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

In the Southeast US, El Niño Southern Oscillation (ENSO), climate variability phenomena affect the quantity of water that is available for irrigation. The goals of this study were to determine the effect of upstream surface water withdrawals for irrigation on the quantity of water available for irrigation in downstream areas as a function of the ENSO phase and quantify the watershed area that can be irrigated using water withdrawn from streams in an ecologically sustainable manner. The study was conducted in the Swan Creek watershed (97 km²) located in Limestone County, Alabama, USA. The soil and water assessment tool (SWAT) model was used to simulate stream flows and develop water withdrawal prescriptions. Results indicated that when simultaneous water withdrawals were made at the outlet of each subwatershed throughout the year, on average water withdrawals were sufficient to irrigate 4–16% of the area upstream of withdrawal point depending on stream order. On making sustainable withdrawals at the outlets of all subwatersheds and at the watershed outlet throughout the year, approximately 40% of the watershed area could be irrigated.

Key words | climate variability, ENSO, irrigation, stream water withdrawal, watershed modeling

INTRODUCTION

The world population is estimated to grow to 8.3 billion in 2050 and 9.3 billion in 2050 with nearly 67 million people being added to the world per year (FAO 2012). To meet the needs of the projected population, crop production should increase by nearly 50% in the next 50 years to sustain our present per capita supply, assuming the productivity of present farmland remains the same (Jury & Vaux 2007). Irrigation can help producers to sustain and increase crop production (Veldkamp et al. 2007), especially in areas that receive a limited amount of rainfall during the crop growing season.

Water withdrawn from streams is one of the major sources of irrigation in southeastern US. Water is typically withdrawn from the streams and stored in on-farm ponds for irrigation. However, it is important that water withdrawals from streams for irrigation should be done in an ecologically sustainable manner. Excessive water withdrawals from streams disturbs in-stream biota by reducing functioning habitat (Scatena & Johnson 2001), blocking the 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 on a long-term basis and at the subwatershed level 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 the rainfall regime caused by climate variability (Diaz et al. 2007). Climate variability in the southeastern 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, ENSO impacts the amount of precipitation in different seasons within a given year, and therefore, the volume of streamflow varies depending on the ENSO phase (Kahya & Dracup 1993a, 1993b; Piechota & Dracup 1999; Gérard-Marchant et al. 2010). Thus, the volume of water available for withdrawals from streams is also a function of the ENSO phase. Ropelewski & Halpert (1986) found that the influence of ENSO on precipitation in the 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 Alabama (AL). Overall, previous studies have shown that the impact of ENSO on precipitation and streamflows cannot be generalized over larger areas.

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). Water withdrawn from streams by farmers for irrigation in upstream areas can reduce the volume of water available for withdrawal in downstream areas. This will not only be harmful to downstream biota, but could also turn out to be an economic disaster for farmers who would have access to a limited amount of water available for withdrawal to irrigate crops. Therefore, it is important to consider how streamflow withdrawal in upstream areas of watershed impact streamflow in downstream areas. 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 (e.g., multiple farmers withdrawing water from streams for irrigation). 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 the ENSO phase in agricultural watersheds. This study aims to quantify: (a) the effects of ENSO on precipitation and streamflow during crop growing and noncrop growing seasons, (b) the impact of upstream water withdrawals on the downstream water withdrawals as a function of the ENSO phase, and (c) the watershed area that can be irrigated using water withdrawn from streams in an ecologically sustainable manner. 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.

