winters since 1896, the sum of precipitation during winters was found to be in the wettest third tercile. On the other hand, El Niño resulted in greater precipitation during the summer months (April to September) as compared to La Niña.

Additionally, it was noted that, irrespective of the phase, the non-crop growing months (Dec. to Mar.) tend to be wetter (average annual precipitation per year = 530 mm) than the summer months (April to September) (average annual precipitation = 505 mm). Percentage difference in precipitation between each ENSO phase was greater than 15% in the months of January, March, June, and September (Figure 2.7). The precipitation in January was significantly ($\alpha = 0.10$) greater in the La Niña phase than the El Niño phase. The negative values of percentage difference indicate the months (April to September) for which the El Niño phase had greater precipitation than the La

Niña phase. The month of September saw the highest percentage difference in precipitation between ENSO phases. For the entire study period, in September, there were ten storm events in the El Niño phase with total precipitation amount greater than 100 mm compared to four storm events in the La Niña phase. This likely resulted in the highest precipitation difference for the month of September. The results indicate that during non-crop growing months there is a potential to harvest rainfall for irrigation during summer months.

2.3.4 Relationship between ENSO and streamflow

Trends were similar between precipitation and streamflow for different ENSO phases. The monthly streamflow from January to April was greater in the La Niña phase than in the El Niño phase (Figure 2.8). These findings are consistent with Sharda et al. (2012), showing that stream flows from December-March are greater during the La Niña phase relative to the El Niño phase in northern AL (climate division 1 through 3). It should be noted that Sharda et al. (2012) did not report greater streamflow for the month of April in the La Niña phase than the El Niño phase. This was because our dataset included a rainfall event that occurred on April 27, 2011, which was recognized as one of the deadliest tornadoes in AL since 1925 (NOAA, 2019). This rainfall event had a return period of 25 years. The average value of streamflow for the April month was seen to be similar for El Niño and La Niña, if this event is excluded from the study. However, from May to December (excluding October), the streamflow was greater in the El Niño phase than in the La Niña phase (Figure 2.8). The month of October showed higher precipitation in La Niña primarily due to two rainfall events (total precipitation from these events = 287 mm) that occurred on 8 and 17 October of 1975. The percentage difference between the streamflows was greater than 30% from November to January. For the months of November and December, streamflow was greater in El Niño phase than in La Niña phase and the percentage difference between El Niño and La

Niña flows was approximately 40% (Figure 2.9). However, for the months of January to March, the streamflow was 10%-30% greater in La Niña phase than in El Niño phase. A significant difference (α =0.10) in the flows was observed between La Niña and El Niño phase in the month of December. The effect of ENSO can vary across the same state and between neighboring states. For example, Mondal et al. (2011) and Sharda et al. (2012) found that in southern AL streamflow was greater during El Niño phase in wither months (January to March). Whereas, in our study we found that streamflows in winter months (January to March) were greater during La Niña phase. Therefore, research results from this study show that it is vital to quantify streamflows across different regions for different ENSO phases. The relationship between ENSO phases and streamflow cannot be generalized over different climatic zones. Overall, in our study, irrespective of the ENSO phase, the streamflow was greater from December to Mar. (non-crop growing season) than April to September (crop growing season) (Figure 2.8). Therefore, research results reveal that water can be withdrawn in non-crop growing months from streams to irrigate crops during the crop growing season. This finding is important to develop water withdrawal prescriptions.

2.3.5 Relationship between ENSO and water withdrawal

The quantity of water that can be sustainably withdrawn from streams depends on the volume of streamflow. Irrespective of stream order, more water can be withdrawn from streams during the months from January to April during the La Niña phase than the El Niño phase (Figure 2.10). From January to April, during the La Niña phase, approximately 14% to 56% more water was available for withdrawal at the watershed outlet relative to the El Niño phase (Figure 2.11). On the contrary, during the El Niño phase, more water was available for withdrawal from May to December (except August and October). As indicated earlier in the manuscript, the effect of ENSO phase on streamflow can vary across a state. Mondal et al. (2011) reported that in south AL (climatic zone 8), greater quantities of water can be withdrawn in winter months during the El Niño phase than the La Niña phase. This difference in primarily due to the conflicting precipitation patterns over southern and northern AL. Therefore, it is important to determine the effect of ENSO phase on the quantity of water that can be sustainably withdrawn from streams across different climatic zones in AL.

Irrespective of the ENSO phase, about 8% more water could be withdrawn during the winter months (December to March) as compared to the crop growing months (April to September) (Figure 2.10). On an annual average, 8,290,944 m^3 of water can be withdrawn in winter months irrespective of the ENSO phase, which was almost twice the average water that can be withdrawn from April to September. In comparison to the La Niña phase, the El Niño phase has more availability of water during the crop growing season. Therefore, it is possible to withdraw water from streams during the crop growing season (April to September) during the El Niño phase. However, to store water in ponds (which can be used during the crop growing season), non-crop growing season water withdrawal (December to March) is recommended since the amount of water that is available for withdrawal in winter months is two times the amount of water available for withdrawal in summer months.

Therefore, it can be presumed that if La Niña occurs during the winter months, water should be withdrawn from the streams from January to April. If La Niña continues into the crop growing season, the quantity of water available for withdrawal will decrease. If El Niño occurs during the crop growing season, water would be available for withdrawal but would be in a relatively smaller amount than the amount that could be withdrawn in winter months. Hence, the water should be withdrawn from December to March during the El Niño phase as more water is available to withdraw as compared to the growing season.

2.3.6 Water withdrawal and percentage of subbasin irrigated

The percentage of subbasin area that can be irrigated upstream of the water withdrawal point was quantified for different order streams. If the water from a stream is withdrawn in an ecologically sustainable manner throughout the year, the average annual percentage of subbasin area that could be irrigated above the withdrawal point as a function of stream order was fairly consistent with an average of 16% (Table 2.6). Similarly, Mondal et al. (2011) reported that on an average 20% of the watershed area can be irrigated by water withdrawn throughout the year for Big creek watershed in southern AL. The percentage area irrigated by the water withdrawal throughout the year in our study watershed located in northern AL (climatic zone 1) was observed to be lesser than area irrigated reported by Mondal et al. (2011) for southern AL (climatic zone 8). This is because the Big Creek watershed used in study by Mondal et al. (2011) in southern AL receives greater average annual precipitation (1,648 mm) than the average annual precipitation (1,350 mm) in our study watershed. At the watershed outlet, on an average annual basis, it was observed that water withdrawal throughout the year was enough to irrigate about 16% of the watershed area in an ecologically sustainable manner. However, at the watershed outlet as a function of year, the amount of water that can be withdrawn in an ecologically sustainable manner varied from 2.79% to 44%. (Figure 2.12). At the watershed outlet, in 2007, only 3.19% of the watershed area could be irrigated (Figure 2.12). This was due to the 2006-2008 southeastern US drought caused by the La Niña phase. It was found that the percentage of drainage area irrigated was not the function of stream order. Mondal et al. (2011) and Srivastava et. al. (2010) also found no effect of stream order on percentage of watershed area that can be irrigated in a forested watershed. Results of our study indicated that a substantial volume of streamflow can be withdrawn during non-crop growing months (December to March) as compared to the crop growing season. On an average annual basis, the percentage of subbasin area (upstream of water withdrawal point) that can be irrigated using the water withdrawn during non-crop growing months (December to March) ranged from 8.2% to 10 % with an average of 9.3% (Table 2.6). These results are similar to those reported by Srivastava et. al. (2010) in southern AL (climatic zone 8). Srivastava et al. (2010) reported that about 10.3% to 11.6% of the area can be irrigated if water was withdrawn in an ecologically sustainable manner during non-crop growing months from streams of different orders. However, water withdrawal based on ENSO phase was not quantified in that study. On the other hand, when an ecologically sustainable water withdrawal from streams was made only in the growing season, i.e., from April to September, the percentage of the watershed area that can be irrigated by the water withdrawn from streams varied from 4.6% to 6.4%. Any effort to irrigate more area in the watershed using stream water during the crop growing season would inversely affect the ecology of the streams. This finding is significant as it affirms the need to schedule water withdrawal in advance. ENSO phases can be predicted fairly well in advance and thus farmers can plan water withdrawals in accordance with the ENSO phase. This would not only provide them ample amount of water for irrigation during the growing season but would also help to maintain the ecology of the streams.

2.3.7 Optimal pond size to store water withdrawn from streams

Water withdrawals made during non-crop growing months need to be stored in on-farm ponds for subsequent irrigation during the growing season. It was observed in the study that as the stream order increased (i.e., watershed drainage area), the volume of water available for the withdrawal increased. The 2nd order and 3rd order streams had more volume of water available for withdrawal compared to 1st order streams. Hence, the pond size required for the water storage would be more at the outlet of 2nd and 3rd order streams than the 1st order streams. Regression analysis was performed to calculate the pond size (with an average depth of 2.14 m (7 feet)) based on the area to be irrigated. Pond size can be determined by the following equation.

$$\text{Pond Size } (m^2) = 0.214 * \text{area under irrigation } (m^2) \quad (6)$$

Based on the above equation, if a farmer has1,214,057 m^2 (300 acres) under irrigation, farmer would require 258,998 m^2 (64 acres) for a pond.

2.4 Summary and Conclusions

ENSO significantly affected the precipitation, streamflow and quantity of water that can be withdrawn sustainably from streams in the study area. La Niña months resulted in more precipitation from January to March compared to El Niño. During crop growing season (April to September), El Niño phase had more precipitation than La Niña phase. Additionally, the November to March time period had more precipitation than the crop growing season irrespective of ENSO phase. Consequently, the surface water withdrawal can be scheduled according to ENSO phase as follows. If La Niña occurs, the non-crop growing withdrawal is more vital as the water availability is limited during the crop growing season. Alternately, El Niño non-crop growing periods (December to March) have more water available for withdrawal than El Niño crop growing seasons. However, during the growing season, more water is available for withdrawals in El Niño phase than in La Niña phase. As a result, farmers can make water withdrawal from streams during the growing season during El Niño phase, but it is still recommended to make withdrawals in non-crop growing months due to excess availability of water in the winter months.

Results of this study show that percentage of area irrigated upstream of a withdrawal point was not a function of stream order. On an average 16% of the upland area can be irrigated while making ecologically sustainable water withdrawals throughout the year from 1st, 2nd or 3rd order streams. However, if withdrawals were made only in the non-crop growing season (December to March) and water was stored in on-farm ponds, on average about 9% of area upstream of the withdrawal point could be irrigated. Furthermore, if water withdrawal is done only in the crop growing season, i.e. April to September, then water would only be sufficient to irrigate 5% of the upstream watershed area. Any effort to irrigate more area using surface water from streams would impact the ecological integrity of the stream. Thus, it is important that water should be withdrawn in the non-crop growing season months and stored in on-farm irrigation ponds to irrigate fields during the crop-growing season. The on-farm pond size required to store water would increase with stream order. The surface area of the pond with the depth of 2.13 m (7 feet) would be 0.214 times the farm area under irrigation.

Future work can focus to quantify the impact of water withdrawals on water quality. Water withdrawn from the streams may contain variable ranges of nutrients and toxic elements which could be problematic when used for irrigation. It would also be interesting to see how water quality for farmers downstream changes once farmers upstream withdraw the water.

Figures:

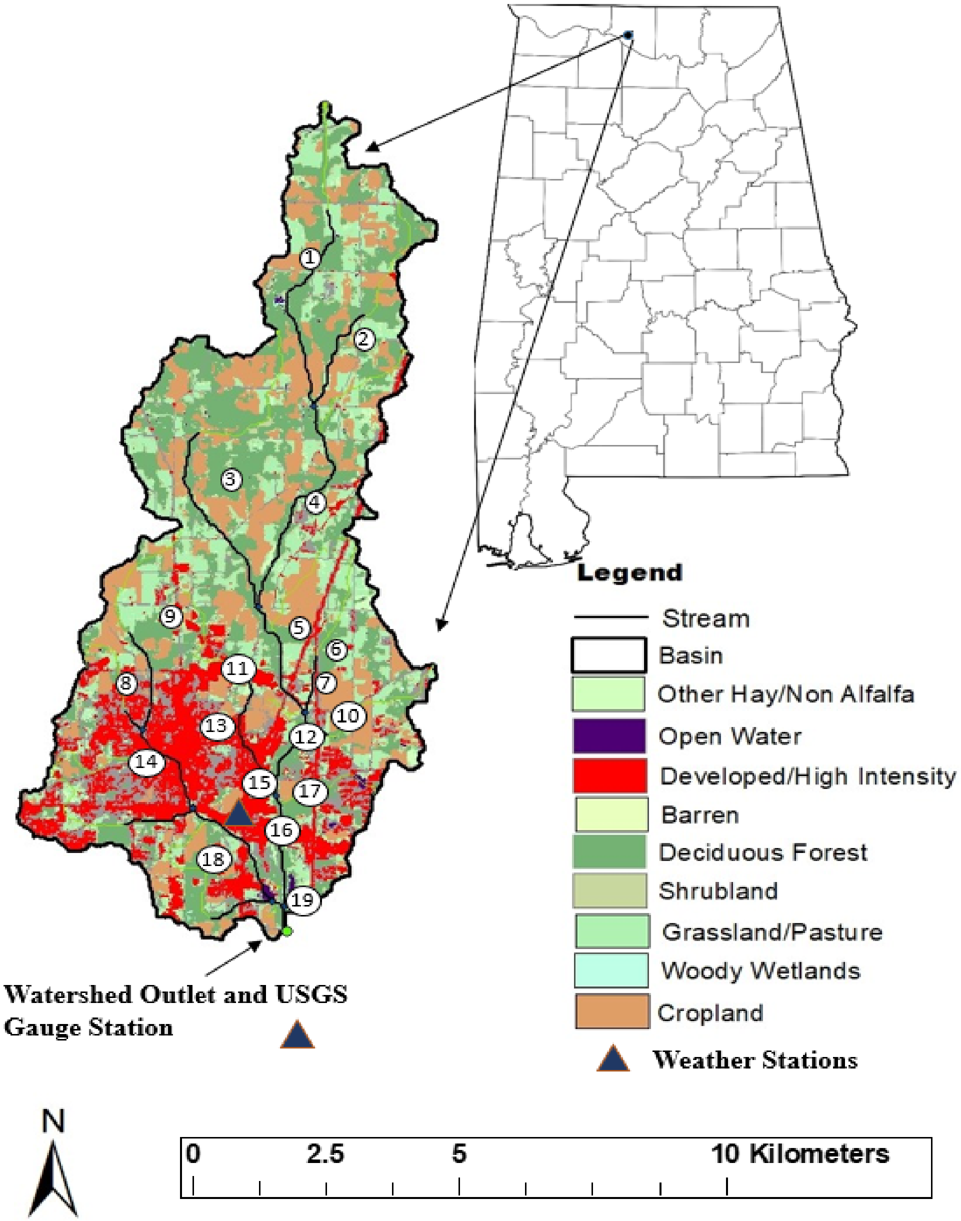

Figure 2. 1 Location and land use distribution of Swan Creek Watershed

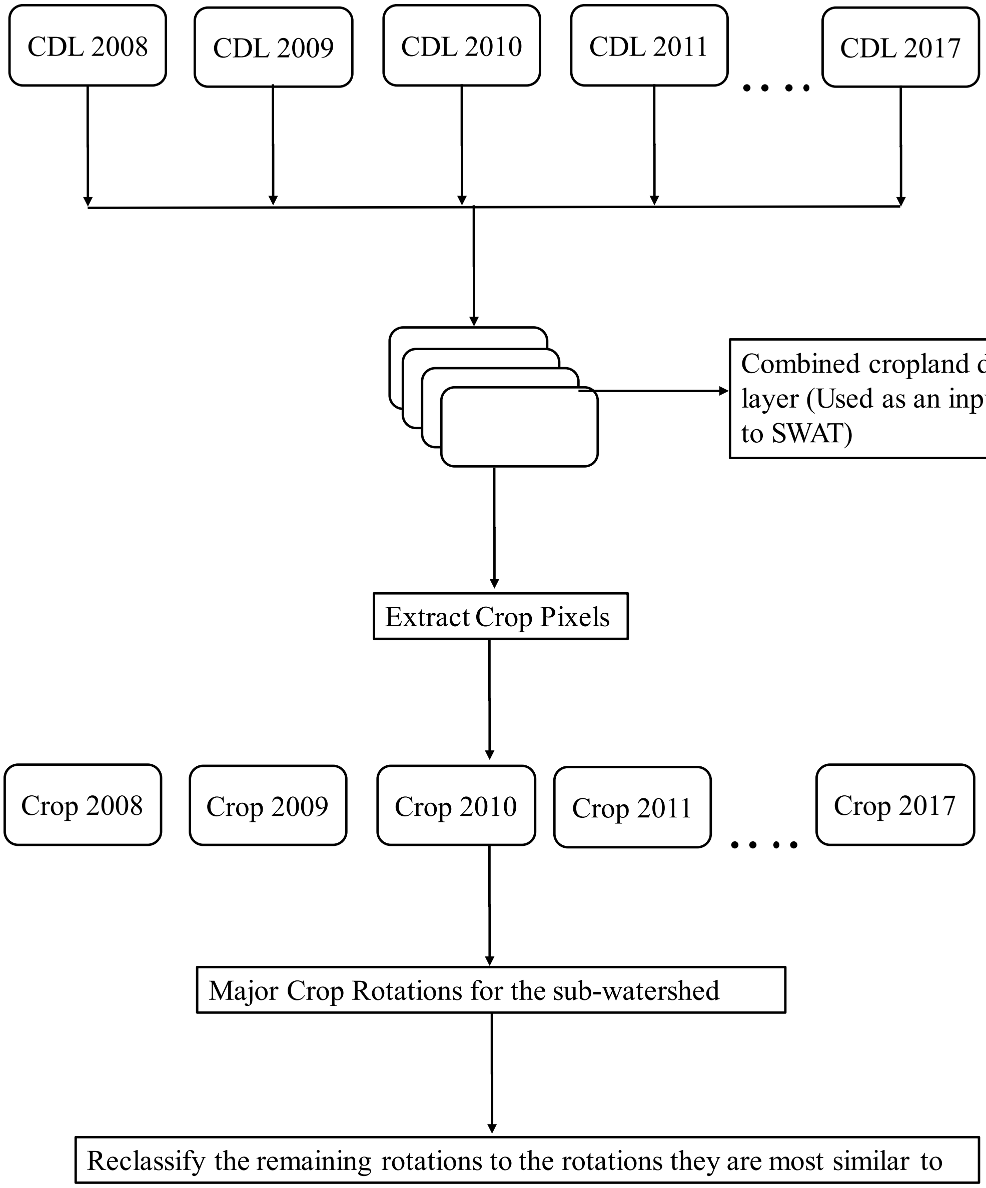

Figure 2. 2 Flowchart representing the steps performed for the allocation of crop rotations in the watershed

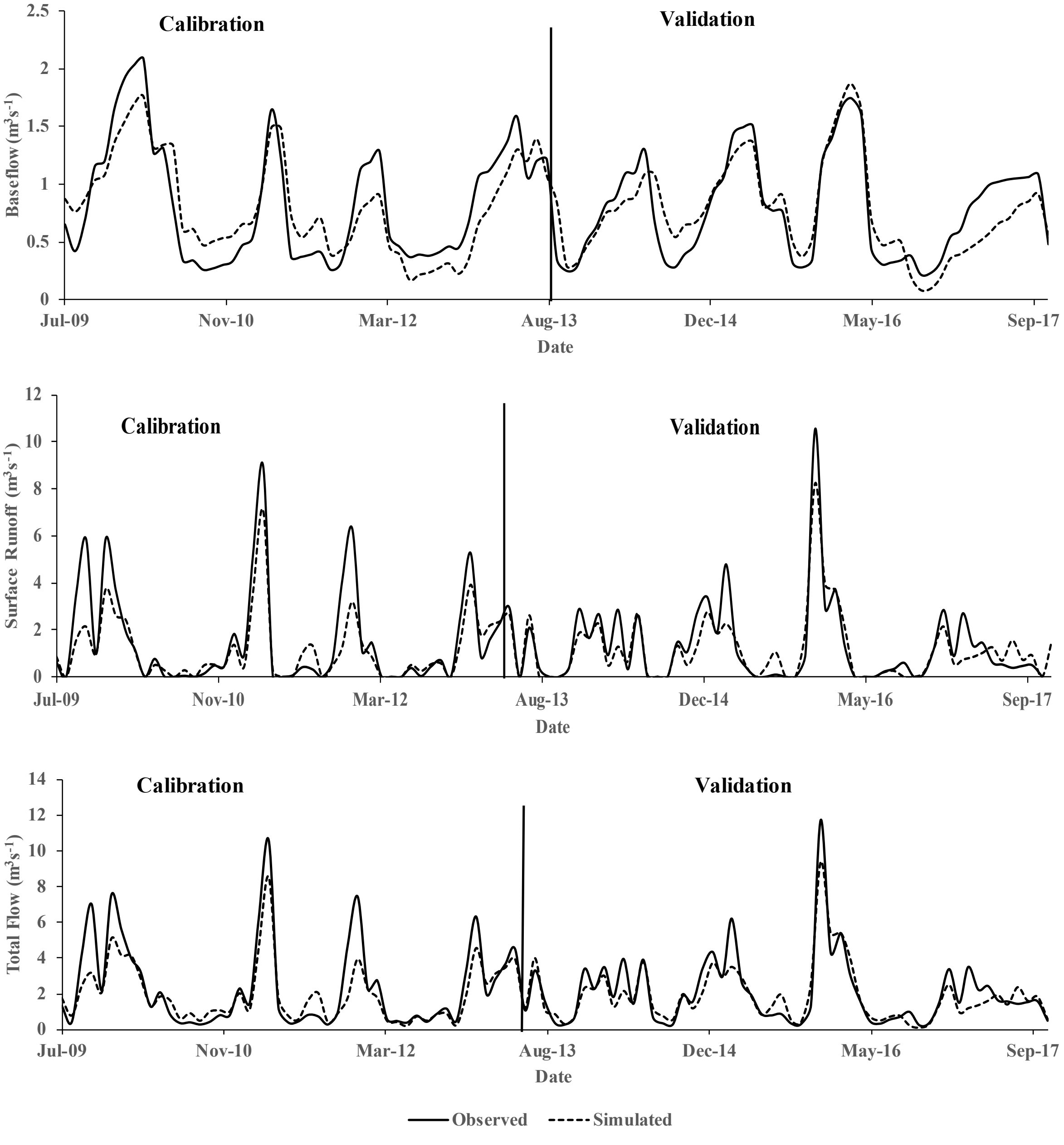

Figure 2. 3 Observed vs. simulated plots of: (a) baseflow (b) surface runoff and (c) total flows for the calibration and validation time periods.

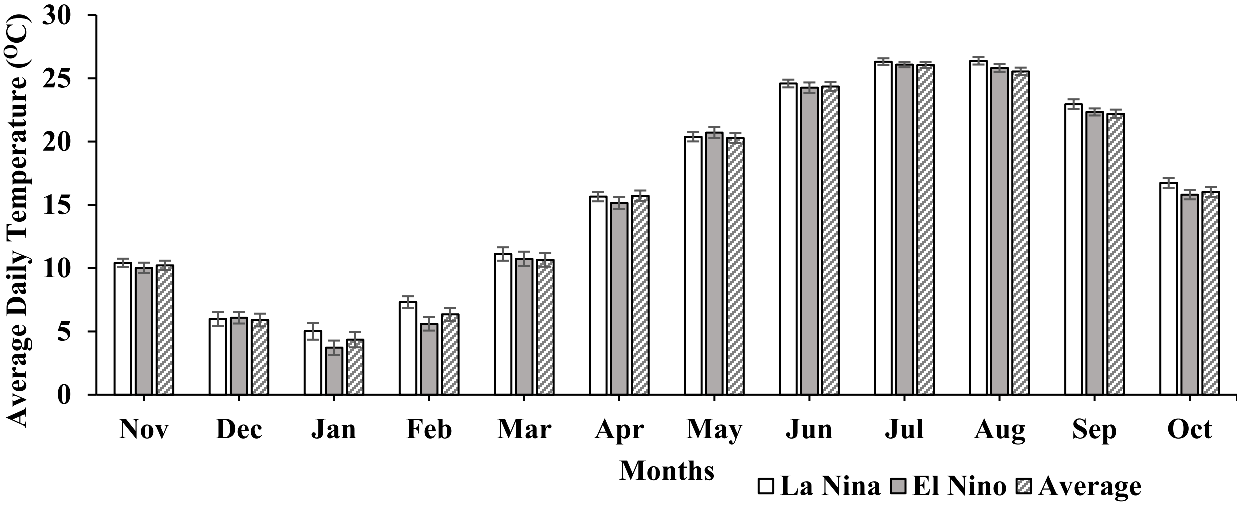

Figure 2. 4 Average daily temperature (^{0}C) for each month (1950-2018) for La Niña and El Niño phase. Also shown are one standard error bars.

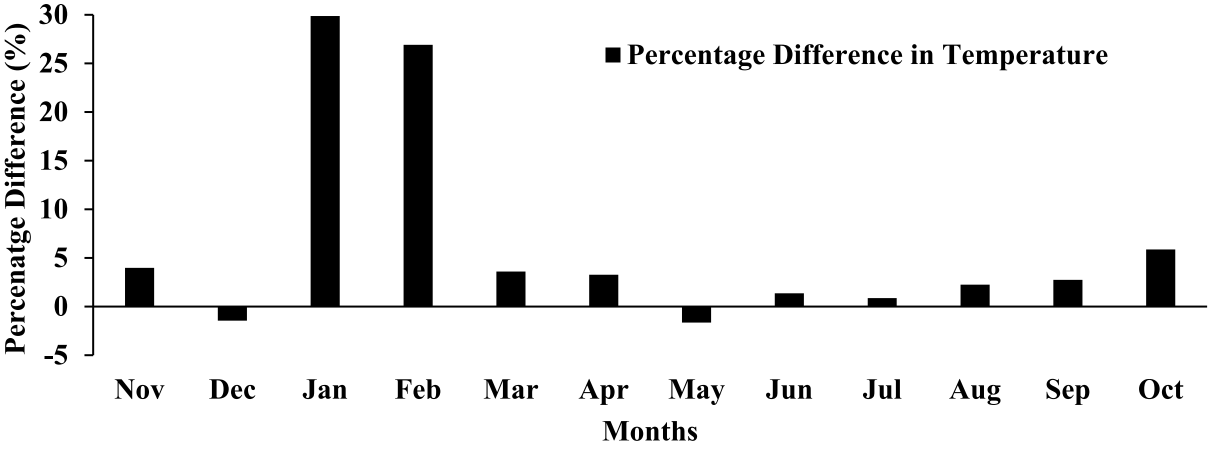

Figure 2. 5 Percentage difference in temperature (1950-2018) for La Niña and El Niño phases.

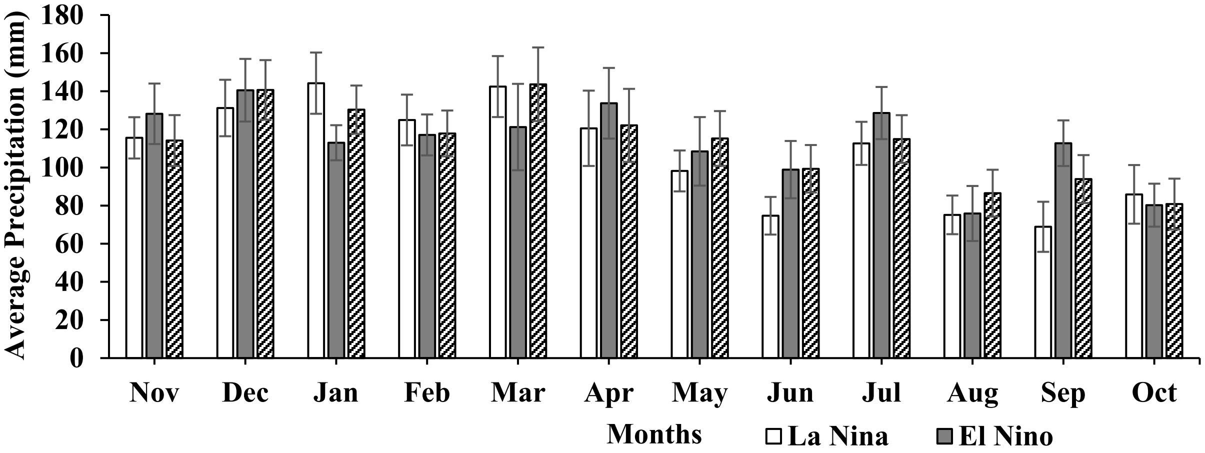

Figure 2. 6 Average monthly precipitation (mm) for each month (1950-2018) in La Niña and El Niño phase. Also shown are one standard error bars.

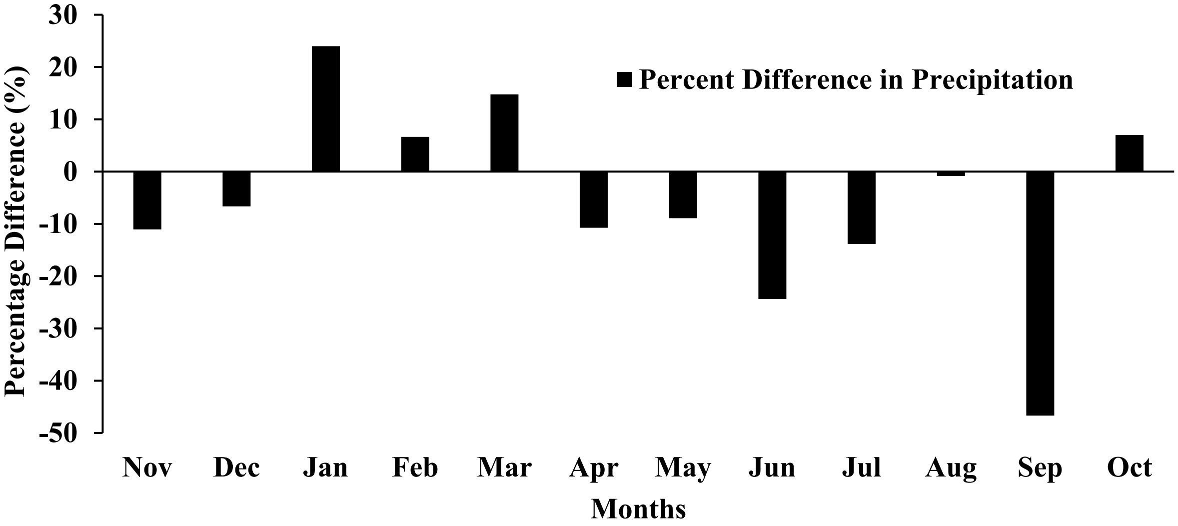

Figure 2. 7 Percentage difference in precipitation (1950-2018) for La Niña and El Niño phase.

