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Hydro-Climatological Analysis for Floods and Droughts

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Ensemble Climate Projection for Hydro-Meteorological Drought Over a River Basin in Central Highland, Vietnam

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Abstract

This study focuses on the Hydro-Meteorological Drought assessments by Ensemble Climate Projections from a regional climate model (Weather Research and Forecasting, WRF) that downscaled 3 Global Climate Models under a baseline period (1961-1990) and under a future scenario A2 for 2071-2100. The Meteorological Drought is assessed using the Standardized Precipitation Index (SPI) while the Hydrological Drought is analyzed by using both the semi-distributed hydrology model SWAT and Standardized Runoff Index (SRI). The catchment under study is a small river basin lying on the Central Highland area of Vietnam. This area is the source for perennial plantation which produces most of the coffee for Vietnam making it the world's second most exporter of coffee next to Brazil. Additionally, this region is also one of the important sources for hydropower of Vietnam and one of the main tributaries for the Mekong river at the downstream. This region has been known prone to drought, especially during dry seasons of March and April. Therefore, simulating drought for this area is significant to study the water supply and water balance for the region for future planning and adaptation.

Keywords: *SWAT, WRF, SPI, SRI, ensemble climate projections*

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) estimates that global surface temperatures may rise to about 1-2°C by the year 2050 and to about 2-5°C by the end of the 21st century, depending on how much of the anthropogenic Greenhouse Gases (GHG) will be emitted to the atmosphere in the coming decades and has noted that human induced changes are the most likely reason for the observed changes (IPCC, 2007a; 2014). Precipitation extremes also increase in intensity over many regions in response to warming climate (Kharin *et al*., 2007; Lenderink and Van Meijgaard, 2008). The response of tropical precipitation extremes to interannual climate variability is strongly correlated win response to longer-term climate changes (O'Gorman, 2012).

Drought is a result of extreme rainfall event when there is shortage of precipitation. As mentioned in the Fourth Assessment Report (AR4) of the IPCC, drought is a 'prolonged absence or marked deficiency of precipitation' (Trenberth *et al*., 2013). Some research studies have mentioned the impact of global warming to changes in drought (Trenberth *et al*., 2013; Dai, 2012; Sheffield and Wood, 2008). The Environment Protection Agency (EPA) of the United States has also listed severe drought as a natural disaster (USEPA website). Drought is often classified into three types: meteorological, hydrological and agricultural (Dai, 2011). Meteorological drought is a period of months to years with below-normal precipitation. Hydrological drought occurs when river streamflow and water storages in aquifers, lakes or reservoirs fall below long-term mean levels. Agricultural drought is a period with dry soils that results from below-average precipitation, intense but less frequent rain events, or above-normal evaporation, all of which lead to reduced crop production and plant growth. Hydrological drought develops more slowly because it involves stored water that is depleted but not replenished. A lack of precipitation often triggers agricultural and hydrological droughts (Dai, 2011).

We use two main drought indices: Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI) to assess the hydro-meteorological drought. The advantage of using SPI (McKee *et al*., 1993) is its input being only precipitation data, which makes it ideal for areas where data collection of other meteorological parameters may not be available, as in the study region of this paper. The SPI is considered as the most appropriate index for monitoring the variability of droughts since it is easily adapted to local climate, has modest data requirements and can be computed at almost any time scale (Ntale and Gan, 2003). SPI is suggested to be used as a universal meteorological drought index for more effective drought monitoring and climate risk

