Water and Environment Journal
Promoting Sustainable Solutions
CIWEM

Water and Environment Journal. Print ISSN 1747-6585

Impact of climate change on meteorological, hydrological and agricultural droughts in the Lower Mekong River Basin: a case study of the Srepok Basin, Vietnam

Truong Thao Sam[1], Dao Nguyen Khoi[2], Nguyen Thi Thanh Thao[3], Pham Thi Thao Nhi[4], Nguyen Trong Quan[4], Nguyen Xuan Hoan[5] & Van Thinh Nguyen[6]

[1]Institute of Research and Development, Duy Tan University, Da Nang, Vietnam; [2]Faculty of Environment, University of Science, Vietnam National University Ho Chi Minh City, Ho Chi Minh City, Vietnam; [3]Institute of Environment Science, Engineering and Management, Industrial University of Ho Chi Minh City, Ho Chi Minh City, Vietnam; [4]Institute for Computational Science and Technology, Ho Chi Minh City, Vietnam; [5]Ho Chi Minh City University of Food Industry, Ho Chi Minh City, Vietnam; and [6]Department of Civil and Environmental Engineering, Seoul National University, South Korea

Keywords
climate change; drought; hydrology; SWAT model; Srepok River Basin.

Correspondence
Dao Nguyen Khoi, Faculty of Environment, University of Science, Vietnam National University Ho Chi Minh City, Ho Chi Minh City, Vietnam. Email: dnkhoi86@gmail.com

doi: 10.1111/wej.12424

Abstract

The objective of this study is to assess future changes in meteorological, hydrology and agricultural droughts under the impact of changing climate in the Srepok River Basin, a subbasin of LMB, using three drought indices; standardized precipitation index (SPI), standardized runoff index (SRI) and standardized soil moisture index (SSWI). The well-calibrated Soil and Water Assessment Tool (SWAT) is used as a simulation tool to estimate the features of meteorological, hydrological and agricultural droughts. The climate data for the 2016–2040 period is obtained from four different regional climate models; HadGEM3-RA, SNU-MM5, RegCM4 and YSU-RSM, which are downscaled from the HadGEM2-AO GCM. The results show that the severity, duration and frequency of droughts are predicted to increase in the near future for this region. Moreover, the meteorological drought is less sensitive to climate change than the hydrological and agricultural droughts; however, it has a stronger correlation with the hydrological and agricultural droughts as the accumulation period is increased. These findings may be useful for water resources management and future planning for mitigation and adaptation to the climate change impact in the Srepok River Basin.

Introduction

Drought is a serious and recurrent natural hazard that has negative consequences on water resources and agriculture. Drought usually starts with abnormal decreases in precipitation that affects hydrological components, such as evaporation, runoff, and soil water content, streamflow, etc. Consequently, it leads to significant impacts on agricultural and socioeconomic systems (Duan and Mei, 2014). Generally, the drought is classified into four main types, including meteorological, agricultural, hydrological and socio-economic droughts, depending on its nature and effects (Thilakarathne and Sridhar, 2017). In recent years, the frequency and severity of the droughts because of climate change have considerably increased (IPCC, 2013). Under the impact of climate change, studies on monitoring and predicting droughts on a long-term scale are necessary to find countermeasures to cope with extreme drought conditions that may occur in the future (Kim *et al.*, 2014).

Studies on climate change impacts on drought have recently drawn the attention of scientists. For instance, Wang *et al.* (2011) investigated the potential impacts of climate change on meteorological, agricultural and hydrological droughts in The Salt Creek Catchment (US) and revealed an increase in drought frequency in the future; Leng *et al.* (2015) conducted the similar study in China and pointed out that droughts will become more extreme and frequent under climate change scenarios. Moreover, von Gunten *et al.* (2016) used drought indices and the HydroGeoSphere hydrological model to project hydrological impacts of droughts in the context of climate change in the Lerma catchment (Spain) and indicated an increase in drought severity in the future. In another study, Kamali *et al.* (2017) assessed meteorological, agricultural and hydrological droughts in the Karkheh River Basin (Iran) using three drought indices and Soil and Water Assessment Tool (SWAT) and found that the frequency of extreme droughts is predicted to increase in the future. In those studies, a common implemented approach is using a hydrological model with two input data sets; one is historical hydro-meteorological data from observations, and another is projected data through outputs of the general circulation models (GCMs) and the hydrological model. These hydro-meteorological data are converted into drought indices, such as the Standardized Precipitation Index (SPI), Standardized Soil Water Index (SSWI), and Standardized Runoff Index (SRI), to predict drought severity. The three drought indices have been widely used to evaluate the agricultural and hydro-meteorological droughts (e.g. Leng *et al.*, 2015; Kamali *et al.*, 2017). Regarding the hydrological modelling, the SWAT model has been popularly used as a modelling tool to study on climate change impact on hydrology at a catchment scale. To date, around 2900 applications of the SWAT model in small and large catchments around the world have been reported (see SWAT database: https://www.card.iastate.edu/swat_articles/, accessed August 2017).