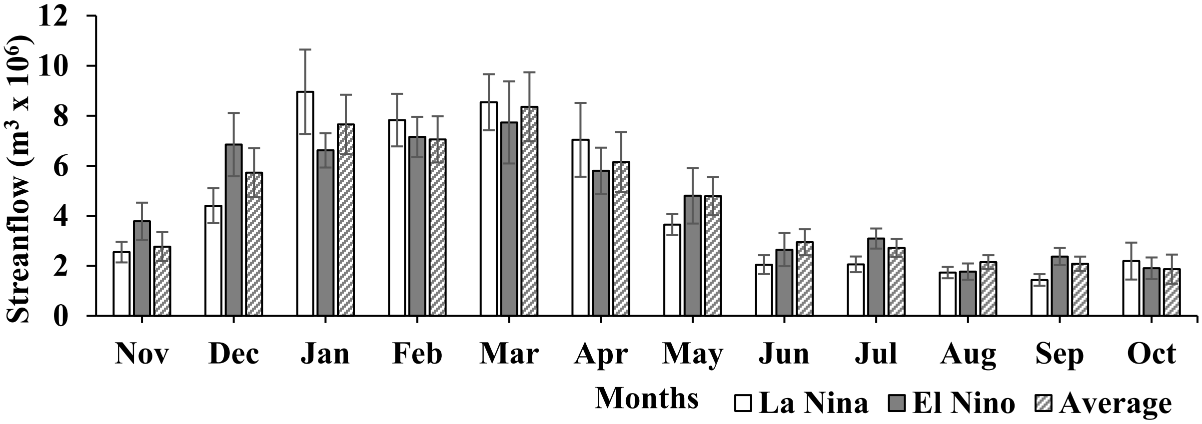

Figure 2. 8 Average monthly streamflow volume for each month (1950-2018) in La Niña and El Niño phase. Also shown are one standard error bars

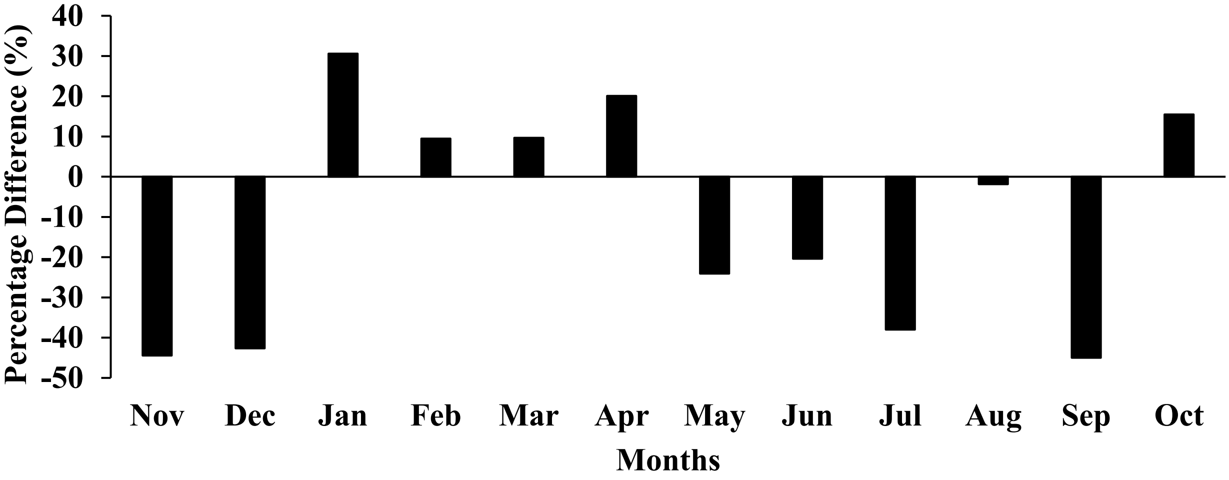

Figure 2. 9 Percentage Difference in streamflow (1950-2018) for La Niña and El Niño phase

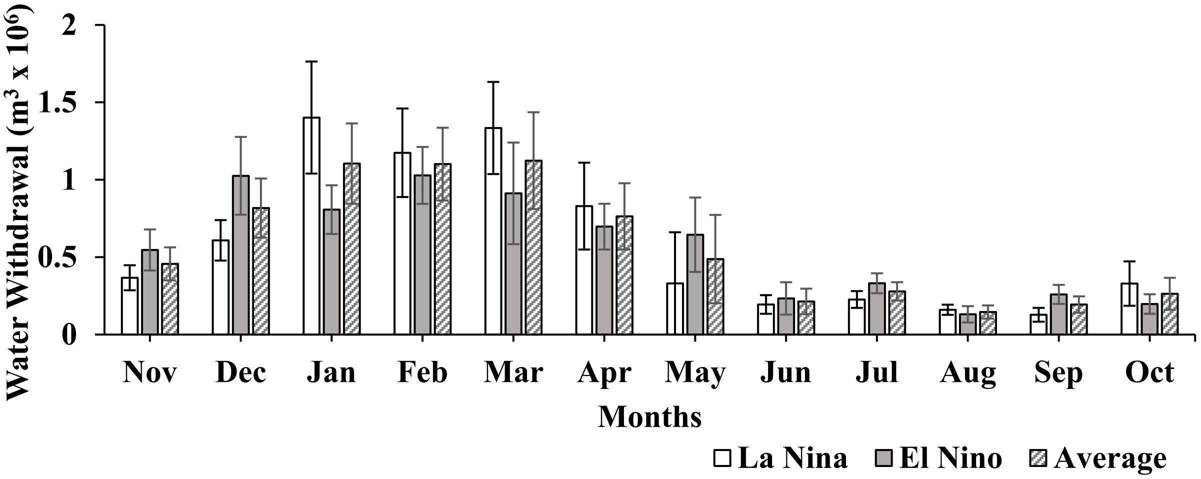

Figure 2. 10 Average monthly withdrawal (m^3 x 10^6) for each month (1950-2018) in La Niña and El Niño phase. Also shown are one standard error bars.

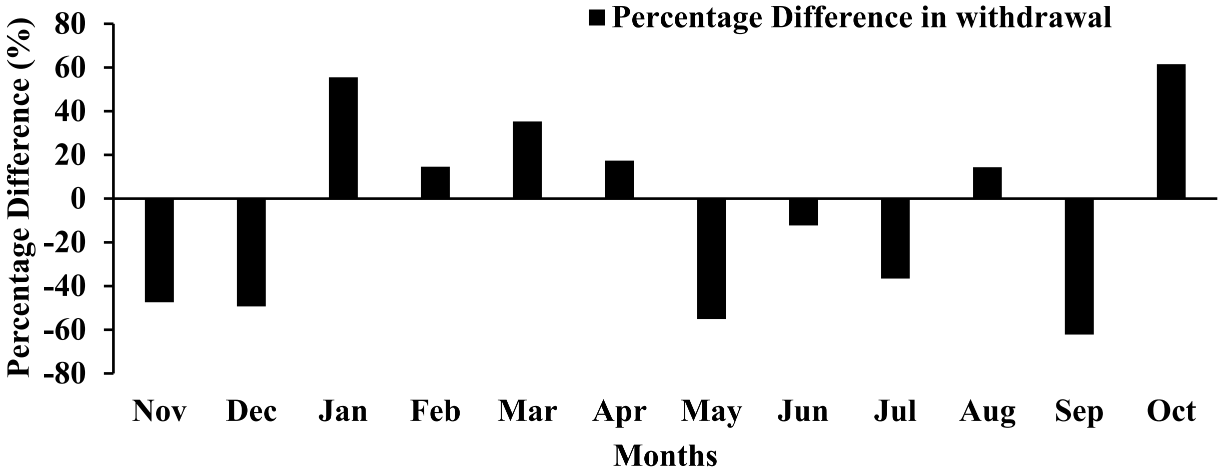

Figure 2. 11 Percentage Difference in withdrawal (1950-2018) for La Niña and El Niño phase

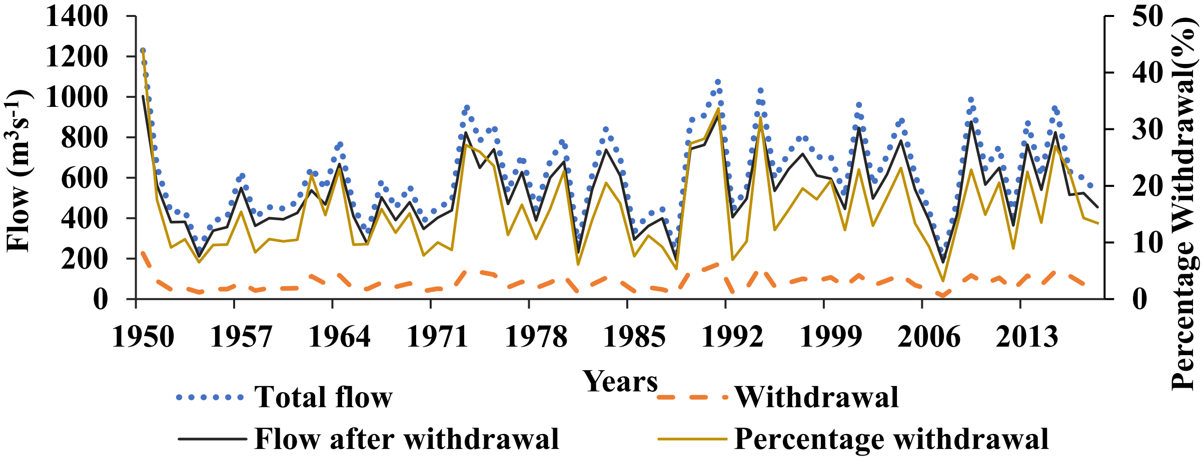

Figure 2. 12 Percentage of subbasin irrigated in each year upstream of watershed outlet. Also shown are the total flow (m^3 s^{-1}), flow withdrawn (m^3 s^{-1}) and the flow (m^3 s^{-1}) after withdrawal

Tables

Table 2.1 Parameters (default and calibrated value) used to calibrate the SWAT model

Parameter	Default Value/Method	Calibrated Value/Method
Evapotranspiration Method	Penman-Monteith	Hargreaves Method
CN	variable	Reduced by 5%
ESCO	0.95	0.7
Alfa Bf (1/days)	0.048	0.486

Table 2.2 **Water Withdrawal criteria adapted from Richter et al. (2003) and USFWS and USEPA (1999)**

Flow Parameters	Guidelines for maintaining sustainable 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 Do not exceed the median in half of the years
Monthly average flow	Maintain the monthly mean flow within the range of 25th and 75th percentile
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

Table 2.3 Calibration and validation statistics for daily baseflow, surface runoff, and total flow.

	Calibration (June 26, 2009-June 26, 2013)			**Validation (June 27, 2013- June 30, 2018)**		
	NSE	**R^2**	**PBIAS (%)**	**NSE**	**R^2**	**PBIAS (%)**
Baseflow (m^3s^{-1})	0.70	0.70	-5.3	0.63	0.65	-3.3
Surface Runoff (m^3s^{-1})	0.53	0.54	-27.7	0.42	0.49	-14.0
Total Flow (m^3s^{-1})	0.57	0.57	-17	0.49	0.53	-8.6

Table 2.4 Calibration and validation statistics for monthly baseflow, surface runoff, and total flow

	Calibration (June 26, 2009-June 26, 2013)			**Validation (June 27, 2013- June 30, 2018)**		
	NSE	R^2	PBIAS (%)	NSE	R^2	PBIAS (%)
Baseflow (m^3s^{-1})	0.77	0.77	-1.5	0.77	0.78	-3.9
Surface Runoff (m^3s^{-1})	0.75	0.83	-23.1	0.81	0.83	10.9
Total Flow (m^3s^{-1})	0.77	0.85	-15.3	0.82	0.84	-8.2

Table 2.5 Average observed and simulated monthly flows ($m^3 s^{-1}$) ± standard error

Parameter	Observed ($m^3 s^{-1}$)	Simulated ($m^3 s^{-1}$)
Baseflow	0.808 ± 0.04	0.786 ± 0.03
Surface Runoff	1.40 ± 0.16	1.15 ± 0.12
Total Streamflow	2.20 ± 0.18	1.94 ± 0.14

Table 2.6 Percentage subbasin irrigated during different withdrawal scenarios for all the streams (shown in figure 1). (* 1st order streams, ** 2nd order streams, ***3rd order stream)

Streams	Withdrawal whole year	Withdrawal non-crop growing months (Dec.- Mar.)	Withdrawal crop growing period (April- Sept)
Stream 1*	14.7	9.0	4.8
Stream 2*	16.1	9.7	5.4
Stream 3*	15.5	9.3	5.0
Stream 6*	15.7	9.3	5.1
Stream 8*	15.7	9.3	5.2
Stream 9*	16.6	9.7	5.9
Stream 10*	15.8	9.3	5.2
Stream 11*	17.1	10.0	6.4
Stream 14*	16.9	9.8	5.9
Stream 18*	17.0	9.8	6.1
Stream 4**	15.7	8.9	5.6
Stream 5**	15.8	9.3	5.2
Stream 7**	16.5	9.2	5.8
Stream 12**	16.1	9.3	5.5
Stream 13**	13.9	8.2	4.6
Stream 15**	16.0	9.1	5.5
Stream 16**	15.6	9.2	5.1
Stream 17**	15.2	8.9	5.1
Stream 19***	15.8	9.2	5.3

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Chapter 3

Effect of ENSO based upstream water withdrawals for irrigation on downstream water withdrawals

Abstract

In the past two decades, the percentage of cropland area irrigated in Alabama (AL) has increased from 42% to 51%. In addition to using groundwater for irrigation, farmers in AL withdraw water from streams to irrigate crops. Typically, water withdrawal from streams for irrigation is not done using an ecologically sustainable in-stream flow approach. Furthermore, the water withdrawn from streams by farmers in upstream areas can reduce the volume of water available for withdraw in downstream areas. In the Southeast U.S., El Nino Southern Oscillation (ENSO), climate-variability phenomena affect the quantity of water that is available for irrigation. The main objectives of this study were to quantify: (a) the effects of ENSO on temperature, precipitation, and streamflow during crop growing and non-crop growing seasons, (b) the impact of upstream water withdrawals on the downstream water withdrawals as a function of ENSO phase, (c) the watershed area that can be irrigated using water withdrawn from streams in an ecologically sustainable manner, and (d) determine the size of pond required to store water withdrawn from streams as a function of stream order. The study was conducted in the Swan Creek watershed (97 km^2) located in Limestone County, AL, U.S. The Soil and Water Assessment Tool (SWAT) model was used to simulate stream flows and develop water withdrawal prescriptions.

While higher precipitation, streamflows and volume of stream water available for withdrawals were observed in La Nina phase than El Nino phase during non-crop growing season, trends were opposite during the crop growing season. Results indicate that when simultaneous water withdrawals were made at the outlet of each subwatershed throughout the year, on average water withdrawals were sufficient to irrigate 4.4% to 16% of the area upstream of withdrawal point depending on stream order. At the watershed outlet, the volume of water available for withdrawal was reduced by 41% and 67% during non-crop growing and crop growing season, respectively, when water withdrawals were at the outlets of all subwatersheds upstream of watershed outlet compared to no water withdrawals made upstream of watershed outlets. Furthermore, it was found that on making stream water withdrawals at multiple locations within the watershed, a greater area of watershed could be irrigated than the total area irrigated by limiting water withdrawals to 2nd order stream subwatersheds or only at watershed outlets.

3.1 Introduction

The world population is estimated to grow to 8.3 billion in 2030 and 9.3 billion in 2050 with nearly 67 million people being added to the world per year (FAO, 2012). This upsurge over time will increase stress on the agriculture industry. To meet the needs of projected population, crop production is required to increase by nearly 50% in the next 50 years to sustain our present per capita supply, considering that the productivity of present farmland remains the same (Jury & Vaux, 2007). In order to achieve this goal, large-scale human interventions would likely take place, including, but not limited to, land use and land cover change, irrigation to enhance food productivity, dams and reservoirs to manage streamflows, and water withdrawals from surface water bodies and groundwater to satisfy water demands (Veldkamp et al. 2017).

Agriculture is the leading user of freshwater and accounts for 85% of the global freshwater consumption (Jury & Vaux, 2007). The United States Department of Agriculture (USDA) reported that in the U.S., 80% of the nation's freshwater is used for irrigating agricultural crops (Aillery, 2019). Irrigation has helped to substantially increase US agricultural production. Irrigated farms accounted for roughly half of the total value of crop sales on 28% of US harvested cropland for the year 2012 (Dieter et al. 2018). The recent decades saw expansion in irrigated acreage in southeastern states of Mississippi, Louisiana, Georgia, and Alabama (AL) (Dieter et al. 2018; Templeton et al. 2014). In AL, the area under irrigation has increased from 322,251,762 m^2 (79,647 acres) in 1997 to 457,230,368 m^2 (113,008 acres) in 2012 (Templeton et al. 2014).

In the U.S., water withdrawals for irrigation from various water sources (e.g., streams, lakes, and aquifers) accounted for 118 billion gallons per day in 2015 with surface withdrawals from rivers and streams accounting for 52% of total water withdrawals for irrigation. In AL, approximately 223 million gallons of water is withdrawn per day from fresh surface water sources for irrigation (Aillery, 2019). Farmers in north AL use surface water from streams for irrigation in addition to ground water. Water is withdrawn from the streams and stored in on-farm ponds. However, it is important that when water is withdrawn from streams for irrigation it should be done in an ecologically sustainable manner. Monfared et al. (2017) found that variation in river flow discharge may modify the assimilation capacity of streams by up to 97% which may prove lethal for instream biota and thus, affirms the need for preservation of minimum flows necessary for aquatic health and dilution of pollutants. Excessive water withdrawal from streams disturbs in-stream biota by reducing functioning habitat (Scatena & Johnson, 2001), blocking entrance to habitat, and causing direct and indirect mortality (Benstead et. al. 1999). Therefore, for effective water management, efficient and planned water withdrawals are required for irrigation.