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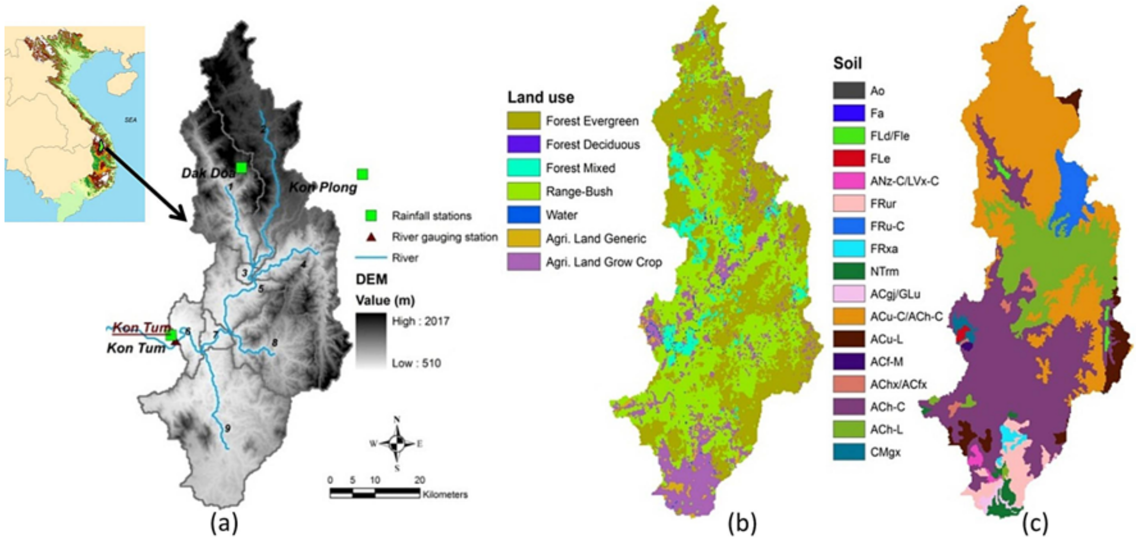

Fig. 1. Spatial Data Input for SWAT Model: (a) Station Locations and DEM, (b) Landuse, (c) Soil Map

management (WMO, 2009). The hydrological drought index, SRI, was proposed by Shukla and Woods (2008), has similar mathematical concepts of deriving SPI index, but SRI uses only monthly runoff as input. Related studies have been documented by Mo and Lettenmaier (2014), Joetzjer *et al.* (2013), Liu *et al.* (2012), Wang *et al.* (2011).

The study region in this paper is the Dakbla river basin over the Central Highland region of Vietnam. The Dakbla river is a small tributary of the Mekong river. The water catchment has a total area of 2560 km^2 (Fig. 1(a)) and lies entirely over the Central Highland region of Vietnam. The catchment is covered mostly by tropical forests. The climate of this region follows the pattern of Central Highland in Vietnam with an annual average temperature of about 20-25°C and a total annual average rainfall of about 1500-3000 mm with high evapotranspiration rates of about 1000-1500 mm per annum. There are 2 main seasons for the Central Highland region: a rainy season from May through to October that accounts for 80% of the total rainfall and a dry season from November through to April which accounts for 20%, thus largely prone to drought over this season. The region is suitable for perennial crops like coffee, rubber or annual plants like cocoa, pepper, sugar cane and cashew.

2. Data

2.1 Station Data

Daily precipitation data for period 1980-2005 from 3 rainfall stations (Kon Plong, Kon Tum, Dak Doa) that lie inside and outside Dakbla river basin were used in this study. This dataset was obtained from the Institute of Meteorology, Hydrology and Environment (IMHEN), Ministry of Natural Resources and Environment (MONRE), Vietnam. The daily data were aggregated to monthly rainfall to be used as inputs to compute SPI.

Daily river discharge at Kon Tum gauging station for the above period was also obtained from IMHEN. This served as a calibration and validation dataset for the hydrological model, SWAT. The monthly data aggregated from the daily runoff were used as input to compute SRI. Locations of the rainfall and river gauging stations are shown in Fig. 1(a).

2.2 Spatial Data Input for SWAT Model

The spatial input data (Digital Elevation Model (DEM) of 250 m) required for SWAT model was obtained from the Department of Survey and Mapping, Vietnam. The land use map was obtained from the Forest Investigation and Planning Institute and the soil map was obtained from the Ministry of Agriculture and Rural Development, both, Vietnam (Fig. 1(a), 1(b), 1(c)).

3. Methodology

3.1 Regional Climate Model

3.1.1 Weather Research and Forecasting model (WRF)

Developed at the National Center for Atmospheric Research (NCAR) in the USA, the WRF model is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. The model incorporates advanced numeric and data-assimilation techniques, a multiple nesting capability and numerous state-of-the-art physics options. Additional information can be obtained from: http://www.wrf-model.org.

The WRF model was first driven by the Reanalysis data ERA40 for baseline period 1961-1990 and then subsequently driven by the 3 GCM: CCSM3.0; ECHAM5 and MIROC-medres for both the baseline (1961-1990) and future (2070-2099) forced under the IPCC A2 future greenhouse gas emission scenario. These 3 GCMs were chosen such that they have a range of climate sensitivities: low (CCSM)-medium (MIROC) and high (ECHAM). This way, a wider bandwidth of uncertainties can be explored. However, the worst case A1FI could not be considered as sufficient data for downscaling were not available from the chosen 3 GCMs. Hence, only an ensemble of A2 scenarios could be considered in this study.