**METHODOLOGY**

**Study area**

The study watershed was Swan Creek watershed (97 km²), which is a part of the larger Tennessee river basin. The watershed is located in Limestone County, north AL (Figure 1). The land use in the watershed has remained fairly consistent (changed <4% over the last 10 years). Dominant land use in this watershed include cropland (21%), deciduous forest (18%), pasture (17%), developed open space (12%), developed/low intensity (10%), shrubland (7%), evergreen forest (4%), and developed/med intensity (4%) (USDA National Agricultural Statistics Service Cropland Data Layer 2019). Elevation values within this watershed range from a minimum of 198 m to a maximum of 248 m with respect to the 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 2010). 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 to 2017 based on the cropland data layer files were soybeans, corn, cotton, and winter wheat (USDA National Agricultural Statistics Service Cropland Data Layer 2019).
Soil and water assessment tool 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, nutrients, and land management are the major
components of the model. In this model, a watershed is divided into various subwatersheds, which are then subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, slope, and soil characteristics within a subwatershed. In our study, the entire watershed was divided into 19 subwatersheds and consisted of 7,200 HRUs. The modified Soil Conservation Service (SCS) curve number method ([USDA-SCS 1972]) was used for the estimation of surface runoff based on HRU land-use, soil type, and initial antecedent soil moisture conditions. 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 & Samani 1985]). The Hargreaves method was used as the evapotranspiration method for this study. 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. 2005]) or the variable-rate storage method ([W illiams 1969]). The variable-rate storage method was used in the study for channel routing. More information about the SWAT model can be found in Neitsch et al. (2011). In this study, the ArcSWAT 2012.10.3.19 version was used.

Data input

Topographical data were obtained using a 10-m digital elevation model (DEM), which was obtained from the USDA-NRCS National Geospatial Data Gateway (https://datagateway.nrcs.usda.gov/). Soil data were obtained from the Soil Survey and Geographic database ([NRCS 2010]). 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) for the state of AL. This database has been used in several recent studies conducted in AL (e.g., Mirhosseini & Srivastava 2016; Arora et al. 2019). 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 1). It should be noted that, for each subwatershed, the model uses weather data from one station at a time depending on which weather station is nearest to the centroid of each subwatershed. The built-in weather generator in the model was used to obtain daily solar radiation, relative humidity, and wind speed data ([Neitsch et al. 2011]) because these data were not available at the weather stations. Crop rotation information for the study watershed was derived using the cropland data layers (CDL) files from 2008 to 2019. In total, 34 different crop rotations practiced on 90% of the watershed’s cropland area over the period of 9 years were incorporated in the model. The use of CDL of multiple years to derive crop rotation information has shown to increase the accuracy of the model ([Sahajpal et al. 2014]). Irrigation rates were obtained from National Engineering Handbook Irrigation Guide ([USDA 2009]).

**SWAT model calibration and validation**

To stabilize the model and get the hydrological cycle fully operational, it is recommended to warm-up the model. No warm-up or insufficient warm-up period may result in reducing model performance, especially in the first few years of simulation ([Huard & Mailhot 2008]). In this study, we used a warm-up period of 8 years (i.e., 1 January 2000–31 December 2008). The model was calibrated and validated for streamflow at a daily time-step. The United States Geological Survey (USGS) stream gage # 03577225, located at the watershed outlet, was used to obtain daily measured streamflow data (June 2009–June 2018) required for streamflow calibration and validation at the watershed outlet. Specific guidelines were followed as presented in Arnold et al. (2012) and Moriasi et al. (2007), and certain sensitive parameters (Table 1) identified from the previous scientific studies were changed to achieve maximum agreement between observed and simulated flows. Based on the availability of the observed streamflow data, the model was

| Parameter                          | Default value | Calibrated value |
|-----------------------------------|---------------|------------------|
| Evapotranspiration method         | Penman–Monteith | Hargreaves method |
| Curve number (CN)                 | variable      | Reduced by 5%    |
| Soil evaporation compensation coefficient (ESCO) | 0.95       | 0.7              |
| Baseflow alpha factor (ALPHA_BF)  | 0.048         | 0.486            |
calibrated and validated at a daily time-step for total streamflow from 26 June 2009 to 26 June 2013, and from 27 June 2013 to 30 June 2018, respectively.

Model evaluation

Time series plots of observed vs. simulated total streamflow were compared to qualitatively evaluate the model performance. Additionally, for quantitative evaluation, we used the coefficient of determination ($R^2$), the Nash-Sutcliffe model efficiency (NSE) coefficient (Nash & Sutcliffe 1970), and percent bias (PBIAS) (Krause et al. 2005). For the calibration and validation period, the model performance was considered satisfactory at a daily time-step if NSE $>0.4$ and $R^2 > 0.5$ and PBIAS $< \pm 25\%$ (Koycegiz et al. 2019).