Hydrological models, capable of simulating watershed level hydrological processes (e.g., Soil and Water Assessment Tool (SWAT)) can help evaluate the effects of management decisions (e.g., water withdrawals from streams) on water resources (e.g., levels of streamflows) (Douglas et al. 2010; Gassman et al. 2014).

Irrigation water demand is expected to rise in the future due to anticipated variations in rainfall regime caused by climate variability (Díaz et al. 2007). Climate variability in the southeastern United States (US) is governed by El Niño Southern Oscillation (ENSO) phenomenon. ENSO refers to the year-to-year variation in surface air pressure, sea surface temperatures, convective rainfall, and atmospheric circulation that appears over the equatorial Pacific Ocean (Philander, 1990). El Niño and La Niña are opposite extremes in the ENSO cycle. El Niño refers to the warm phase of the ENSO cycle and is identified by a large-scale weakening of the trade winds and warming of the sea surface layers. La Niña depicts the cold phase of the ENSO cycle and is characterized by lower than average sea surface temperatures. Neutral phase refers to those periods where neither El Niño nor La Niña is present and sea surface temperatures are near the long-term average.

In the southeastern US, streamflow is impacted by ENSO, and the volume of streamflow varies depending on the ENSO phase (Kahya & Dracup, 1993a, 1993b; Piechota & Dracup, 1999; Pierre G.F.et at., 2010). Thus, the volume of water available for withdrawals from streams is also a function of the ENSO phase. Studies in the southeastern US have shown that the months from October to April tend to be wetter in El Niño phase than La Niña phase (Kiladis and Diaz, 1989; Ropelewski and Halpert ,1996; Sittel, 1994). However, Ropelewski et al. (1986) found that the influence of ENSO on rainfall in southeastern US is spatially less consistent. This was also confirmed in a study by Sharda et al. (2012), in which opposite correlations were found between

ENSO and precipitation, and ENSO and streamflow patterns between northern and southern AL. Similarly, Leung et. al. (2003) reported opposite dry and wet patterns in the northwest U.S. and California during ENSO phases.

The instant effect of water withdrawal from streams is a drop in stream water levels in the downstream areas, which differs within a watershed (Henderson, 1966; Lai et al. 2014). Various studies have shown that water management practices (e.g., irrigation water withdrawals from streams, reservoir and dam construction) have significant impacts on downstream flows. Therefore impacts of upstream water management practices on downstream flows must be accounted for (Mckinney et al. 1999; Shah & Raju, 2001; Vema et al. 2018). Water withdrawn from streams by farmers in upstream areas can reduce the volume of water available for withdraw in downstream areas. This will not only be harmful for downstream biota but could also turn out to be an economic disaster for farmers who would have access to limited amount of water available for withdrawal to irrigate crops. Previous studies have investigated the effect of streamflow alterations via water withdrawals on fish assemblage, sediment erosion and deposition processes (Kanno and Vokoun, 2010; Jay and Simenstad, 2006; Andrews, 1986). Mondal et al. (2011) conducted a study in a forested watershed in south AL and quantified the area within a watershed that can be irrigated using water withdrawn from streams. However, Mondal et al. (2011) assumed that the withdrawals are made only at the outlet of a particular stream order at a time. Typically, in agricultural watersheds water withdrawals are made simultaneously at the outlets of various subwatersheds at a time for irrigation. Therefore, it is important to consider how streamflow withdrawal in upstream areas of a watershed impact streamflow in downstream areas. To our knowledge, no study has evaluated the effect of upstream surface water withdrawals for irrigation on the quantity of water available for irrigation in downstream areas as a function of ENSO phase in agricultural watersheds. This study aims to quantify: (a) the effects of ENSO on temperature, precipitation, and streamflow during crop growing and non-crop growing seasons, (b) the impact of upstream water withdrawals on the downstream water withdrawals as a function of ENSO phase, (c) the watershed area that can be irrigated using water withdrawn from streams in an ecologically sustainable manner, and (d) determine the size of pond required to store water withdrawn from streams as a function of stream order. The research results from this study will provide a valuable dataset for conservation planners that can be used to plan water withdrawals from streams for irrigation without disturbing the ecological integrity of streams.

3.2 Material and Methods

3.2.1 Study Area

The study watershed was Swan Creek watershed (97 km^2), which is a part of the larger Tennessee river basin. The watershed is located in Limestone County, north AL (Figure 3.1). Observed streamflow data is available from the USGS stream gage 03577225 located at the watershed outlet. The land use in the watershed has remained fairly consistent (change < 4% over last 10 years) with a 10-year average landuse of 22% pastures, 21% agricultural land, 20% deciduous forest, 12% open space, 11% developed low intensity, 3% evergreen forest, and 3% shrubland (NRCS, 2019). Elevation values within this watershed range from a minimum of 198 m to maximum of 248 m with respect to mean sea level. The main soil types in the watershed are Dickson silt loam (26%), Guthrie silt loam (14%), Cookeville silt loam (9%), Lawrence silt loam (8%), Melvin silt loam (8%), Sango silt loam (7%) and Abernathy-Emory silt loam (2%) (NRCS, 2019). The 68-year mean annual precipitation of the watershed is about 1,350 mm (53 in). The major crops grown in the watershed from 2008-2017 based on cropland data layer files were soybeans, corn, cotton and winter wheat (NRCS, 2019).

3.2.2 Soil and Water Assessment Tool (SWAT) model

The Soil and Water Assessment Tool (SWAT) model has proven to be a useful tool for evaluating water resource problems for a wide range of watershed scales and environmental conditions across the globe (Francesconi et al. 2016). The model is physically based, computationally efficient, and can simulate hydrological processes over long periods. Hydrology, weather, soil properties, plant growth, pesticides, nutrients, and land management are the major components of the SWAT model. In SWAT, a watershed is divided into various subwatersheds, which are then subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics within a subwatershed. In our study, the Swan Creek watershed was divided into 19 subwatersheds and consisted of 7,200 HRUs. Modified SCS curve number method was used for the estimation of surface runoff based on HRU landuse, soil type and initial moisture conditions. Manning 's formula was used for calculation of both overland and channel flow (Chow et al. 1968). Depending on the availability of the data, potential evapotranspiration can be modeled using Penman–Monteith (Monteith, 1965), Priestley–Taylor (Priestley, & Taylor, 1972) or Hargreaves method (Hargreaves and Samani, 1985). The hydrologic balance was simulated for each HRU. Streamflows at the outlet of each subwatershed are calculated after summing up runoff and baseflows from all HRUs within a subwatershed and routed through the stream system using either the Muskingum method (Neitsch et al. 2005a) or the variable-rate storage method (Williams, 1969). The variable-rate storage method was used in the study for routing. Applications of SWAT to simulate the effect of natural and anthropogenic activities on hydrological processes have increased extensively over the past decades (TempQsim, 2006; Van Griensven et al. 2005; Volk et al. 2007). More information about SWAT model can be found in Neitsch et al. (2011). In this study, ArcSWAT 2012.10.3.19 version was used.

3.2.3 Data Input

Topographical data was obtained using a 10 m digital elevation model (DEM) which was obtained from National Geospatial Gateway (https://datagateway.nrcs.usda.gov/). Soil data was obtained from the Soil Survey and Geographic (SSURGO) database (NRCS, 2019). Planting date, tillage methods, timing and rate of nutrient and pesticide applications, and harvest timing were obtained from the database developed by Butler & Srivastava, (2007). The daily precipitation (1950-2018) and temperature (maximum and minimum) data (1950-2018) were obtained from weather stations at Belle Mina and Athens, AL (Figure 3.1). It should be noted that, for each subwatershed, SWAT uses weather data from one station at a time depending on which station is nearest to the centroid of each subwatershed. The climatic parameters unavailable at the weather station, i.e., solar radiation, relative humidity and wind speed were generated using a built-in SWAT weather generator (Neitsch, et al. 2011). Crop rotation information for Swan Creek watershed was derived using the cropland data layers (CDL) files from 2008-2019 (Figure 3.2). In total, 34 different crop rotations practiced on 90% of the watershed's cropland area over the period of nine years were incorporated in the SWAT model. Use of cropland data layers of multiple years to derive crop rotation information has shown to increase accuracy of the model (Sahajpal et al. 2014). Irrigation rates were obtained from National Engineering Handbook Irrigation Guide (USDA, 2009). The United States Geological Survey (USGS) stream gage was used to obtain daily measured streamflow data (June 2009 to June 2018) required for streamflow calibration and validation.

3.2.4 Model Calibration and Validation

To stabilize the SWAT model and get the hydrological cycle fully operational, it is recommended to warm-up the model. Insufficient warm-up period may result in reducing model performance, especially in the first few years of simulation (Huard and Mailhot, 2008). It is recommended by the developers to use at least a two to three years warm-up period for hydrological processes and five to ten years for sediment and nutrient processes (Daggupati et al. 2015). Therefore, a period of eight years from January 2000 to December 2008 was used as a warmup period. SWAT model was calibrated and validated separately for baseflows and storm runoff at a daily time step. Web-based Hydrograph Analysis Tool (WHAT) program developed at Purdue University, Indiana, USA was used for separation of streamflow into surface runoff and baseflow (Lim et al. 2005). Specific guidelines were followed as presented in Arnold et al. (2012) and Moriasi et al. (2007) and certain parameters (Table 3.1) were changed to achieve maximum agreement between observed and simulated flows. Based on the availability of the observed streamflow data, the SWAT model was calibrated and validated at a daily time-step for surface runoff, baseflow and total streamflow from June 26, 2009 to June 26, 2013 and from June 27, 2013 to June 30, 2018, respectively.

3.2.5 Model Evaluation

Time series plots of observed vs. simulated surface runoff, baseflow and streamflow were compared to qualitatively evaluate SWAT model performance. Additionally, for quantitative evaluation, we used regression correlation coefficient (R^2), the Nash- Sutcliffe model efficiency (NSE) coefficient (Nash and Sutcliffe, 1970) and PBIAS (Krause et al. 2005). The R^2, PBIAS and NSE have been most commonly used in previous studies to evaluate model performance quantitatively (Gassman et al. 2007 ; Chen et al. 2017). The R^2 value tests how well the simulated versus observed regression line resembles an ideal match and ranges from 0 to 1, with a value of 0 symbolizing no correlation and a value of 1 signifying that the projected distribution equals the measured distribution (Krause et al. 2005). It was calculated using the following equation:

$$R^2 = \frac{\left[\sum_{i=1}^{n}(O_{obs,i}-\bar{O}_{obs})\,(O_{sim,i}-\bar{O}_{sim})\right]}{\left[\sum_{i=1}^{n}(O_{Obs,i}-\bar{O}_{obs})^2\right]^{0.5}\left[\sum_{i=1}^{n}(O_{sim,i}-\bar{O}_{sim})^2\right]^{0.5}} \quad (1)$$

Where $O_{sim,I}$ and $O_{obs,I}$ are simulated and observed flows, respectively, for the i^{th} observation; n is the number of observations, $\bar{O}_{sim}\ and\ \bar{O}_{obs}$ are mean simulated and observed flows for the simulation period, respectively.

The NSE ranges from $-\infty$ to 1 and tests how well the simulated versus observed data match the regression line with slope equal to 1. An NSE value of 1 indicates a precise fit between the simulated and observed data. However, the value for NSE as 0 or less than 0 shows that the mean of the observed data is a more reliable predictor than the model output.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs}-Y_{mean})^2}\right] \quad (2)$$

PBIAS measures the tendency of the simulated data to be larger or smaller than the corresponding observed values. Positive values of PBIAS indicate model underestimation bias, and negative values indicate model overestimation bias. (Gupta et al. 1999).

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(Y_i^{obs}-Y_i^{sim})*100}{\sum_{i=1}^{n}(Y_i^{obs})}\right] \quad (3)$$

Y_i^{obs} is the i^{th} observation for the component being calculated, Y_i^{sim} is the i^{th} simulated value for the component being evaluated, Y^{mean} is the mean of observed data for the component being evaluated, and n is the total number of observations. For the calibration and validation period the model performance is considered satisfactory at daily time step if NSE and $R^2 > 0.4$ (Ahmad et al. 2011) and PBIAS $< \pm 25\%$ (Moriasi et al. 2007). The performance of model is considered to be adequate at monthly time step if NSE and $R^2 > 0.5$ (Santhi et al. 2001) and value of PBIAS is $\pm 25\%$ (Moriasi et al. 2007).

3.2.6 El Niño Oscillation Index: Niño 3.4

El Niño Southern Oscillation (ENSO) is one of the most significant climate anomalies that influence agriculture in various ways. The Niño 3.4 index is the proxy variable used by the National Oceanic and Atmospheric Administration's Climate Prediction Center for the determination of El Niño and La Niña phase (NOAA 2019). The positive deviation (greater than 0.5°C) in the temperature anomaly of the sea surface for a minimum of 5 consecutive months implies El Niño conditions and the similar negative (less than -0.5°C) deviation implies La Niña conditions. When the index is between 0.5 and -0.5 the neural conditions prevail. NOAA (2019) was used to classify all the months from 1950-2018 into El Niño, La Niña or Neutral phases. For El Niño and La Niña phases, we determined volume of water available for withdrawal in an ecologically sustainable manner from streams for irrigation.

3.2.7 Water Withdrawal Criteria and Procedure

The change in streamflow characteristics caused by the water withdrawals from streams could cause stress on the river biota and can result in water quality impacts. Therefore, it is important to withdraw water from streams in an ecologically sustainable manner. Freshwater biota and ecosystem processes could be affected by different aspects of hydrological variability. However, for developing the water withdrawal prescriptions, the primary focus should be to inspect normal high flows, wet and dry season base flows, extreme drought and flood conditions; and the interannual variability associated with flows (Trush et al. 2000). Such a criteria were used in this study which were developed by Ritcher et al. (2003) and USEPA and USFWS (1999) for Apalachicola-Chattahoochee-Flint (ACF) River basin in AL, Florida, and Georgia (Table 3.2). These criteria are also agreed upon by US Environmental Protection Agency and US Fish and

Wildlife Service. The detailed methodology as mentioned in USEPA and USFWS (1999) was followed to withdraw the water from the streams.

First, baseline streamflows (no water is withdrawn from streams) values at the outlet of each subwatershed were obtained from the SWAT model calibrated and validated for surface runoff, baseflow and streamflow. Then we calculated how much water can be withdrawn from streams at the outlet of each subwatershed based on the water withdrawal criteria without making any withdrawals upstream of the withdrawal point. This provided the baseline conditions for the streamflows that must be maintained in all the reaches of different stream orders. The water withdrawal criteria used in this study (Ritcher et al. 2003; USEPA and USFWS 1999) are very sensitive to the streamflows below 25th percentiles and the streamflows that exceed 95th percentile. No water was withdrawn from streams when the flows are below 25th percentile for daily flows of the entire study period (1950-2018). For the flows between 25th and 95th percentiles, the water was withdrawn in a way to keep the flows in the streams above 25th percentile. For the flows above 95th percentile, 20% of the flow was withdrawn from the streams. This restriction on water withdrawals for the flows above 95th percentile was based on the practical pumping or diversion constraints (Mondal et al. 2011). The crop water requirement is not similar for all crops, however, approximately 457 mm (18 in) (i.e., about 4570 m^3 for one irrigated ha area [3.7 ac ft]) has been reported to be adequate for the crop growth in AL (ACES 1994). We quantified how much area of a watershed can be irrigated if the water was withdrawn in an ecologically sustainable manner throughout the year, withdrawn only in the non-crop growing period (Dec.-Mar.), and withdrawn only in the crop growing period (Apr.-Sep.).