The last 30 years of the future climate period has been considered in this study as the emission scenario shows a clear signal of change towards the end of the century (IPCC, 2007a). For simplicity in reading, the simulations of WRF model driven by the GCMs CCSM3.0, ECHAM5 and MIROC-medres are referred to, in this paper, as WRF/CCSM, WRF/ECHAM and WRF/MIROC, respectively. All climate simulations used the updating of sea surface temperatures, which is recommended for long-term climate simulations. The spatial resolution of the WRF model was 30 × 30 km.

3.2 Soil and Water Assessment Tool

SWAT is a river basin scale model, developed by the United States Department of Agriculture - Agriculture Research Service in early 1990s (Arnold *et al.*, 1998). It is designated to work for a large river basin over a long period of time. Its purpose is to quantify the impact of land management practices on water, sediment and agriculture chemical yields with varying soil, land use and management conditions. Detailed information can be obtained at: http://swatmodel.tamu.edu.

3.3 Standardized Precipitation Index (SPI)

The SPI was first introduced by McKee (1993) by analyzing historical monthly precipitation. A set of averaging periods are selected on a moving window basis to determine a set of time scale of period 'i' months (i = 3, 6, 12, 24, 48). Each dataset is fitted to the Gamma distribution that has the density probability function as:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}x^{\alpha-1}e^{-x/\beta}, \text{for } x>0 \quad (1)$$

where $x > 0$ is the amount of accumulated precipitation. Based on each data set, a set of shape parameter $\alpha > 0$ and shape parameter $\beta > 0$ is estimated. $\Gamma(\alpha)$ is the Gamma function that is defined by the integral:

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1}e^{-y}dy \quad (2)$$

After estimating coefficients α and β, we obtain an expression for cumulative probability $G(x)$ that represents a certain amount of rain has been observed for a given month at time scale i:

$$G(x) = \int_0^{\infty} g(x)dx \quad (3)$$

However, Gamma function is not defined by $x = 0$, and there may be no precipitation. If q is the probability of zero precipitation, the cumulative probability of precipitation $H(x)$ observed is computed as follow:

$$H(x) = q + (1-q)G(x) \quad (4)$$

The cumulative probability $H(x)$ is then transformed into a normal standard distribution with mean $\mu = 0$ and standard deviation $\sigma = 1$ from which we obtain SPI. The SPI is the inverse of the normal cumulative distribution function at the corresponding probability $H(x)$.

The drought classification based on SPI is shown in Table 1.

Table 1. Drought Category based on SPI Values (Adapted from McKee *et al.*, 1993)

SPI Values	Drought Category
0 to -0.99	Mild drought
-1 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
≤ -2.00	Extreme drought

3.4 Standardized Runoff Index (SRI)

The SRI complements the SPI for studying the hydrologic aspects of drought. Although SRI and SPI employ similar concepts when based on long accumulation periods, the SRI incorporates hydrologic processes that determine seasonal lags in the influence of climate on streamflow. The input for SRI is river runoff. When applied for river runoff in United States, Shukla and Woods (2008) found that the 2 parameter log normal (LN2) distribution provided a better fit at high extremes than the Gamma distribution (which may perform better at low flow). However, the probability distribution function selected will depend on the data series. Abril and Trevino (2012) applied the Gamma distribution on European basins and suggested that users can choose the PDFs that better fit their data. We did the sensitivity study for this region by applying both Gamma and LN2 distribution functions to calculate SRI. The correlation between two SRIs computed from these two distributions above is 0.9996 and the RMSE is 0.033. As the two distribution functions are very much similar in generating the SRI, we chose to follow the Gamma distribution function to calculate the SRI later on.

3.5 Methodology

The SWAT model was calibrated and validated over the period 1980-2005 using 3 rainfall stations and a gauging discharge at Kon Tum. The runoff all over sub-catchments derived from SWAT model was used to calculate the SRI index. The corresponding rainfall value at these catchments was used to simulate the SPI index. The meteorological and hydrological drought over the study region was assessed by analyzing SPI and SRI and compared with historical records. The SWAT model was used to derive future runoff from future rainfall obtained from the climate model simulations, WRF/CCSM, WRF/ECHAM and WRF/MIROC. Future SPI and SRI were used to compare against the present day climate to assess the change in drought for the study region over the end of the 21^{st} century.