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 the El Niño and La Niña phases (NOAA 2019). This index is based on a 3-month running mean of sea surface temperature anomalies in the Niño 3.4 region. The Niño 3.4 index above +0.5 °C implies El Niño conditions and the La Niña phase is defined when the Niño 3.4 index is below −0.5 °C. When the index is between 0.5 and −0.5, the neutral conditions prevail. The data from NOAA were used to classify all the months from 1950 to 2018 into El Niño, La Niña, or Neutral phases. For El Niño and La Niña phases, we determined the volume of water available for withdrawal in an ecologically sustainable manner from streams for irrigation.

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 criteria were used in this study, which were developed by Richter et al. (2003) and USEPA & USFWS (1999) for Apalachicola-Chattahoochee-Flint (ACF) River basin in AL, Florida, and Georgia (Table 2). These criteria are also agreed upon by the US Environmental Protection Agency and US Fish and Wildlife Service. The detailed methodology as mentioned in USEPA & USFWS (1999) was followed to withdraw the water from the streams.

First, baseline daily streamflow (no water is withdrawn from streams) values at the outlet of each subwatershed were obtained from the SWAT model calibrated and validated for streamflow at the daily time-step. 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 (USEPA & USFWS 1999; Richter et al. 2003) are very sensitive to the streamflows below 25th percentiles and the

| 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 values in half of the years |
| Annual 1-day maxima   | Exceed the minimum in all years                                                  |
|                       | Exceed the 25th percentile in 3 out of 4 years                                   |
|                       | Exceed the median in half of the years                                           |
| Annual high flow duration | Exceed the minimum in all years                                                |
|                       | Exceed the 25th percentile in 3 out of 4 years                                   |
|                       | Exceed the median in half of the years                                           |
streamflows that exceed 95th percentile. No water was withdrawn from streams when the flows were below the 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 the 25th percentile. For the flows above the 95th percentile, 20% of the flow was withdrawn from the streams. This restriction on water withdrawals for the flows above the 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 4,570 m³ 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 (assuming 457 mm as the crop water requirement) if the water was withdrawn in an ecologically sustainable manner throughout the year, withdrawn only in the noncrop growing period (December–March), and withdrawn only in the crop growing period (April–September) as a function of the ENSO phase.

Water was withdrawn from all the streams in a chronological manner in the watershed (i.e., water was withdrawn from first-order streams, then second-order followed by third-order streams). 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 the stream to vary at a daily time-step. Therefore, water withdrawal analysis was done outside the model using variables from the reach (.rch) and subwatershed (.sub) output files of the model. The values of FLOW_IN (average daily flow into reach during the time-step for a given subwatershed), FLOW_OUT (average daily streamflow out of reach during the time-step for a given subwatershed), WYLD (water yield for each day for each subwatershed), and TLOSS (average daily rate of water loss from reach by transmission through the streambed) were obtained from the model. At the outlet of each subwatershed, the 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 a downstream watershed using the above-mentioned variables obtained from the model output files (e.g., .rch and .sub). This procedure was repeated for all subwatersheds to determine how water withdrawals in upstream areas impact downstream water withdrawals and eventually quantify the area of watershed that can be irrigated using water withdrawn sustainably from streams.

**Relationship between the ENSO phase and precipitation, streamflow, and water withdrawn**

Daily streamflows, precipitation, and water withdrawals from 1950 to 2018 were added to get their monthly values. The streamflows were further averaged for each ENSO phase, i.e., El Niño and La Niña from 1950 to 2018 for a given month. The monthly streamflows, precipitation, and water withdrawals for each phase were then averaged for the noncrop growing (December–March) and crop growing (April–September) seasons. The percent difference was used to find the difference between the precipitation, streamflows, and withdrawals for each season in a respective ENSO phase based on the methodology described in Mondal et al. (2011). For example, the percentage difference for streamflows 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 (1950–2018). A similar procedure was used to calculate the percent difference for precipitation and water withdrawals. A negative percentage difference indicates that a given variable had a higher value in the El Niño phase than the La Niña phase, while a positive percentage difference indicates the opposite. To evaluate the significant difference between the precipitation, streamflows, and water withdrawals for El Niño and La Niña, an analysis of variance (ANOVA) at the significance level of $\alpha = 0.10$ was conducted using SAS Statistical Software (SAS Institute, Inc., Cary, NC, United States).