In recent years, Vietnam has faced severe and prolonged droughts, which cause water scarcity and loss of agricultural productions with damaged costs of hundreds of billion Vietnamese Dong (VND) (FAO, 2016). Especially in the dry season of 2015–2016 with the effects of El Niño phenomenon, the Central Highlands region has faced the most severe droughts in the past 100 years, causing severe damage to agriculture with a 14.9% decrease in perennial crops (cashew, coffee, and pepper). Regarding impacts of crop damage, about 2 million people are estimated to lose their incomes because of the drought impact on agriculture (UNDP, 2016). Moreover, Vietnam has been grouped into the most vulnerable countries to climate change (IPCC, 2013). Annual temperature increased by 0.62°C, and annual precipitation decreased by 5.8–12.5% in the northern regions and increased by 6.9–19.8% in the southern regions over the past 57 years (1958–2014) (MONRE, 2016). These changes have significantly affected on water availability and droughts in Vietnam. Many studies on climate change impacts conducted in Vietnam have focused on water availability (Phan *et al.*, 2010; Khoi and Suetsugi, 2012; Raghavan *et al.*, 2014; Le and Sharif, 2015; Huyen *et al.*, 2017). Another study conducted by Vu *et al.* (2015) considered future projection of hydro-meteorological droughts for Dakbla River Basin in the Central Highlands of Vietnam. However, there are still limited studies concerning agricultural drought in Vietnam. In general, most of the studies on climate change impacts in Vietnam have been conducted using climate change scenarios in the IPCC-Fourth Assessment Report (AR4). In 2014, IPCC released new climate change scenarios in the Fifth Assessment Report (AR5). This has provided an opportunity to improve the projections of water availability and droughts under impacts of climate change in Vietnam.

The purpose of this study was to investigate the impacts of climate change on meteorological, agricultural and hydrological droughts in the Srepok River Basin in the Central Highlands of Vietnam. The results obtained in this study are expected to help water managers to understand more insight into the climate change impacts on the droughts in the study area.

Study area

The Srepok River Basin, one of the subbasins of the Mekong River Basin, is located in the Central Highlands of Vietnam. This area is located between latitudes 11°45′–13°15′N and longitudes 107°15′–109°E (Fig. 1). The Srepok River has contained two main tributaries, the Krong No and Krong Ana Rivers. The basin has a total land area of 12 000 km^2 with the population of about 2.5 million (GSO, 2015). In this basin, acrisols and ferrasols are two dominant soil types. These soils are very compatible with agricultural development. About 50% of the total land area in the basin is agricultural land. The main crops in the region are coffee, rubber, cashew, black pepper and fruit trees for domestic and export markets (CCAFS-SEA, 2016). More importantly, this region plays a crucial role for Vietnam economy, since the most coffee beans are produced here; and Vietnam became the world's second largest coffee exporter nowadays.

The elevation of the basin ranges from 140 to 2400 masl (meters above sea level) in the direction of the northwest to southeast. The climate in the area is mainly influenced by the southwest monsoon, with high humidity of around 78–83% and annual rainfall ranging from 1700 to 2300 mm. The climate features two distinct wet and dry seasons. The wet season lasts from May to October, accounting for about 75–95% of the annual precipitation. The mean annual temperature ranges from is 20 to 25°C.