4. Results

4.1 SWAT Model Result

The calibration and validation of the SWAT model has been done in our previous studies (Raghavan *et al.*, 2012; 2014). The value of the Nash-Sutcliffe index and the Coefficient of Determination R^2 for monthly flow is 0.7 (Refer Table 2). Fig. 2 shows the runoff for 1980-2005 at Kon Tum station in monthly scale. It is therefore possible to use the monthly simulated flow for drought assessment over the Dakbla river basin.

4.2 Assessing Meteorological Drought and Hydrological Drought at Present Day Climate

The four accumulation periods (Section 3.3) 1, 3, 6 and 12 month scale for SPI and SRI are assessed for the years 1980-2005 done at Kon Tum station (Fig. 3). Table 3 shows the correlation value between SPI and SRI for all accumulation period. The differences between the indices increase as the accumulation period decreases, with SPI to SRI correlations dropping from 0.71 for the 12-month period to 0.64 for 6-month and to 0.54 and to 0.39 for the 3-, and 1-month period indices, respectively.

Table 2. Goodness of Fits Results for SWAT Model

Type	Cali	Vali
Coefficient of Determination: R^2	0.72	0.73
Nash-Sutcliffe Index: NSE	0.74	0.66

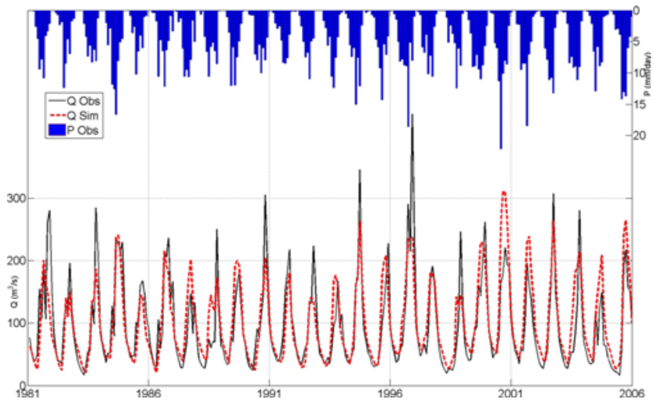

Fig. 2. Calibration and Validation of SWAT Model

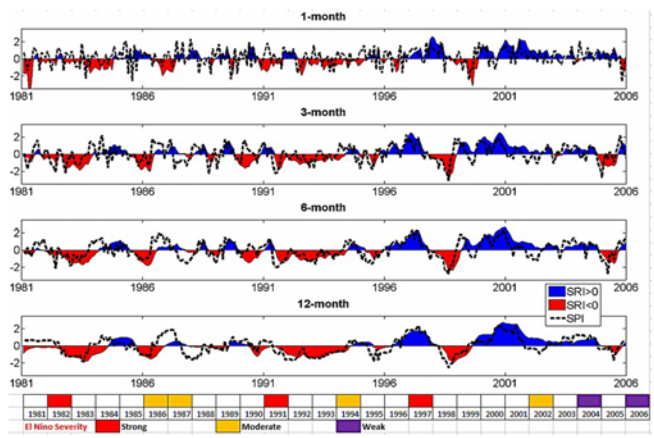

Fig. 3. SPI and SRI value for 1, 3, 6 and 12 Accumulation Months (top to bottom)

Table 3. Correlation between SPI and SRI

Accumulation period (month)	Correlation SPI vs SRI
1	0.39
3	0.54
6	0.64
12	0.71

It needs to be stressed here that the drought can be identified when SPI first falls below zero and ends with the positive value of SPI following a value of -1.0 or less (McKee *et al*., 1993). The SPI/SRI 6 and 12 month accumulation clearly show the trend of significant events over 1983, 1992-1993 and 1998. The interesting finding here is that all these events occur about a year after the strong El Nino years hit Vietnam (Strong El Nino in 1982; 1991; 1997) (as shown in Fig. 3 and partially adapted from Vu *et al*., 2013). Both SPI and SRI indices agreed on the timing and magnitude during these years. Detailed studies about the relation of El Nino to drought over Southeast Asia were done by Dai and Wigley (2000), Kane (1999), Ummenhofer *et al.* (2012), Li *et al*. (2014). The SPI-12 and SRI-12 is selected to assess the future climate meteorological and hydrological drought because it has the highest correlation among 4 accumulation periods.