**RESULTS AND DISCUSSION**

**Calibration and validation of the SWAT model**

Overall graphical representations of observed vs. simulated total streamflows show similar trends for the calibration
and validation periods (Figure 2). At the daily time-step, the total streamflow statistics values for calibration and validation periods are presented in Figure 2. As depicted by NSE, PBIAS, and $R^2$ values (Figure 2) for both calibration and validation time periods, model performance was rated ‘satisfactory’ for total streamflow at the daily time-step (Koycegiz et al. 2019). The average daily simulated streamflow by the model at the watershed outlet was 1.96 m$^3$ s$^{-1}$ relative to the observed flow of 2.27 m$^3$ s$^{-1}$. Although the model captured low flows accurately, there were occasions when model overpredicted or underpredicted peak flows. Several studies have highlighted the inability of the model to capture peak flows (King et al. 1999; Arnold et al. 2000; Anand et al. 2007; Green et al. 2007; White et al. 2008). The simple empirical curve number (CN) method used in the model might have resulted in the deviations between simulated and observed peak flows. Limitations associated with the CN method have been highlighted in several studies (e.g., Gassman et al. 2007; Hawkins 2014; Bartlett et al. 2016; Ogden et al. 2017). Overall, based on the graphical comparison of observed and simulated flow values and quantitative evaluation, the SWAT model satisfactorily captured temporal trends in streamflow and represented hydrological processes in the watershed.

**Relationship between ENSO and precipitation**

Precipitation trends were examined for crop growing, noncrop growing season, and throughout the year for La Niña and El Niño phases of ENSO. During the noncrop growing season, more precipitation was observed in the La Niña phase than the El Niño phase (Figure 3(a)). The average precipitation per month during the nongrowing season in the La Niña phase was 135 mm as compared with 123 mm in

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**Figure 2** | Observed vs. simulated plots of total flows for the calibration and validation time periods. Also shown are calibration and validation statistics at daily time-step for total flows and semiannual gridlines.
the El Niño phase. A considerable difference in precipitation for the La Niña and El Niño phases 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 the La Niña phase. The precipitation was found to be significantly (\(\alpha = 0.10\)) greater in the El Niño phase than the La Niña phase during the crop growing season. Specifically, a substantial difference in precipitation was observed for the months of June (–25%) and July (–14%). The average precipitation per month during crop growing season during the La Niña phase was 88 mm as compared with 111 mm for the El Niño phase. It was also observed that irrespective of the phase, the noncrop growing season resulted in 20% more precipitation than the crop growing season. Fraisse et al. (2006) also reported wet conditions in the north AL during the noncrop growing season. The percentage difference of –22% was observed for precipitation in the crop growing season between El Niño and La Niña phases (Figure 3(b)). The negative percentage difference in the crop growing season (Figure 3(b)) indicates higher precipitation in the El Niño phase than the La Niña phase. Similar trends with greater precipitation during the El Niño phase than La Niña phase in the crop growing season were documented by Mourtzinis et al. (2016) and Sarkar et al. (2012) in the southeastern US The more precipitation in crop growing seasons during the El Niño phase is bloom for the crops and could likely reduce the irrigation water demands, whereas lesser precipitation in the 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 the optimum amount of water for irrigation in an ecologically sustainable manner.