Water was withdrawn from all the streams in a chronological manner in the watershed. The water was withdrawn using the criteria explained previously in the manuscript. The certain volume of water was withdrawn from the outlet of each subwatershed while maintaining the minimum levels in the streams required to sustain the in-stream ecology. One of the limitations of the SWAT model is that it does not allow the amount of water withdrawn from stream to vary at a daily time step. Therefore, water withdrawal analysis was done outside the SWAT model using certain variables from the reach (.rch) and subwatershed (.sub) output files of SWAT. The values of FLOW_IN (average daily flow in the reach during the time step), FLOW_OUT (the average daily streamflow out of the reach during the time step), WYLD (the water yield for each day for each subwatershed), TLOSS (the transmission losses from channel in HRU through stream bed) were obtained from the SWAT model. TLOSS per day was almost zero for the streams. At the outlet of each subwatershed, amount of water that can be sustainably withdrawn from streams was determined and was subtracted from the total streamflow. The updated streamflows were calculated for downstream watershed using the above-mentioned variables from obtained from the SWAT output files (.rch and .sub). This procedure was repeated for all subwatersheds.

3.2.8 Relationship between ENSO phase and Temperature, Precipitation, Stream Flow, and Water Withdrawn

Daily streamflows, precipitation and water withdrawals from 1950-2018 were added to get their monthly values. Daily temperatures were averaged to get the monthly temperatures. The streamflows were further averaged for each ENSO phase i.e. El Niño and La Niña from 1950-2018 for a given month. The monthly streamflows, precipitation and water withdrawals for each phase were then averaged for non-crop growing (Dec.-Mar.) and crop growing (Apr.-Sept.) seasons. The percent difference was used to find the difference between the precipitation, temperature and withdrawals for each season in a respective ENSO phase. For each season of the year, the percentage difference was calculated by finding the difference between average seasonal streamflows of La Niña and El Niño phases and then dividing it by the average seasonal streamflows for the entire study period (equation 4). Similar procedure was used to calculate percent difference for temperature, precipitation and water withdrawals.

$$S_m = \frac{\bar{S}_{La\ Nina,s} - \bar{S}_{El\ Nino,s}}{\bar{S}_s} \qquad (4)$$

where S_m is streamflows percentage difference (%), $\bar{S}_{\mathrm{La\ Nina,s}}$ denotes streamflows in La Nina phase during a particular season ($m^3\ s^{-1}$), $\bar{S}_{\mathrm{El\ Nino,s}}$ denotes average streamflow during the same season in El Nino phase, and $\bar{S}_{\mathrm{s}}$ denotes the average streamflows in the particular season for the whole study period (1950-2018). To evaluate the significant difference between the temperature, precipitation, streamflows, and water withdrawals for El Niño and La Niña, an Analysis of Variance (ANOVA) at the significance level of α=0.10 was conducted using SAS Statistical Software (SAS Institute, Inc., Cary, North Carolina, United States).

3.2.9 Pond size for storage of withdrawn water

During the drought and critical crop growth stages, water harvested during non-crop growing season in on-farm ponds could be used to irrigate crops. The size of the pond is dependent on the area available for pond, the water available for withdrawal, water requirement of the crops grown, rainfall expected in the growing season, and losses due to evaporation and seepage. The guidelines from the USDA-NRCS, Ponds, Planning, Design, Construction Agriculture Handbook Number 590 were used to determine pond size that would be adequate to store water withdrawn from streams using the ecologically sustainable withdrawal criteria.

$$Surface\ area\ of\ pond = \frac{Capacity\ of\ Pond}{Maximum\ Depth\ of\ pond * 0.4} \qquad (5)$$

The minimum depth of pond recommended by USDA (1997) in north-AL is 1.82-2.13 m (6-7 feet). Therefore the average depth of pond considered in this study was 2.13 m (7 feet) (5.33*0.4). Thus, a deep spot of up to 5.33 m (17.5 feet) could be created in the pond to store ample amount of water withdrawn and reduce the evaporative losses.

3.3 Results and Discussion

3.3.1 Calibration and Validation of SWAT model

The SWAT model was manually calibrated and validated separately for baseflow, surface runoff and streamflows at daily time step. Overall graphical representations of observed vs. simulated surface runoff, baseflows and total streamflows show similar trends for the calibration and validation periods (Figure 3.3). At the daily time step the surface runoff, baseflow and streamflow statistics values for calibration and validation periods are presented in table 3.3. NSE R^2 values in table 3.3 indicates that a satisfactory model performance at the daily time-step was obtained for baseflow and total streamflow with NSE and R^2 criteria as used by Ahmad et al. 2011 (NSE >0.4 , R^2>0.5) and Moriasi et al. 2007 (PBIAS < ±25). As depicted by NSE and R^2 values (Table 3.4) for both calibration and validation time periods, model performance was rated “very good” for baseflow, surface runoff and streamflow at the monthly time step (Moriasi et al. 2007). The PBIAS values indicated model performance was rated “very good” for baseflow and satisfactory for surface runoff and streamflow. The average monthly baseflow, surface runoff and streamflow values showed variation within 10%, 17% and 11%, respectively, between observed and simulated values. Overall, based on graphical comparison of observed and simulated flow values and quantitative evaluation, SWAT model satisfactorily represented hydrological processes in the watershed.

3.3.2 Relationship between ENSO and Temperature

Temperature patterns were studied for ENSO phases for crop growing and non-crop growing seasons. The average annual temperature in the non-crop growing season (Dec.-Mar.) was 0.9 ºC higher in La Niña phase than El Niño phase (Figure 3.4). NOAA, (2016) also reported the similar trend between La Niña and El Niño during non-crop growing season where the temperatures in southeast were found to be warmer than normal in La Niña phase. This temperature difference between the ENSO phases was more prominent in non-crop growing season than in crop growing season. A 9.7% difference was observed between the temperatures during non-crop growing season between the La Niña and El Niño phase as compared to 4.1% during the crop growing season (Figure 3.5). The higher temperature in La Niña phase than El Niño phase continues in the crop growing season (Figure 3.4). Mourtzinis et al. (2016) also reported lower temperatures during El Niño phase as compare to La Niña phase during the crop growing period in southeastern US. When El Niño or La Niña continues throughout the year, percentage difference between the temperatures in La Niña and El Niño phase was 6.85% (Figure 3.5). Specifically, temperature differences were more prominent in the non-crop growing season of January (29%) and February (26%) relative to the other months. Similarly, Gershunov, (1998) documented the reduction in warm temperature extremes during the El Niño phase in non-crop growing season. This finding is important for irrigation scheduling, management practices and crop yields. Higher temperatures increase the evapotranspiration demand of the crops and yield reductions are evident if the water requirements are not met in the critical stages of the crop growth (Andales, 2014).

3.3.3 Relationship between ENSO and Precipitation

Precipitation trends were examined for crop growing, non-crop growing season, and throughout the year for La Niña and El Niño phases of ENSO. During the non-crop growing season, more precipitation was observed in La Niña phase than El Niño phase. (Figure 3.6). Average precipitation per month during the non-growing season in the La Niña phase was 135 mm as compared to 123 mm in the El Niño phase. A considerable difference in precipitation for La Niña and El Niño phase was observed for the months of January (24%) and March (15%). However, during the crop growing season, wet conditions were observed during the El Niño phase relative to La Niña phase. The precipitation was found to be significantly ($\alpha = 0.10$) greater in El Niño phase than La Niña phase during the crop growing season. A substantial difference in precipitation was observed for the months of June (25%) and July (14%). Average precipitation in each month during crop growing season during La Niña phase was 88 mm as compared to 111 mm for El Niño phase. It was also observed that irrespective of the phase, the non-crop growing season resulted in 20% more precipitation than crop growing season. Fraisse et al. (2006) also reported wet conditions in the north AL during the non-crop growing season. The percentage difference of 22% was observed for precipitation in the crop growing season between El Niño and La Niña phase (Figure 3.7). The negative percentage difference in the crop growing season (Figure 3.7) indicates higher precipitation in El Niño phase than La Niña phase. Similar trends with greater precipitation during El Niño phase than La Niña phase in crop growing season were documented by Mourtzinis et al. (2016) and Sarkar et al. (2012) in southeastern US. The more precipitation in crop growing seasons during El Niño phase is bloom for the crops and could likely reduce the irrigation water demands whereas lesser precipitation in La Niña phase could result in increase in irrigation water demand. Lesser precipitation would also affect the streamflows during the crop growing season, which would assert the need for irrigation water withdrawal management practices to obtain optimum amount of irrigation in an ecologically sustainable manner.

3.3.4 Relationship between ENSO and Streamflow

ENSO and streamflows are documented to have a strong and consistent trends in southeastern US (Schmidt et al. 2001). Similar to precipitation trends, in non-crop growing season, the streamflows at the watershed outlet in La Niña phase were greater than El Niño phase (Figure 3.8). This trend was opposite than that observed by Mondal et al. (2011) where greater streamflows were observed in El Niño phase during non-crop growing season. Sharda et al. (2012) reported that the streamflow patterns in response to ENSO phase varies within the state of AL. The trends in north AL region doesn't comply with the trends seen in southern AL. Therefore, results suggest that the impact of ENSO on the water resources should be quantified for different climatic divisions (NCEI, 2019). The trends in crop growing season were opposite of that seen in non-crop growing season, i.e., El Niño phase produced greater volume of stream flows than La Niña phase. The percentage difference of 12% in streamflows was observed between El Niño and La Niña phase during crop growing season (Figure 3.9). However, it should also be noted that the streamflows in El Niño phase were higher during non-crop growing season than crop growing season. Similarly, the average streamflows in La Niña phase during non-crop growing season were more than double of the average streamflows during crop growing season. Moreover, irrespective of the phase, on an average the streamflows in non-crop growing season were almost double of the streamflows in crop growing season. This finding is very important for water resource management, especially in La Niña phase. The lesser streamflows in La Niña phase would limit the water withdrawals for irrigation during the crop growing season. If the irrigation water withdrawals continue during the crop growing season, the lower precipitation and lower streamflows during La Niña phase would highly intensify the impact on water resources. This effect on the water resources could be countered with the adoption of irrigation water withdrawals during the non-crop growing season. Especially, the streamflows in month of January were found to be 30% greater in La Niña phase than in El Niño phase. Thus, due to higher availability of water, the month of January could be the main focus for making the stream water withdrawals.

3.3.5 Water withdrawals and ENSO phase

Stream water withdrawal was performed at the outlet of each subwatershed (e.g., farmers at the outlet of each subwatershed were withdrawing water from streams). Similar trends between ENSO phases and water withdrawals were observed at the outlet of all the subwatersheds. Therefore, to reduce the redundancy, the results observed at the watershed outlet are discussed here. At the watershed outlet, in the non-crop growing period, 14% more volume of streamflow could be withdrawn in La Niña phase than El Niño phase (Figure 3.10). However, during the crop growing season, the amount of water that can be sustainably withdrawn from streams was less in La Niña phase than El Niño phase (Figure 3.10). If the La Niña phase continues during the growing season, the average volume of water available for withdrawal would be limited (76,546 m^3) as compared to water available for withdrawal during El Niño phase (99,578 m^3) (Figure 3.10). The average quantity of water that can be withdrawn sustainably from streams in crop growing season during La Niña phase was almost one-fourth (76,546 m^3) of the amount of water available to withdraw sustainably in non-crop growing season (301,064 m^3) (Figure 3.10). For both La Niña and El Niño phases, regardless of a stream order or location within a watershed, on an average 55% more amount of water could be withdrawn sustainably from streams during non-crop growing season compared to crop growing season. Therefore, it would be advised that the water withdrawals from streams should be made during non-crop growing season and water should be stored in on-farm ponds. However, if the El Niño occurs during the crop growing season, more water is available for withdrawal when compared to La Niña phase. About 21% difference was observed in volume of water that can be sustainably withdrawn between El Niño and La Niña phase during crop growing season (Figure 3.11). However, it should also be noted that even though more water is available for withdrawal during El Niño phase in crop growing season, the volume of water available for withdrawal during non-crop growing season in El Niño phase was almost thrice the volume of water available for withdrawal during crop growing season. Thus, results of this study show that the winter withdrawals, especially during La Niña phase are vital to have an adequate amount of water for irrigation during crop growing season without impacting the ecological integrity of streams. The water could be stored in on-farm ponds and used later at the time of irrigation during the growing season.

3.3.6 Water withdrawal and area irrigated

Water withdrawal was performed at the outlet of each subwatershed and the area of watershed that could be irrigated by making water withdrawal at the outlet of each subwatershed was quantified for three scenarios, i.e. water withdrawal performed whole year, crop growing and non-crop growing seasons.

3.3.6.1 First order streams

The outlets of 1st order stream subwatersheds such as 1, 2, 3, 6, 8, 9, 10, 11, 14 and 18 (Figure 3.12) were the foremost points of water withdrawals in the watershed. When the withdrawals from stream were made throughout the year on an average 16% of the area upstream of withdrawal point could be irrigated (Table 3.5). It was observed that on an average, the water withdrawn in an ecologically sustainable manner throughout the year at the outlet of 1st order stream subwatershed was sufficient to irrigate 109 x 10^4 m^2 (271 acres) (Table 3.5). If the water withdrawals were only made in non-crop growing season, on an average 10% of the area (i.e., 64 x 10^4 m^2) upstream of withdrawal point could be irrigated by the water withdrawn (Table 3.5). The results show that if water is withdrawn only in crop growing season on an average only about 5.6% of the area upstream of the water withdrawal could be irrigated. Mondal et al. (2011) conducted a study in a forested watershed in south AL and reported that on an average 20% of the area upstream of 1st order stream subwatershed outlet can be irrigated when water was withdrawn from streams throughout the year in an ecological sustainable manner. The percentage of area upstream of 1st order stream that can be irrigated using stream water was less in our study compared to Mondal et al. (2011). This was likely due to greater average annual precipitation in Mondal et al. (2011) study watershed (1,648 mm) compared to Swan creek watershed in north AL (1,350 mm).

3.3.6.2 Second order streams

The outlets of 2nd order stream subwatersheds such as 4, 5, 7, 12, 13, 15, 16 and 17 (Figure 3.12) were succeeding withdrawal points after the withdrawals have been made at the outlet of 1st order stream subwatersheds. Due to the water withdrawals made at the outlets of 1st order stream subwatersheds, the amount of water available for withdrawal at the outlets of 2nd order stream subwatersheds was less than natural flows (i.e., when water was not withdrawn from 1st order streams). When the withdrawals were made throughout the year from the outlets of all the 2nd order stream subwatersheds, on an average 8.3% of the area (i.e., 298 x 10^4 m^2 (736 acres)) upstream of 2nd order stream subwatershed could be irrigated by the stream water withdrawals (Table 3.5). It should be noted that on an average 109 x 10^4 m^2 (269 acres) of the upland area has already been irrigated by the water withdrawn at the outlet of 1st order stream subwatershed. Therefore, on an average when water is withdrawn throughout the year, the total area irrigated by the water withdrawals made at the outlet of 1st and 2nd order stream subwatersheds was 1254 x 10^4 m^2 (3098 acres), which was approximately 40% of the area upstream of 2nd order stream subwatershed.

When withdrawals were made in the non-crop growing season at the outlet of 2nd order stream subwatershed outlets, on an average, 4.8% of the upland area (i.e., 172 x 10^4 m^2 (425 acres)) upstream of 2nd order stream subwatershed could be irrigated. When the withdrawals were made only in crop growing season at the outlet of 2nd order stream subwatershed, on an average 2.8% of the area upstream of 2nd order streams subwatershed could be irrigated which was enough to irrigate 98 x 10^4 m^2 (242 acres). The total irrigated area by stream water withdrawals done in crop growing season from 1st and 2nd order stream subwatersheds was 418 x 10^4 m^2 (1032 acres), which was approximately four percent of the area upstream of 2nd order stream subwatershed. Due to increase in drainage area, the volume of water available for withdrawal at the outlet of 2nd order stream subwatersheds was greater than 1st order stream subwatersheds in all three scenarios (water withdrawal performed whole year, crop growing and non-crop growing seasons). Therefore, results of this study show that even if water was withdrawn from 1st order streams, downstream farmers could still withdraw water from streams sustainably. However, quantity of water they can withdraw would depend on the amount of water withdrawn in upstream areas. Similar results reported for 1st order stream, the percentage of area irrigated by the water withdrawn throughout the year in our study was less than that reported by Mondal et al. (2011).