4.3 Future Climate Projections

The future climate projections derived from the three downscaled climate model scenarios, WRF/CCSM, WRF/ECHAM and WRF/MIROC are shown in Fig. 4 as anomalies between the future climate 2071-2100, scenario A2 and present day climate 1961-1990, The figures indicate an increase in temperature of about 2.6-3.2°C (Fig. 4(a)) and an increase in precipitation of about 10-50% (Fig. 4(b)). The ensemble climate projections also indicate the same trend of increasing both temperature and rainfall. The simulation by SWAT model indicates that the future hydrological streamflow is expected to increase by 38-48% with respected to present day climate (Fig. 5) for all scenarios. It is therefore likely that the region will experience a wetter climate in the future. But to assess whether this increasing rainfall trend will mean less drought in the future than the present day climate, a drought characteristics analysis is essential.

4.4 Characteristics of Future Meteorological and Hydrological Drought

Table 4 summarizes the drought characteristics for SPI and SRI over the 1961-1990 and 2071-2100 A2 scenario for the 3 downscaled datasets. The 3 characteristics taken into account are: (1) Number of drought events for the whole study period (2) Drought Intensity: summation of all SPI/SRI values occurred during drought events. It has the negative sign as the values of SPI/SRI for drought are negative and (3) Drought Frequency: the division of total duration of drought period (in months) with total number of months in the study period.

Table 4 shows that there are slightly more drought events in the future meteorological and hydrological climate using ensemble

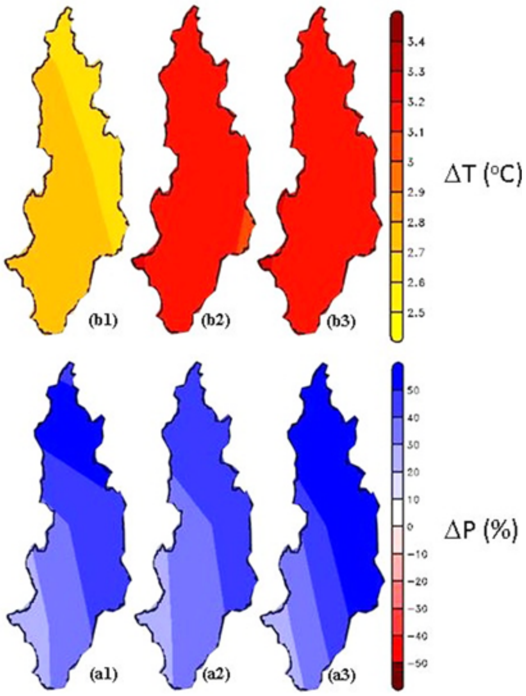

Fig. 4. Future Climate Change: (a) Temperature Anomaly (°C), (b) Precipitation Anomaly (%)

study. There are 7 SPI/SRI events for WRF/CCSM future scenario compared to 6 events over the baseline. The number of SPI events remain the same for future period in WRF/ECHAM and WRF/MIROC (at 6 events). The number of SRI events of WRF/ECHAM increase by 1 in the future while it is decreased by 1 using WRF/MIROC data.

Table 4. Baseline (1961-1990) and Future Climate (2071-2100) Drought Characteristic

Characteristics	Baseline		Future	
CCSM	SPI	SRI	SPI	SRI
Number of drought events	6	6	7	7
Drought Intensity	-127.0	-129.3	-118.0	-120.9
Drought Frequency	0.40	0.41	0.36	0.38
ECHAM	SPI	SRI	SPI	SRI
Number of drought events	6	5	6	6
Drought Intensity	-120.1	-119.4	-102.4	-108.0
Drought Frequency	0.41	0.43	0.31	0.36
MIROC	SPI	SRI	SPI	SRI
Number of drought events	6	5	6	4
Drought Intensity	-117.7	-118.2	-107.5	-115.0
Drought Frequency	0.34	0.36	0.35	0.38

However, the Future Drought Intensity (SPI/SRI= -118/-120.9) and Frequency (SPI/SRI = 0.36/0.38) of WRF/CCSM are lower than the baseline (-127/-129 and 0.40/0.41 respectively) due to wetter climate as described in the previous section. Similar responses can be identified for WRF/ECHAM responses. The result for WRF/MIROC is slightly different than two above datasets with the Drought Frequency in the future slightly higher than baseline (SPI/SRI = 0.35/0.38 compared to 0.34/0.36). The