### Relationship between ENSO and streamflow

Similar to precipitation trends, in the noncrop growing season, the streamflows at the watershed outlet in the La Niña phase were greater than the El Niño phase...
This trend was opposite that observed by Mondal et al. (2011), where greater streamflows were observed in the El Niño phase during the noncrop growing season. Sharda et al. (2012) reported that the streamflow patterns in response to the ENSO phase vary within the state of AL. The trends in the north AL region does not 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 in AL (NCEI 2019). The trends in streamflow in the crop growing season were opposite those seen in the noncrop growing season, i.e., the El Niño phase produced a greater volume of stream flows than the La Niña phase. The percentage difference of −12% in streamflows was observed between El Niño and La Niña phases during the crop growing season (Figure 4(b)). However, it should also be noted that the streamflows in the El Niño phase were higher during the noncrop growing season than the crop growing season. Similarly, the average streamflows in the La Niña phase during the noncrop growing season were more than double the average streamflows during the crop growing season. Moreover, irrespective of the phase, on an annual average basis, the streamflows in the noncrop growing season were almost double the streamflows in the crop growing season. This finding is very important for water resource management, especially in the La Niña phase. The lesser streamflows in the 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 the La Niña phase would intensify the impact on water resources. This effect on the water resources could be countered with the adoption of irrigation water withdrawals during the noncrop growing season. Especially, the streamflows in the month of January were found to be 30% greater in the La Niña phase than in the El Niño phase. Thus, due to the higher availability of water, the month of January could be the main focus for making the stream water withdrawals.

(Figure 4(a)).

![Figure 4](http://iwaponline.com/hr/article-pdf/51/4/602/730616/nh0510602.pdf)

**Figure 4** Average monthly stream flows ($\times 10^3$ m$^3$) (a) and percentage difference (b) during noncrop growing, crop growing and whole year for the La Niña and El Niño phases (1950–2018). Standard error bars are at 5% of error.
Water withdrawals and the 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 noncrop growing period, 14% more volume of streamflow could be withdrawn in the La Niña phase than the El Niño phase (Figure 5(a)). However, during the crop growing season, the amount of water that can be sustainably withdrawn from streams was less in the La Niña phase than the El Niño phase (Figure 5(a)). If the La Niña phase continues during the growing season, the average annual volume of water available for withdrawal would be limited (76,546 m³) as compared with water available for withdrawal during the El Niño phase (99,578 m³) (Figure 5(a)). The average quantity of water that can be withdrawn sustainably from streams in crop growing season during the La Niña phase was almost one-fourth (76,546 m³) of the amount of water available to withdraw sustainably in the noncrop growing season (301,064 m³) (Figure 5(a)). For both La Niña and El Niño phases, regardless of a stream order or location within a watershed, on average 55% greater amount of water could be withdrawn sustainably from streams during the noncrop growing season compared with the crop growing season. Therefore, it would be advised that the water withdrawals from streams should be made during the noncrop 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 with the La Niña phase. About –21% difference was observed in the volume of water that can be sustainably withdrawn between the El Niño and La Niña phases during the crop growing season (Figure 5(b)). However, it should also be noted that even though more water is available for withdrawal during the El Niño phase in the crop growing season, the volume of water available for withdrawal during the noncrop growing season in the El Niño phase was almost three times the volume of water available for withdrawal during the crop growing season. Thus, the results of this study show that the winter

![Figure 5](http://iwaponline.com/hr/article-pdf/51/4/602/730616/nh0510602.pdf)
withdrawals, especially during the La Niña phase, are vital to have an adequate amount of water for irrigation during the 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 crop growing season.

**Sustainable water withdrawal and area irrigated**

Water withdrawal was performed at the outlet of each subwatershed and the area of the 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 a whole year, crop growing, and non-crop growing seasons.

**First-order streams**

The outlets of first-order stream subwatersheds such as 1, 2, 3, 6, 8, 9, 10, 11, 14, and 18 (Figure 6) were the foremost points of water withdrawals in the watershed. When the withdrawals from the stream were made throughout the year, on average 16% of the area upstream of withdrawal point could be irrigated (Table 3). It was observed that on average, the water withdrawn in an ecologically sustainable manner throughout the year at the outlet of first-order stream subwatershed was sufficient to irrigate 109 × 10^4 m^2 (269 acres) (Table 3). If the water withdrawals were only made in the noncrop growing season, on average 10% of the area (i.e., 64 × 10^4 m^2) upstream of withdrawal point could be irrigated by the water withdrawn (Table 3). The results show that if water is withdrawn only in the crop growing season, on average only about 6% of the area upstream of the withdrawal point could be irrigated. Mondal et al. (2011) conducted a study in a forested watershed in south AL and reported that on average 20% of the area upstream of first-order stream subwatershed outlet can be irrigated when water was withdrawn from streams throughout the year in an ecologically sustainable manner. The percentage of the area upstream of first-order stream that can be irrigated using stream water was less in our study compared with Mondal et al. (2011). This was likely due to greater average annual precipitation in Mondal et al. (2011) study watershed (1,648 mm) compared with Swan creek watershed in north AL (1,550 mm).