3.3.6.3 Third order stream

At the watershed outlet (i.e., 3rd order stream), when water was withdrawn throughout the year, the stream water withdrawal was enough to irrigate on an average 4.4% of the area upstream of withdrawal point (Table 3.5), which was enough to irrigate 431 x 10^4 m^2 (1065 acres). When the stream water withdrawals were made only in non-crop growing season and crop growing season, the percentage of area that could be irrigated upstream of the withdrawal point was 2.6% and 1.4 %, respectively. This water withdrawn during non-crop growing season and crop growing season would meet the irrigation needs of 252 x 10^4 m^2 (622 acres) and 140 x 10^4 m^2 (346 acres) area, respectively. The watershed outlet was the most downstream point in the watershed for making the stream water withdrawals. Before this point water withdrawals were made at all the upstream subwatershed outlets. On making withdrawals at the outlets of all subwatersheds and watershed outlet throughout the year, a total area of 3912 x 10^4 m^2 (9666 acres) i.e. 40% of the watershed area could be irrigated. During non-crop growing and crop growing seasons, the ecologically sustainable water withdrawal from streams at the watershed outlet and upstream subwatersheds was sufficient to irrigate area of 2276 x 10^4 m^2 (5624 acres), i.e. 23.3% of the watershed area and 1303 x 10^4 m^2 (3219 acres), i.e. 13% of the watershed area, respectively.

The analysis affirms the need for stream water withdrawals during the non-crop growing season. The area irrigated by making the water withdrawals only in the crop growing season at the watershed outlet was half of the area that could be irrigated by making the withdrawals only in the non-crop growing season. Thus, to meet irrigation needs and to maintain the ecological sustainability of the streams, it is important to withdraw water in non-crop growing season.

3.3.7 Comparison of volume of water withdrawn at the outlet of a particular stream order subwatershed with the water withdrawn simultaneously at the outlet of different stream order subwatersheds:

3.3.7.1 No Water withdrawal upstream (Scenario 1)

Chapter 2 discusses the scenario where water was withdrawn at the outlet of each subbasin as a function of stream order with no water withdrawals upstream of the withdrawal point for whole year, non-crop growing, and crop growing season. It was observed on making water withdrawals throughout the year, crop growing season and non-crop growing season, on average at the watershed outlet 16%, 10% and 5.4% of the area upstream of the withdrawal point could be irrigated, respectively. At the watershed outlet, on annual average 6,999,530m^3 of water was available for withdrawal on making the withdrawals throughout the year (Figure 3.13). However, 41% reduction in the volume of water available for withdrawal was observed when water was withdrawn only in the non-crop growing season compared to water withdrawn throughout the year. The volume of water available to withdraw reduced by 67% when water was withdrawn only in crop growing season compared to when water was withdrawn throughout the year. (Figure 3.13).

3.3.7.2 Simultaneous water withdrawal from all subwatersheds (Scenario 2)

In the second scenario**,** stream water withdrawals were made at the outlet of all the subwatersheds in a sequential manner. At the watershed outlet, when no water was withdrawn from the upstream reaches (Scenario 1), on an annual average, 6,999,530 m^3 water could be sustainably withdrawn throughout the year (Figure 3.13). When water withdrawals were made from all upstream reaches throughout the year (Scenario 2), a substantial reduction of 72% in volume of water available for withdrawal was observed at the watershed outlet compared to Scenario 1. Similar trends were observed for crop growing and non-crop growing seasons (Figure 3.13). This reduction in volume of water available for withdraw at the watershed outlet was because of water withdrawals in the upstream reaches. Batchelor et al. (2003) also reported that the change in upstream flow conditions affected downstream streamflows leading to reduced water availability for irrigation in downstream areas. Therefore, irrigation management plans should be developed which could assure that water withdrawals in upstream areas do not affect the quantity of water available in downstream areas substantially. Various other studies (Chandrakanth et al. (2004); Kerr et al. (2002), Diwakara and Chandrakanth, (2007)) also lay emphasis on the development of suitable upstream irrigation water management practices in terms of effect on downstream irrigation water availability especially for the low flow conditions.

3.3.7.3 Water withdrawal only at outlet of 2nd order streams (Scenario 3)

Water was withdrawn at the outlet of all 2nd order stream subwatersheds (stream 4, 5, 7, 12, 13, 15, 16, 17, 19). Flows in the 1st order streams were left undisturbed which resulted in higher flows in 2nd order streams. Therefore, on an average, when the water withdrawals were made throughout the year, the second order streams could irrigate 10.6% of area upstream of withdrawal point compared to 8.3% in the scenario 2 (when the water was withdrawn from the outlet of 1st order streams). On making the withdrawals throughout the year, at the watershed outlet, on average the volume of water available for withdrawal was greater than second scenario (Figure 3.13). Similar trends were observed for water withdrawals made in crop growing and non-crop growing seasons (Figure 3.13). When no water was withdrawn from 1st order streams, on average, 6% of the area upstream of 3rd order stream subwatershed could be irrigated by the water withdrawn throughout the year. Compared to scenario 2, when water was withdrawn simultaneously at the outlet of 1st and 2nd order stream subwatersheds, the percentage of total area that could be irrigated upstream of 2nd order stream subwatershed outlet was reduced by 23%. No withdrawals at the outlet of 1st order stream subwatersheds resulted in greater flows at the outlet of 2nd order stream subwatersheds. It was found that increase in streamflow with drainage area helped to counter the effects of upstream water withdrawals thus still providing enough water withdrawals to be made down streams. Therefore, findings of this study show that if water is withdrawn sustainably at multiple locations within a watershed, greater amount of watershed area can be irrigated compared to a scenario in which water was withdrawn only at the outlet of a second order stream subwatershed or only at the watershed outlet.

3.3.8 Interannual variability in the quantity of water available for withdrawal

The volume of water that can be sustainably withdrawn from streams at the watershed outlet exhibited interannual variability (Figure 3.14). Similar interannual variability trends were observed at the watershed outlet for all three scenarios (i.e., no water withdrawal upstream, water withdrawal from all subwatersheds, and water withdrawal at the outlet of 2nd order stream subwatersheds). Interannual variability trends were found similar for withdrawals made in crop growing and non-crop growing season for all the three scenarios. The higher water withdrawal during 1950, 1974 and 1989 was due to occurrence of La Niña phase during winter months in these years. However, lower water withdrawals were observed in certain years (e.g., 1988, 2007) due to occurrence of La Niña season in the crop growing season. Results show that the volume of water available for withdrawal is highly impacted by the ENSO phase. Therefore, water withdrawal strategies should be planned according to ENSO phase which can be predicted in advance. This will allow farmers to withdraw water from streams sustainably for irrigation.

3.3.9 Optimal pond size to store water withdrawn from streams

Higher withdrawals during crop growing seasons may impact the ecological sustainability of the streams. A counter to this problem is to withdraw the water during the non-crop growing season and store it in on-farm ponds and use it at the time of requirement, i.e., during crop growing season. The pond size required to store water withdrawn from streams was directly proportional to stream order. However, a number of farmers could be withdrawing water from a single point (outlet). A farmer can determine a pond size based on the water availability and area under irrigation. A regression analysis was performed to calculate the pond size for the farmers based on area under irrigation (equation 5). Based on the different size of land holdings and area under irrigation, pond size with an average depth of 2.13 m (7 feet) would be 0.214 times the area under irrigation

$$\text{Pond Size } (m^2) = 0.214 * \text{area under irrigation } (m^2) \qquad (5)$$

Summary and Conclusions

The results of the study indicate that precipitation and streamflows observed during La Niña phase in non-crop growing season were greater compared to El Niño phase. Whereas, during crop growing season, El Niño phase had more precipitation and high streamflows than La Niña phase. Overall, the non-crop growing season was observed to have a wetter and greater amount of stream water available for withdraw than crop growing months regardless of ENSO phase. Thus, results suggest that water withdrawals should be made in the non-crop growing season rather than the crop growing season (especially during La Niña season) to minimize the impact to the ecological integrity of streams.

When water was withdrawn simultaneously at the outlet of each subwatershed and watershed outlet throughout the year based on water withdrawal criteria, on an average, the quantity of water withdrawn was sufficient to irrigate 4.4% to 16% of area upstream of withdrawal point depending on the stream order. Results of this study reveal that it was possible to irrigate more area when water was simultaneously withdrawn at the outlet of 1st and 2nd order stream subwatersheds relative to a scenario in which water was withdrawn only at the outlet of 2nd order stream subwatersheds. The surface area of the pond would be 0.214 times the area under irrigation and with the average depth of 2.13m (7 feet).

Future studies should be done to quantify the impact of water withdrawals on sediment and nutrient transportation in the watershed. Withdrawals might lead to the accumulation of sediment in the streams with lower flows. Furthermore, studies should investigate how smart irrigation practices can help increase irrigated acreage within a watershed.

Tables

Table 3. 1 Parameters (default and calibrated value) used to calibrate the SWAT model

Parameter	Default Value/Method	Calibrated Value/Method
Evapotranspiration Method	Penman-Monteith	Hargreaves Method
CN	variable	Reduced by 5%
ESCO	0.95	0.7
Alfa Bf (1/days)	0.048	0.486

Table 3. 2 Water Withdrawal criteria adapted from Richter et al. (2003) and USFWS and USEPA (1999)

Flow Parameters	Guidelines for maintaining sustainable 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 Do not exceed the median in half of the years
Monthly average flow	Maintain the monthly mean flow within the range of 25th and 75th percentile
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

Table 3. 3 Calibration and validation statistics for daily baseflow ($m^3 s^{-1}$), surface runoff ($m^3 s^{-1}$), and total flow ($m^3 s^{-1}$)

	Calibration (June 26, 2009-June 26, 2013)			Validation (June 27, 2013- June30, 2018)		
	NSE	R^2	PBIAS (%)	NSE	R^2	PBIAS (%)
Baseflow ($m^3 s^{-1}$)	0.70	0.70	-5.3	0.63	0.65	-3.3
Surface Runoff ($m^3 s^{-1}$)	0.53	0.54	-27.7	0.42	0.49	-14.0
Total Flow ($m^3 s^{-1}$)	0.57	0.57	-17	0.49	0.53	-8.6

Table 3. 4 Calibration and validation statistics for monthly baseflow (m^3 s^{-1}), surface runoff (m^3 s^{-1}), and total flow (m^3 s^{-1})

	Calibration (June 26, 2009-June 26, 2013)			Validation (June 27, 2013- June 30, 2018)		
	NSE	R^2	PBIAS (%)	NSE	R^2	PBIAS (%)
Baseflow (m^3s^{-1})	0.77	0.77	-1.5	0.77	0.78	-3.9
Surface Runoff (m^3s^{-1})	0.75	0.83	-23.1	0.81	0.83	10.9
Total Flow (m^3s^{-1})	0.77	0.85	-15.3	0.82	0.84	-8.2

Table 3. 5 Percentage subwatershed irrigated and area irrigated during different withdrawal scenarios for all the streams (shown in figure 3.1). (* 1st order streams, ** 2nd order streams, ***3rd order stream)

Streams	Percentage subwatershed irrigated when water withdrawn whole year	Percentage subwatershed irrigated when water withdrawn in non-crop growing months (Dec-Mar)	Percentage subwatershed irrigated when water withdrawn in crop growing months (April-Sept)	Area Irrigated withdrawal whole year (m^2 x 10^4)	Area Irrigated withdrawal (Dec-Mar) (m^2 x 10^4)	Area Irrigated withdrawal (Apr-Sept) (m^2 x 10^4)
1*	15	9	4.8	138	83	44
2*	16	10	5.4	101	61	34
3*	16	9	5.0	252	150	82
6*	17	10	6	97	57	34
8*	17	10	6	56	33	21
9*	17	10	6	106	61	37
10*	17	10	6	75	43	27
11*	16	9	6	122	69	43
14*	16	9	6	95	55	32
18*	15	9	5	54	32	18
4**	13	7	4	319	186	105
5**	10	6	3	438	257	151
7**	8	4	2	382	223	126
12**	6	4	2	358	208	116
13**	12	7	4	159	90	58
15**	4	2	1	79	45	14
16**	9	5	3	222	126	76

17**	6	3	2	428	246	145
19***	4	3	1	431	253	140
Avg 1st order	16	10	5.6	109	64	37
Avg 2nd Order	8.3	4.8	2.8	298	172	98
Avg 3rd Order	4.4	2.6	1.4	431	252	140
Average Total	12.2	7	4.2	206	120	68

Figures:

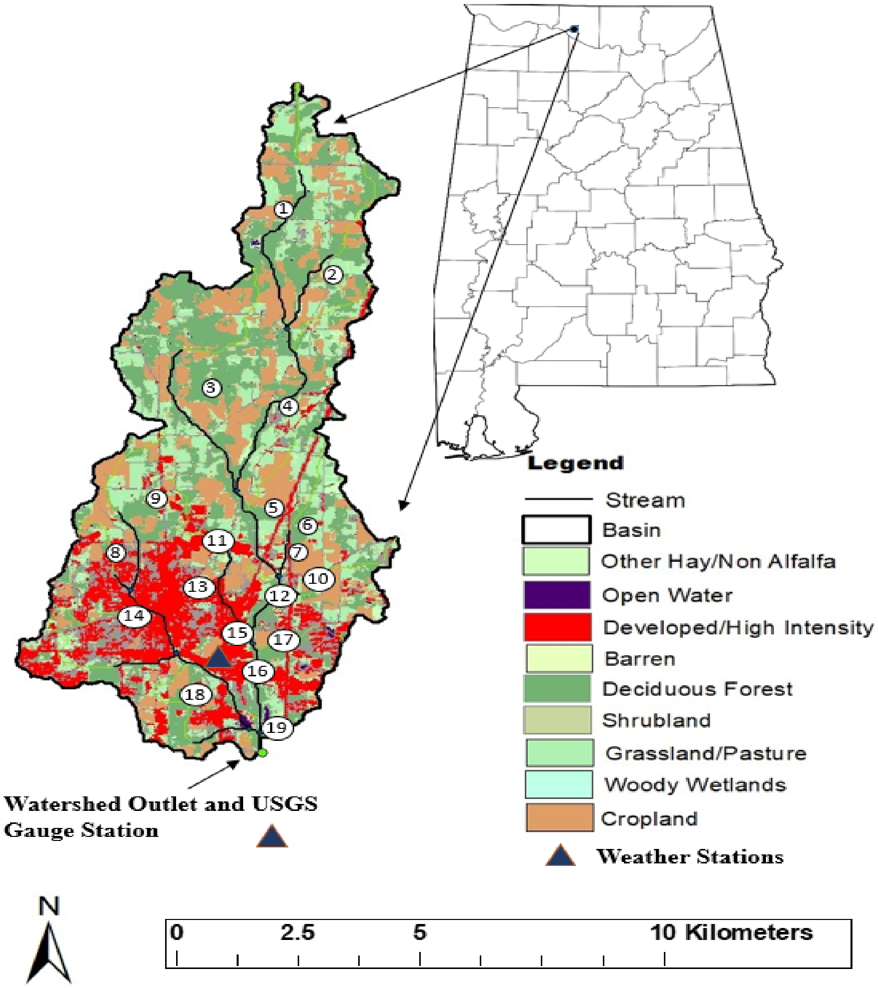

Figure 3. 1 Location and land use distribution of Swan Creek Watershed

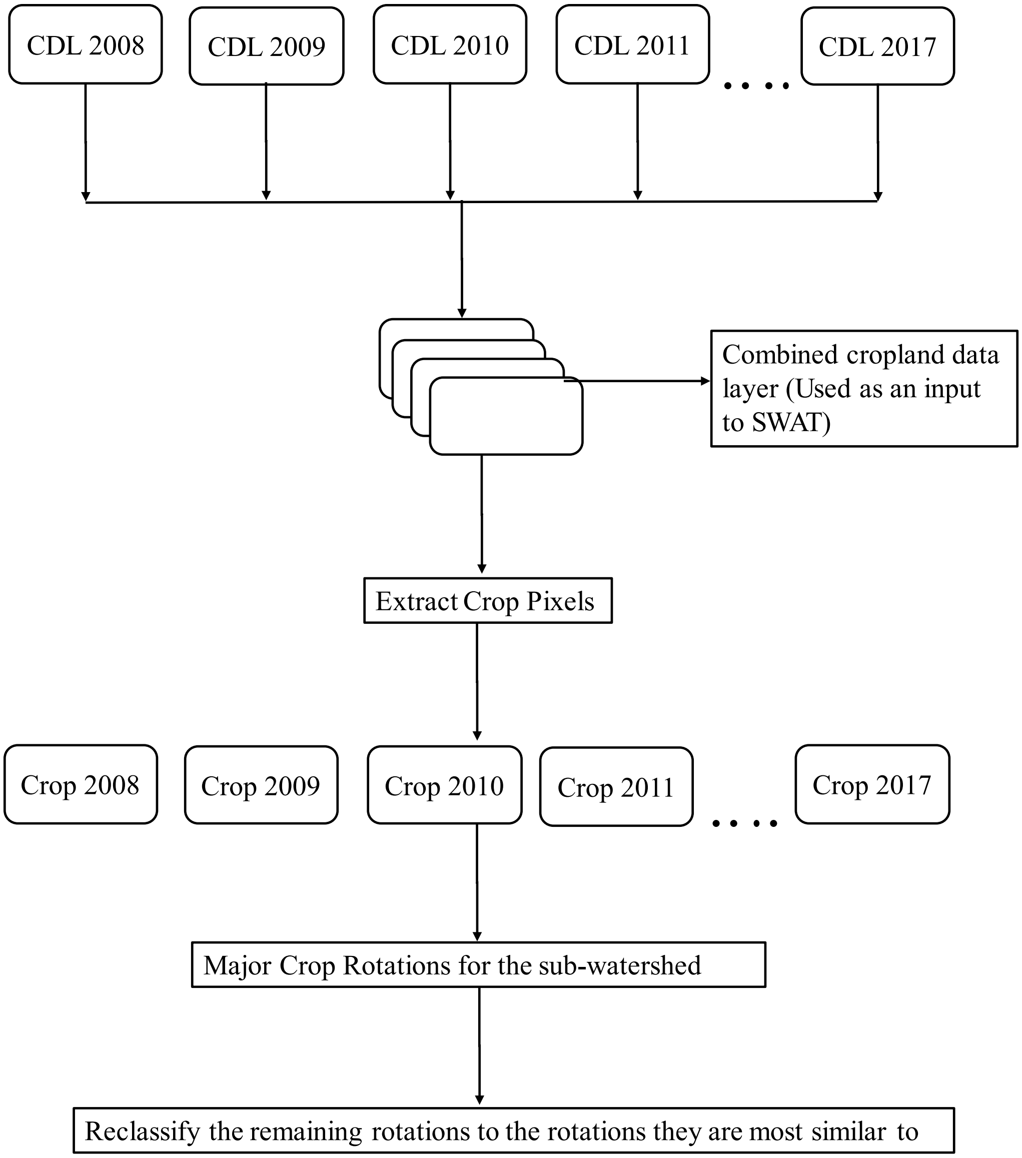

Figure 3. 2 Flowchart representing the steps performed for the allocation of crop rotations in the watershed

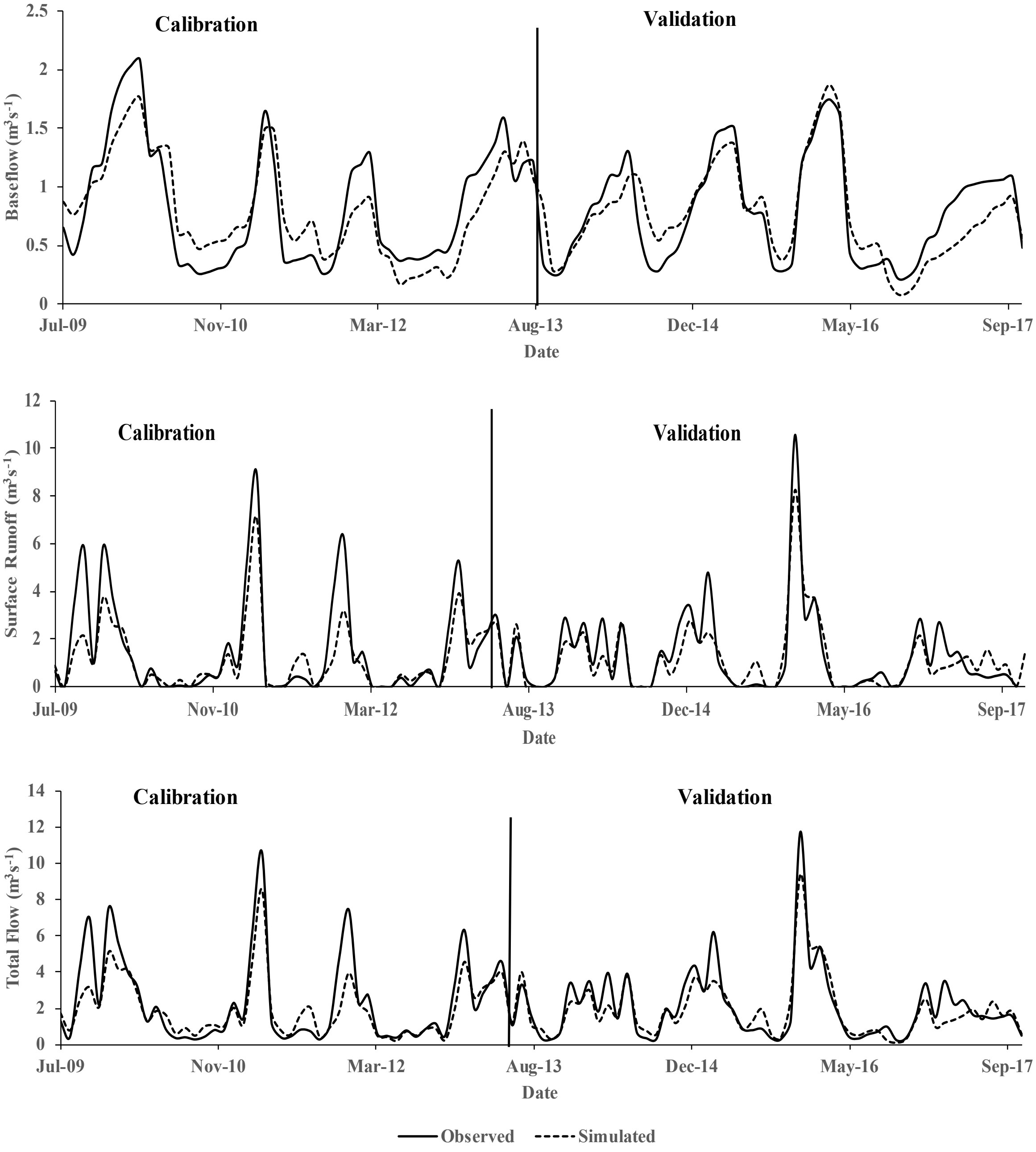

Figure 3. 3 Observed vs. simulated plots of: (a) baseflow (b) surface runoff and (c) total flows for the calibration and validation time periods

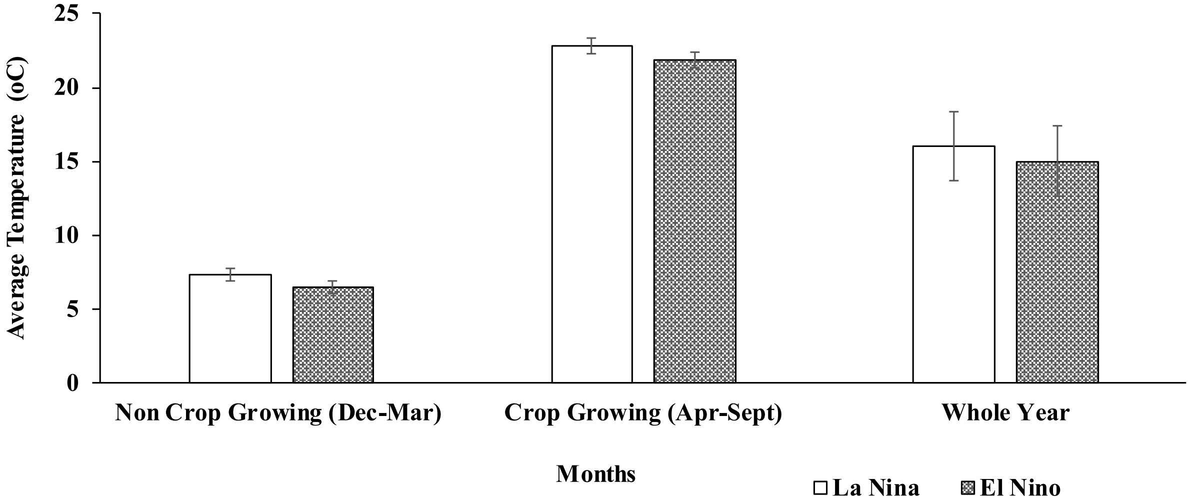

Figure 3. 4 Average daily temperature (^{0}C) during non-crop growing, crop- growing and whole year for La Niña and El Niño phase (1950-2018). Also shown are one standard error bars.

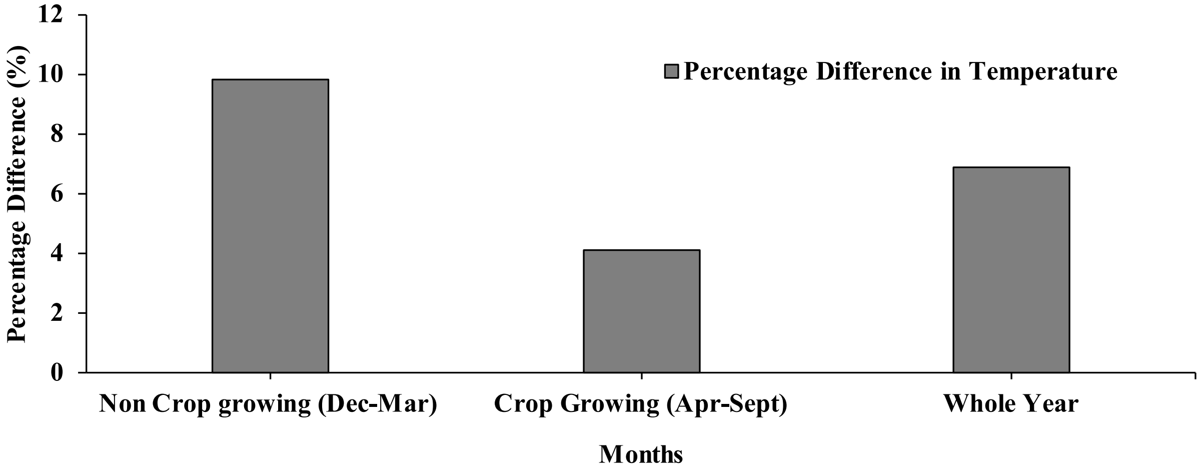

Figure 3. 5 Percentage difference in La Niña and EL Niño phase for crop growing, non-crop growing and whole year (1950-2018)

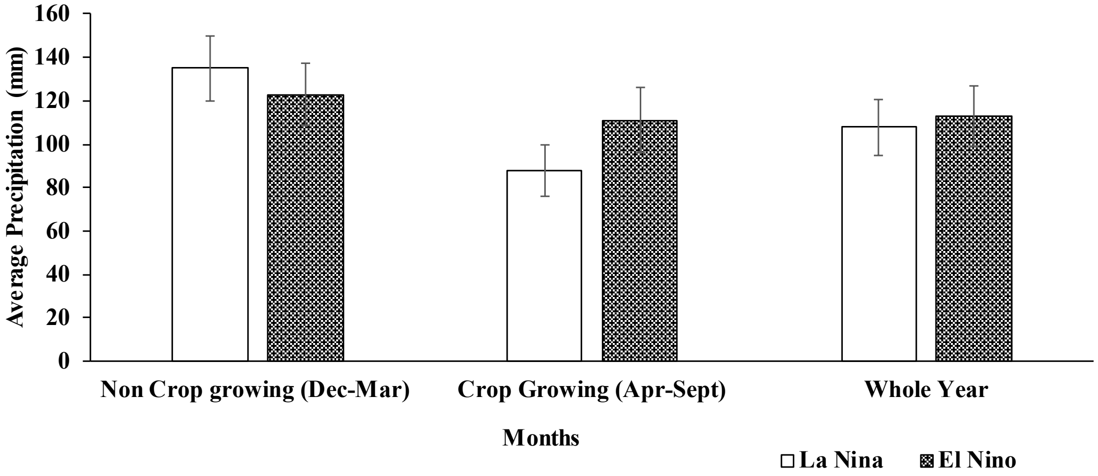

Figure 3. 6 Average monthly precipitation (mm) during non-crop growing, crop- growing and whole year for La Niña and El Niño phase (1950-2018). Also shown are one standard error bars.

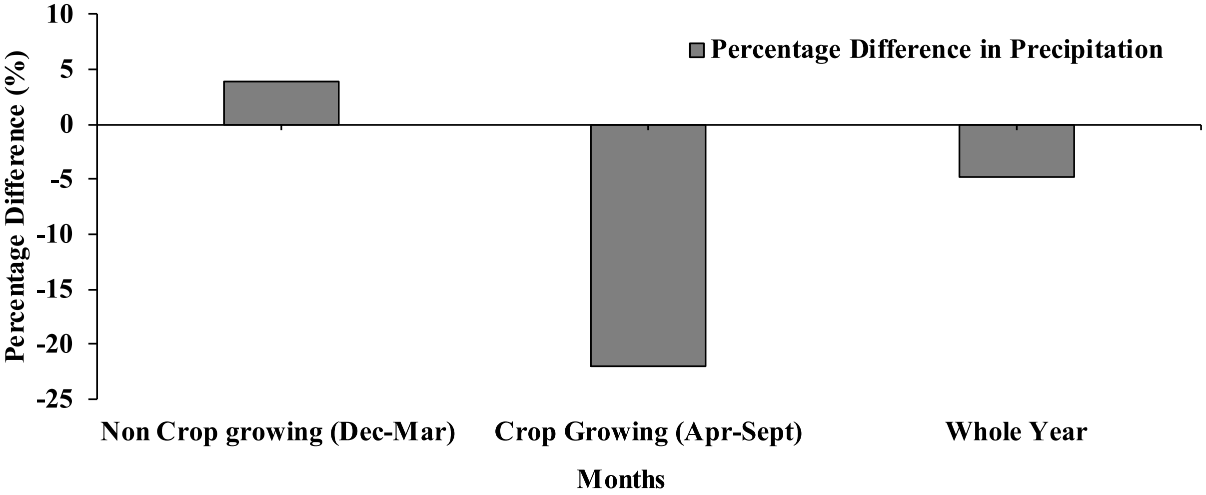

Figure 3. 7 Percentage difference in precipitation for La Niña and EL Niño phase during crop growing, non-crop growing and whole year (1950-2018)

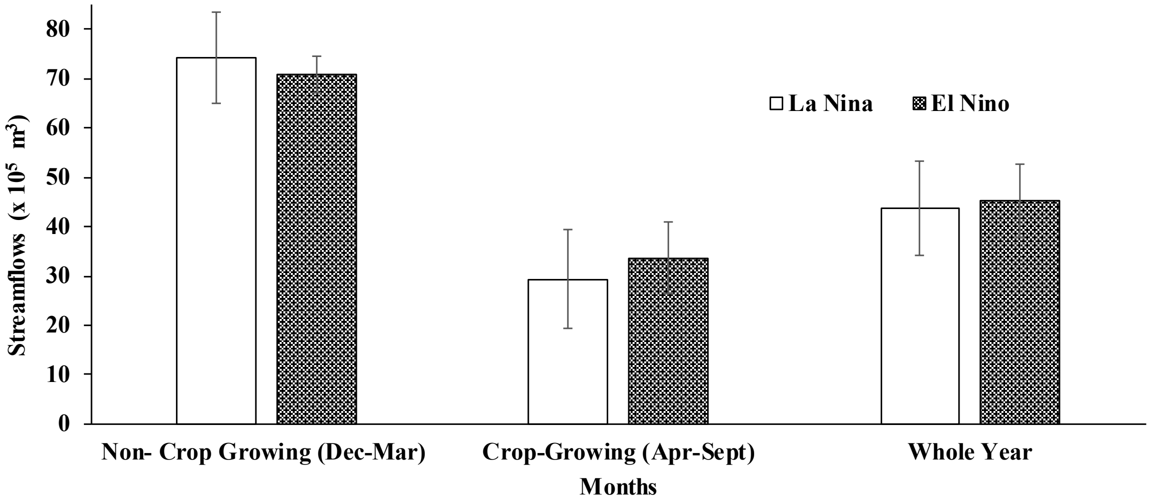

Figure 3. 8 Average monthly streamflows (x 10^5 m^3) during non-crop growing, crop- growing and whole year for La Niña and El Niño phase (1950-2018). Also shown are one standard error bars