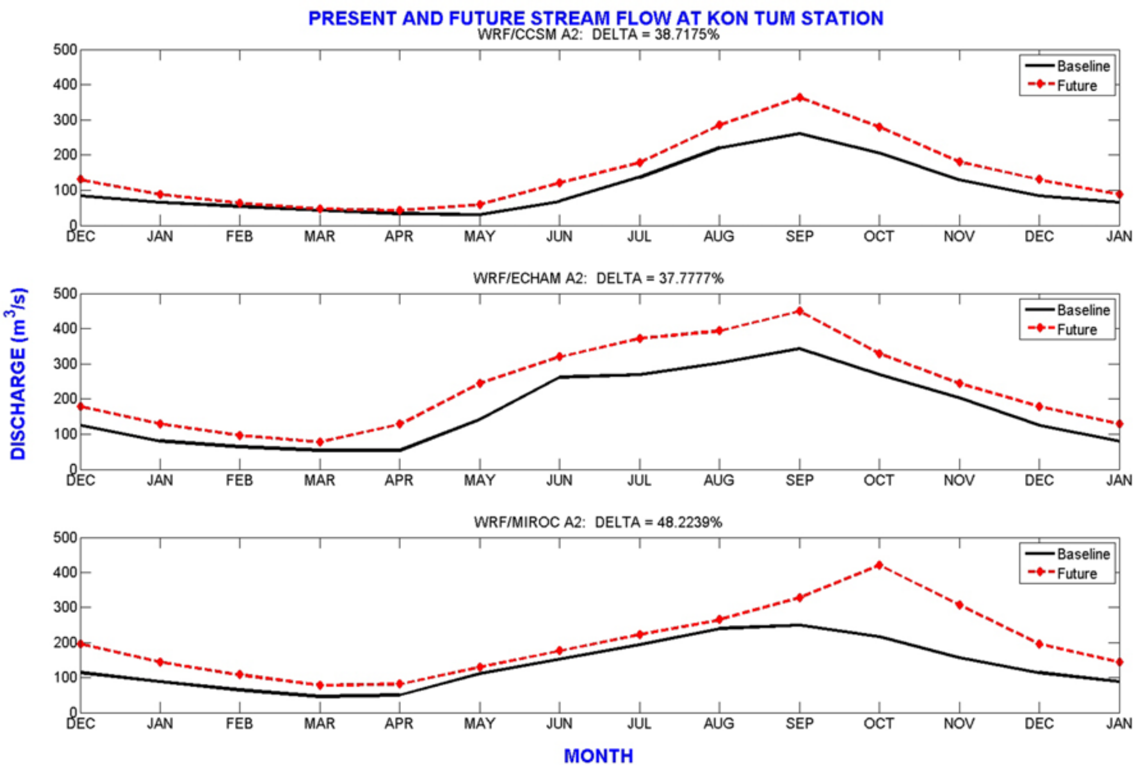

Fig. 5. Annual Cycle of Baseline and Future Streamflow

value for Drought Intensity of WRF/MIROC follows the trend of WRF/ECHAM and WRF/CCSM. Overall, this ensemble shows a marginal increase in the number of Drought events, a slight decrease in the Drought Frequency and a decrease in Drought Intensity in the future A2 scenario compared to baseline period.

5. Conclusions

This paper attempted to study the meteorological and hydrological drought conditions of Dakbla river basin over Central Highland, Vietnam, based on the SPI and SRI indices, respectively. The SRI index was assessed by output of the semi-distributed SWAT model calibrated for the Dakbla river basin while the SPI index was based on the rainfall data. The SPI has a higher correlation with SRI when increasing the accumulation period. The 6-month and 12-month SPI/SRI are able to portray the historical drought as observed. An interesting finding is that the extreme drought events occurred after the strong El Nino events after a year of the events. SPI and SRI were also calculated for all sub-catchments based on the simulation outputs of SWAT model. The climate changes between future and present day climate derived from RCM scenarios indicated significant increase in temperature and precipitation over the study region, thus leading to increasing future runoff over the Dakbla river basin. The future meteorological and hydrological drought was characterized by SPI and SRI indices which indicated an increase in future drought events but decrease in terms of intensity and frequency.

Given these results, analyzing future drought conditions using the RCM results of downscaled future climates under different emission scenarios and pathways would be immensely helpful for adaptation and policy decisions. This will be a continued exercise of this study and a larger ensemble of climate simulations could be accounted for improved confidence.

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