**Second-order streams**

The outlets of second-order stream subwatersheds such as 4, 5, 7, 12, 13, 15, 16, and 17 (Figure 6) were succeeding withdrawal points after the withdrawals have been made at the outlet of first-order stream subwatersheds. Due to the water withdrawals made at the outlets of first-order stream subwatersheds, the amount of water available for withdrawal at the outlets of second-order stream subwatersheds was less than natural flows (i.e., when water was not withdrawn from first-order streams). When the sustainable water withdrawals were made throughout the year from the outlets of all the second-order stream subwatersheds, on average 8% of the area (i.e., 298 × 10^4 m^2 (736 acres)) upstream of second-order stream subwatershed could be irrigated by the stream water withdrawals (Table 3). It should be noted that on average 109 × 10^4 m^2 (269 acres) of the upland area has already been irrigated by the water withdrawn at the outlet of first-order stream subwatersheds. Therefore, when water is withdrawn throughout the year, the total area irrigated by the water withdrawals made at the outlet of first- and second-order stream subwatersheds was found to be 3,481 × 10^4 m^2 (8,601 acres), which was approximately 35% of the total watershed area. On average on making the simultaneous withdrawals at each first- and second-order streams, 1,254 × 10^4 m^2 (3,098 acres), of the area upstream of the withdrawal point, could be irrigated. This was approximately 13% of the area upstream of the withdrawal points. During the noncrop growing season, the total area irrigated by first- and second-order stream was 2,024 × 10^4 m^2 (5,000 acres), which was 20% of the watershed area. On average, above each withdrawal point, 733 × 10^4 m^2 (1,811 acres) of the area could be irrigated on making the withdrawals in the noncrop growing season. On making the withdrawals during the crop growing season, 12% of the total watershed area, i.e., 1,163 × 10^4 m^2 (2,873 acres) could be irrigated. On average 418 × 10^4 m^2 (1,032 acres) of the area upstream of the withdrawal point could be irrigated on making the withdrawals in the crop growing season. Due to an increase in the drainage area, the volume of water available for withdrawal at the outlet of second-order stream subwatersheds was greater than first-order stream subwatersheds in all.
three scenarios (water withdrawal performed a whole year, crop growing, and noncrop growing seasons). Therefore, the results of this study show that if water was withdrawn from first-order streams sustainably, downstream farmers could still withdraw water from streams sustainably. However, the quantity of water they can withdraw would depend on the amount of water withdrawn in upstream areas. Similar to the results reported for first-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) due to less precipitation in our study watershed.

**Third-order stream**

At the watershed outlet (i.e., third-order stream), when water was withdrawn throughout the year, the stream water...
withdrawal was enough to irrigate an average 4% of the area upstream of withdrawal point (Table 3), which was enough to irrigate $431 \times 10^4$ m$^2$ (1,065 acres). When the stream water withdrawals were made only in noncrop growing and crop growing seasons, the percentage of area that could be irrigated upstream of the withdrawal point was 3 and 1%, respectively. This water withdrawn during noncrop growing and crop growing seasons would meet the irrigation needs of $252 \times 10^4$ m$^2$ (622 acres) and $140 \times 10^4$ 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 at the watershed outlet throughout the year, a total area of $3,912 \times 10^4$ m$^2$ (9,666 acres), i.e., 40% of the watershed area could be irrigated. During noncrop growing and crop growing seasons, the ecologically sustainable water withdrawal from streams at the watershed outlet and upstream subwatersheds was sufficient to irrigate an area