Methodology

Soil and Water Assessment Tool (SWAT)

The SWAT model is a catchment-scale and semi-distributed model designed to predict the impact of environmental changes on water, sediment and agricultural chemical yields (Neitsch *et al.*, 2011). In SWAT, a catchment is subdivided into a number of sub-catchments, which are further separated into hydrological response units (HRUs) based on land-use and soil characteristics. Hydrological simulation is based on the mass conservation law of water contents, which comprises precipitation, evapotranspiration, infiltration, surface runoff and subsurface flow. Further details of the SWAT hydrological model can be

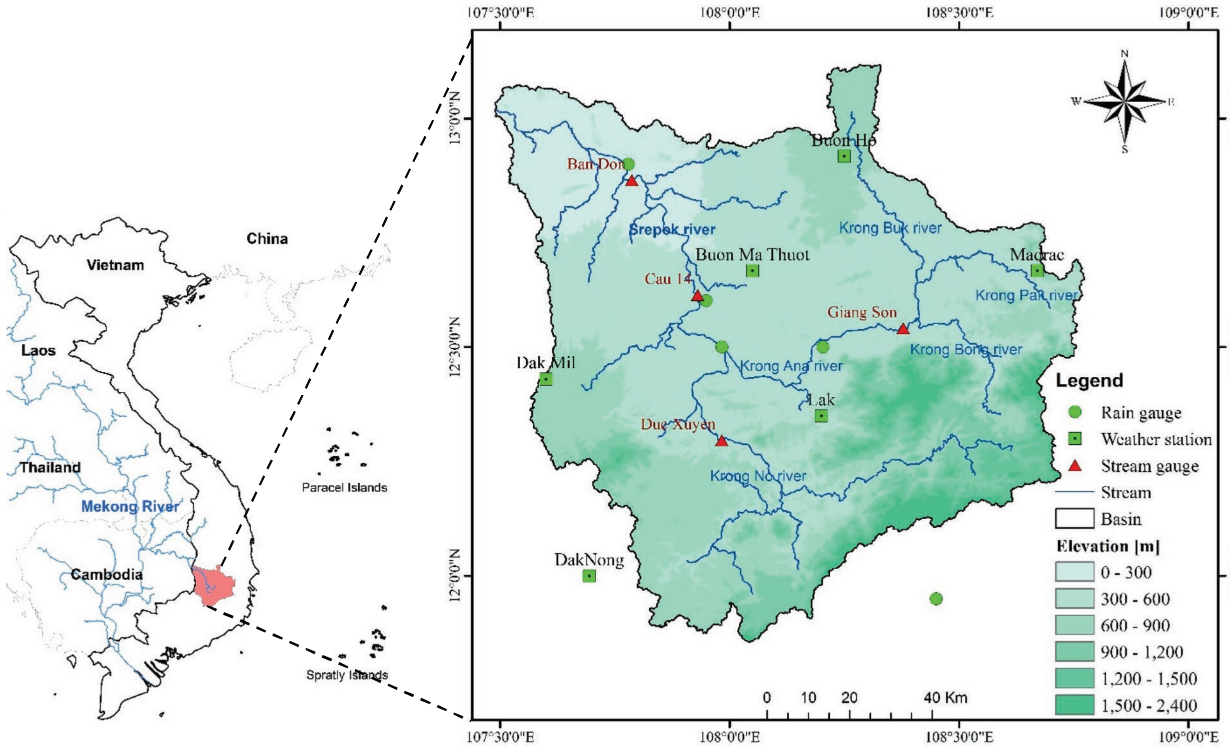


Fig. 1. Location of the Srepok River Basin. [Colour figure can be viewed at wileyonlinelibrary.com]

found in the theoretical documentation given by Neitsch *et al.* (2011).

Input data for the SWAT model, including topographic features, land-use types, soil types and weather data as shown in Table 1, were collected. A 90 m resolution Digital Elevation Map (DEM) of the study area was extracted from United States Geological Survey (USGS), a land-use map in 2003 with a spatial resolution of 1 km was obtained from Mekong River Commission (MRC), and a soil map with 10 km spatial resolution were derived from SOIL-FAO database from the Food and Agriculture Organization (FAO) of United Nations. Regarding meteorological data, the data derived from nine rain gauges and three temperature stations located within or near the basin for the period 1981–2015, collected from the Hydro-Meteorological Data Centre of Vietnam (HMDC), were used (Fig. 1). Streamflow data from four stream gauges for the period 1982–2011, obtained from HMDC, were used for model calibration and validation. The data used in this study are presented in Table 1. The ArcSWAT version 2012 with a supported interface of ArcGIS version 10.3 was used in this study.