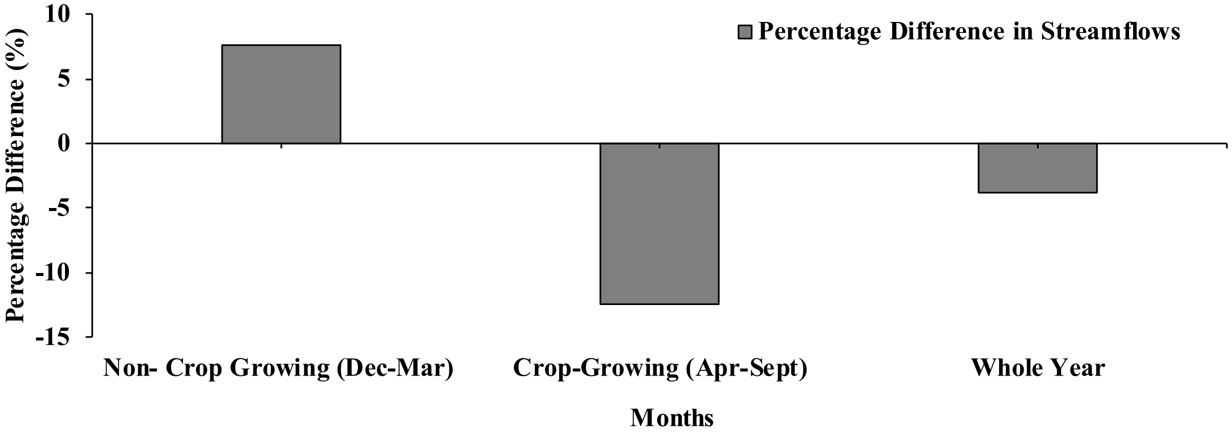

Figure 3. 9 Percentage difference in streamflows for La Niña and EL Niño phase during crop growing, non-crop growing and whole year (1950-2018)

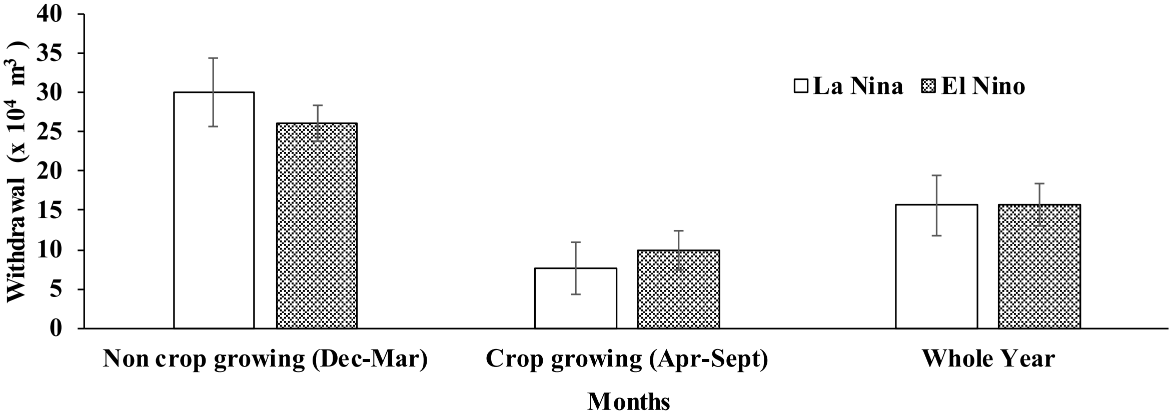

Figure 3. 10 Average monthly withdrawals (x 10^4 m^3) during non-crop growing, crop- growing and whole year for La Niña and El Niño phase (1950-2018). Also shown are one standard error bars

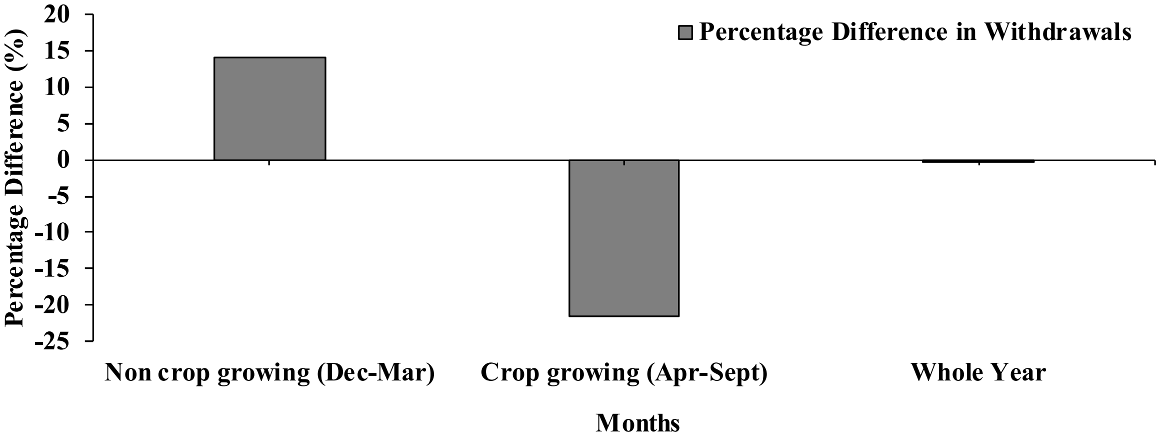

Figure 3. 11 Percentage difference in withdrawals for La Niña and EL Niño phase during crop growing, non-crop growing and whole year (1950-2018)

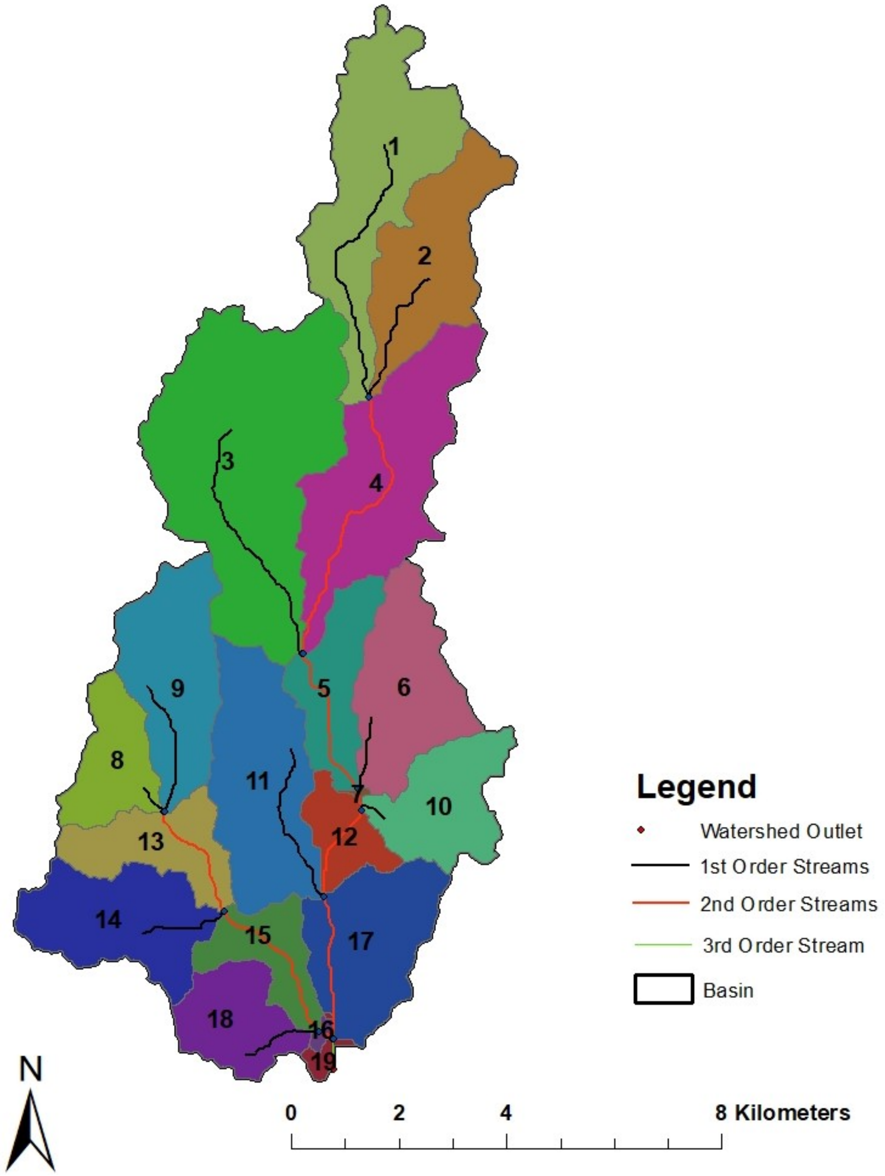

Figure 3. 12 Swan Creek Watershed and labeled are the reaches existing in the watershed

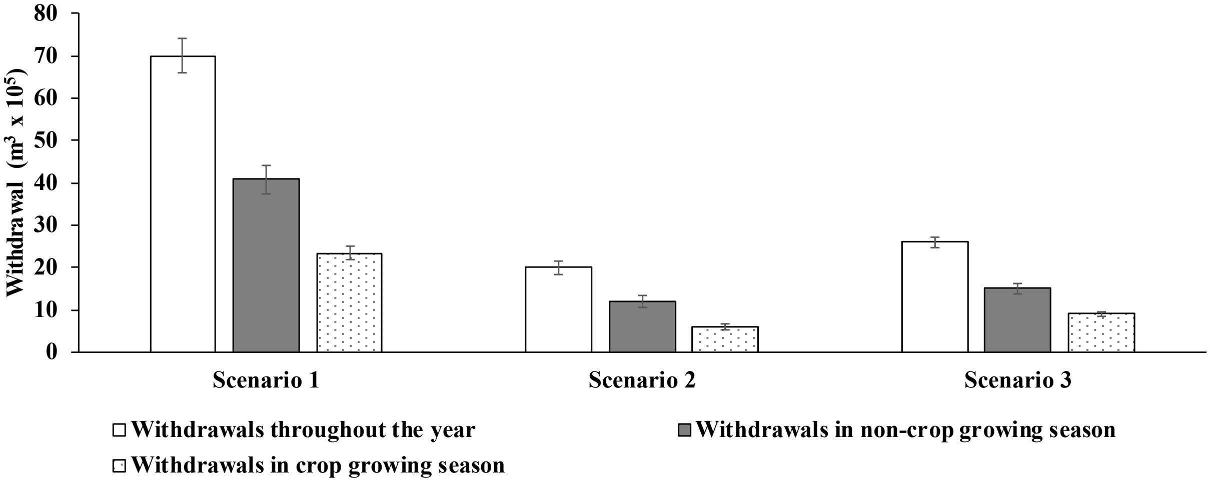

Figure 3. 13 Effect of water withdrawals from upstream reaches on the water withdrawal at the watershed outlet in three different scenarios: Scnerio1: when no water was withdrawn from upstream reaches; Scenario 2 when water was withdrawn from all the upstream reaches; Scenario 3: when water was withdrawn simultaneously only from 2nd order streams Also shown are one standard error bars

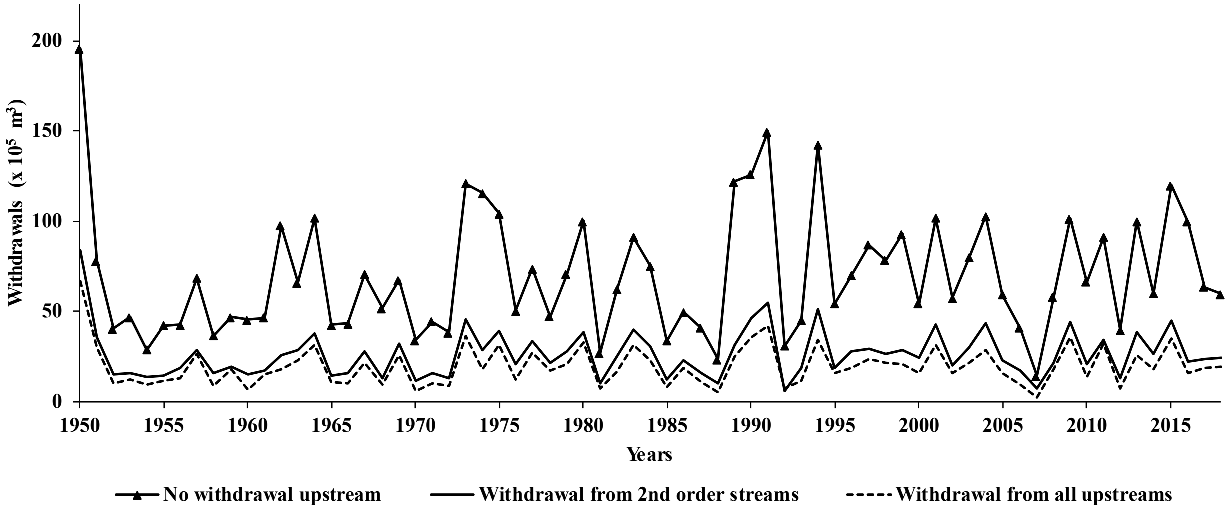

Figure 3. 14 Interannual variation in the water withdrawal at the watershed outlet in three different scenarios (a) when no water is withdrawn from upstream reaches (b) when water is withdrawn from 2nd order streams (c) when water is withdrawn from all the upstream

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Chapter 4

Conclusions

The major conclusions of the study were: (a) volume of water available for withdrawal during crop growing season was greater in El Niño phase than La Niña phase, whereas, during non-crop growing season trends were opposite, (c) irrespective of the ENSO phase, higher precipitation, streamflows and stream water withdrawals were observed in non-crop growing season than in crop growing season, and (d) greater area of watershed can be irrigated if sustainable water withdrawals were made at multiple locations (i.e., different stream orders) within the watershed compared to withdrawals made at the outlet of one particular stream order subwatershed.

Based on the individual chapter following conclusions were made:

The results of the study (Chapter 2) showed that La Niña phase resulted in more precipitation and streamflows from January to March compared to El Niño. During crop growing season (April to September), El Niño phase had more precipitation and streamflows than La Niña phase. Additionally, the November to March time period has more precipitation and streamflows than crop growing season irrespective of the ENSO phase. If La Niña occurs in crop growing season, the non-crop growing (Dec. to Mar.) water withdrawal is more vital as the water availability is limited during the crop growing season. It is possible to make water withdrawal from the streams in crop growing season during El Niño phase, but it would be recommended to make withdrawals in non-crop growing period due to more availability of water. If the water withdrawals are made throughout the year from 1st, 2nd and 3rd order streams subwatershed outlets, 16% of area upstream of the withdrawal point can be irrigated on an average annual basis. Trends between area that can be irrigated as a function of stream order were similar for the withdrawals made in crop growing and non-crop growing seasons. The area that can be irrigated using water withdrawn from streams was not a function of stream order.

The research findings of this study (chapter 3) reveal that on making the simultaneous withdrawals throughout the year, in non-crop growing season and crop growing season at the outlets of 1st order stream subwatersheds, 16%, 10%, 5.6% of the area, respectively, upstream of the withdrawal point could be irrigated. Similar trends were observed between withdrawals made at the outlet of 2nd and 3rd order stream subwatersheds, and area upstream of the withdrawal point that could be irrigated. At the watershed outlet, volume of water available for withdrawal reduced by 41% and 72% during non-crop growing and crop growing season, respectively, when water withdrawals were at the outlets of all subwatersheds upstream of watershed outlet compared to no water withdrawals made upstream of watershed outlet. The size of the pond (assuming average depth of 2.13 m (7 feet)) could be calculated based on the area under irrigation. The surface area of pond (m^2) was found to be 0.214 times the area under irrigation (m^2). For example, pond with surface area 1,295,008 m^2 (320 acres) was required to store water withdrawn at the watershed outlet relative to pond with 159,263 m^2 (40 acres) surface area was required to store water withdrawn at the outlet of 1st order stream subwatershed.

In this study, uniform irrigation application was assumed. Future studies should be conducted to quantify area of watershed that can be irrigated if smart irrigation practices are followed within a watershed. Since effect of ENSO on precipitation varies regionally, it will be important to conduct studies across different regions and determine area of watershed that can be irrigated using water withdrawn sustainably from streams.