| Streams | Percentage subwatershed irrigated when water withdrawn whole year | Percentage subwatershed irrigated when water withdrawn in noncrop growing months (Dec.–Mar.) | Percentage subwatershed irrigated when water withdrawn in crop growing months (April–Sept.) | Area irrigated when water withdrawn whole year (m$^2 \times 10^4$) | Area irrigated when water withdrawn in noncrop growing months (m$^2 \times 10^4$) | Area irrigated when water withdrawn in crop growing months (April–Sept.) (m$^2 \times 10^4$) |
|---------|---------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|
| 1a      | 15                                                            | 9                                                                                               | 5                                                               | 138                                                      | 83                                                              | 44                                                              |
| 2a      | 16                                                            | 10                                                                | 5                                                               | 101                                                      | 61                                                              | 34                                                              |
| 3a      | 16                                                            | 9                                                                                               | 5                                                               | 252                                                      | 150                                                             | 82                                                              |
| 6a      | 17                                                            | 10                                                                | 6                                                               | 97                                                       | 57                                                              | 34                                                              |
| 8a      | 17                                                            | 10                                                                | 6                                                               | 56                                                       | 33                                                              | 21                                                              |
| 9a      | 17                                                            | 10                                                                | 6                                                               | 106                                                      | 61                                                              | 37                                                              |
| 10a     | 17                                                            | 10                                                                | 6                                                               | 75                                                        | 43                                                              | 27                                                              |
| 11a     | 16                                                            | 9                                                                                               | 6                                                               | 122                                                      | 69                                                              | 43                                                              |
| 14a     | 16                                                            | 9                                                                                               | 6                                                               | 95                                                       | 55                                                              | 32                                                              |
| 18a     | 15                                                            | 9                                                                                               | 5                                                               | 54                                                       | 32                                                              | 18                                                              |
| 4b      | 13                                                            | 7                                                                                               | 4                                                               | 319                                                      | 186                                                             | 105                                                             |
| 5b      | 10                                                            | 6                                                                                               | 3                                                               | 438                                                      | 257                                                             | 151                                                             |
| 7b      | 8                                                             | 4                                                                                               | 2                                                               | 382                                                      | 223                                                             | 126                                                             |
| 12b     | 6                                                             | 4                                                                                               | 2                                                               | 358                                                      | 208                                                             | 116                                                             |
| 13b     | 12                                                            | 7                                                                                               | 4                                                               | 159                                                      | 90                                                              | 58                                                              |
| 15b     | 4                                                             | 2                                                                                               | 1                                                               | 79                                                       | 45                                                              | 14                                                              |
| 16b     | 9                                                             | 5                                                                                               | 3                                                               | 222                                                      | 126                                                             | 76                                                              |
| 17b     | 6                                                             | 3                                                                                               | 2                                                               | 428                                                      | 246                                                             | 145                                                             |
| 19c     | 4                                                             | 3                                                                                               | 1                                                               | 431                                                      | 253                                                             | 140                                                             |
| Average first order | 16                                                                  | 10                                                               | 6                                                               | 109                                                      | 64                                                              | 37                                                              |
| Average second order | 8                                                                   | 5                                                                | 3                                                               | 298                                                      | 172                                                             | 98                                                              |
| Average third order | 4                                                                   | 3                                                                | 1                                                               | 431                                                      | 252                                                             | 140                                                             |
| Average total | 12                                                                  | 7                                                                | 4                                                               | 206                                                      | 120                                                             | 68                                                              |

*aFirst-order streams.  
bSecond-order streams.  
cThird-order stream.
of \(2,276 \times 10^4\) m\(^2\) (5,624 acres), i.e., 23% of the watershed area and \(1,303 \times 10^4\) m\(^2\) (5,219 acres), i.e., 13% of the watershed area, respectively.

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

Comparison of the 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

No water withdrawal upstream (Scenario 1)

Sangha et al. (2020) discusses the scenario where water was withdrawn at the outlet of each subwatershed as a function of stream order with no water withdrawals upstream of the withdrawal point for the whole year, noncrop growing, and crop growing season in the study watershed. The percentage of the area irrigated above the withdrawal point was found to be independent of the stream order. It was observed that on making water withdrawals throughout the year, crop growing season and noncrop growing season, on average at the watershed outlet, 16, 10, and 5% of the area upstream of the withdrawal point could be irrigated, respectively. At the watershed outlet, on annual average 6,999,530 m\(^3\) of water was available for withdrawal on making the withdrawals throughout the year (Figure 7). However, 41% reduction in the volume of water available for withdrawal was observed when water was withdrawn only in the noncrop growing season compared with water withdrawn throughout the year. The volume of water available to withdraw reduced by 67% when water was withdrawn only in the crop growing season compared with when water was withdrawn throughout the year (Figure 7).

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 annual average, 6,999,530 m\(^3\) water could be sustainably withdrawn throughout the year (Figure 7). When water withdrawals were made from all upstream reaches throughout the year (Scenario 2), a substantial reduction of 72% in the volume of water available for withdrawal was observed at the watershed outlet compared with Scenario 1. Similar trends were observed for crop growing and noncrop growing seasons (Figure 7). This reduction in the volume of water available for withdrawal at the watershed outlet was because of water withdrawals in the upstream reaches. Batchelor &
Rao (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 & Chandrakanth (2007)) also lay emphasis on the development of suitable upstream irrigation water management practices in terms of the effect on downstream irrigation water availability, especially for the low flow conditions.

Water withdrawal only at the outlet of second-order streams (Scenario 3)

Water was withdrawn at the outlet of all second-order stream subwatersheds (stream 4, 5, 7, 12, 13, 15, 16, 17, 19). Flows in the first-order streams were left undisturbed which resulted in higher flows in second-order streams. Therefore, on average, when the water withdrawals were made throughout the year, the second-order streams could irrigate 11% of the area upstream of the withdrawal point compared with 8% in scenario 2 (when the water was withdrawn from the outlet of first-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 the second scenario (Figure 7). When no water was withdrawn from first-order streams, on average, 6% of the area upstream of third-order stream subwatershed could be irrigated by the water withdrawn throughout the year. Similar trends were observed for water withdrawals made in crop growing and noncrop growing seasons (Figure 7). Compared with Scenario 2, when water was withdrawn simultaneously at the outlet of first- and second-order stream subwatersheds, the percentage of the total area that could be irrigated upstream of second-order stream subwatershed outlet was reduced by 23%. No withdrawals at the outlet of first-order stream subwatersheds resulted in greater flows at the outlet of second-order stream subwatersheds. It was found that an increase in streamflow with drainage area helped to counter the effects of upstream water withdrawals thus still providing enough water withdrawals to be made downstream. Therefore, findings of this study show that if the water is withdrawn sustainably at multiple locations within a watershed, a greater amount of watershed area can be irrigated compared with a scenario in which water was withdrawn only at the outlet of a second-order stream subwatershed or only at the watershed outlet.

Interannual variability in the quantity of water available for withdrawal

The volume of water that can be sustainably withdrawn throughout the year from streams at the watershed outlet exhibited interannual variability (Figure 8). Similar interannual variability trends were observed at the watershed outlet for all three scenarios (i.e., no water withdrawal upstream, water withdrawal at the outlet of all subwatersheds, and...
water withdrawal at the outlet of second-order stream subwatersheds). Interannual variability trends were found similar for withdrawals made in crop-growing and non-crop-growing seasons for all three scenarios. The higher water withdrawal during 1950, 1974, and 1989 was due to the occurrence of the La Niña phase during winter months in these years. However, lower water withdrawals were observed in certain years (e.g., 1988 and 2007) due to the 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 the ENSO phase which can be predicted in advance. This will allow farmers to plan and withdraw water from streams sustainably for irrigation.

**SUMMARY AND CONCLUSIONS**

The results of the study indicate that precipitation and streamflows observed during the La Niña phase in the non-crop growing season were greater compared with the El Niño phase. Whereas, during the crop growing season, the El Niño phase had more precipitation and high streamflows than the La Niña phase. Overall, the noncrop growing season was observed to have a wetter and greater amount of stream water available for withdrawal than the crop-growing months regardless of the 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 on 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 average, the quantity of water withdrawn was sufficient to irrigate 4–16% of the area upstream of withdrawal point depending on the stream order. Results of this study reveal that it was possible to irrigate more areas when water was simultaneously withdrawn at the outlet of first- and second-order stream subwatersheds relative to a scenario in which water was withdrawn only at the outlet of second-order stream subwatersheds. Future studies should be done to quantify the impact of water withdrawals on sediment and nutrient transportation in the watershed. Water 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.

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