The SWAT model was set-up for the study area, including total of 48 subbasins and 482 HRUs. Subsequently, data set for the 1982–1990 period has been used for the calibration procedure after subtracting the first year (1981) as a warm-up year. The Sequential Uncertainty Fitting version 2 (SUFI-2) in SWAT-CUP (SWAT – Calibration and Uncertainty Procedures) (Abbaspour, 2015) was used for parameter sensitivity analysis and model calibration. Among five techniques of parameter uncertainty analysis (i.e. GLUE, MCMC, PSO, ParaSol, and SUFI-2) in the

Table 1 Input data for the Srepok River Basin

Data type	Description	Scale	Source
DEM	Topological features	90 m	United States Geological Survey (USGS)
Land-use	Land-use characteristics in 2003	1 km	Mekong River Commission (MRC)
Soil	Soil types and physical properties	10 km	Food and Agriculture Organization (FAO)
Meteorology	Precipitation and maximum/minimum temperature in the period 1981–2009 at three temperature stations and nine rain gauges	Daily	Hydro-Meteorological Data Centre (HMDC)
Hydrology	Streamflow in the period 1981–2000 at the Ban Don, Cau 14, Duc Xuyen, and Giang Son stations	Daily	HMDC

SWAT-CUP package, the SUFI-2 technique was selected for this study because it has been proven to be an efficient optimization algorithm with a minimum number of runs to achieve good simulation results (Khoi and Thom, 2015; Wu and Chen, 2015). The simulation period for validation was 1991–2011. The best fits between observed and simulated streamflow were evaluated using graphical and quantitative statistical techniques. The quantitative statistics, including the coefficient of determination (R^2), Nash-Sutcliffe efficiency (E_{NS}), and percent bias (PBIAS) are used to evaluate the simulation results. According to Moriasi *et al.* (2015), the values of $R^2 > 0.60$, $E_{NS} > 0.5$, and PBIAS $\leq \pm 15\%$ indicate that model performance for flow simulation can be judged as 'satisfactory'.

Drought analysis method

In this study, drought indices are used for quantitative analysis of droughts. The widely used three drought indices are SPI, SSWI and SRI to characterize the meteorological, hydrological and agricultural droughts, respectively (e.g. Wang *et al.*, 2011; Duan and Mei, 2014; Leng *et al.*, 2015; Kamali *et al.*, 2017). The SPI is estimated based on the probability distribution of precipitation using gamma density function for specified monthly time scales (1, 3, 6, 12 or 24-months). The calculation procedure of SPI was also applied to streamflow and soil water content as the indicators of agricultural drought (SSWI) and hydrological drought (SRI). The calculation procedure for SPI, SSWI and SRI can be found in McKee *et al.* (1993) and Kamali *et al.* (2017). The long-term records of precipitation, soil water content and streamflow are needed in order to estimate SPI, SSWI and SRI, respectively. A drought event was considered when values of the drought indices are below –1.0. According to McKee *et al.* (1993), droughts can be classified into moderate (–1.0 ≤ SPI, SSWI and SRI ≤ 1.5), severe (–1.5 ≤ SPI, SSWI and SRI ≤ 2.0) and extreme (–2.0 ≤ SPI, SSWI and SRI) droughts.

In order to analyse the drought features, three drought aspects were classified as follows: (1) severity based on the average values of drought indices for a drought event, (2) duration based on the number of months of a drought event, and (3) frequency based on the number of drought months over a particular period. In this study, the drought indices for 12-months time scale (SPI12, SSWI12 and SRI12) were selected for examining the drought features. The fundamental reason of this selection is that a medium-term accumulation period (12 months) is more appropriate to portray the hydro-meteorological regimes than the short-term (3 and 6 months) or long-term (24 and 48 months) accumulation periods (Spinoni *et al.*, 2014).

Climate change scenarios

Climate change scenarios were generated for the Mekong River Basin in the period 2016–2040 based on four downscaled climate projections of the Coordinated Regional climate Downscaling Experiment – East Asia (CORDEX-EA) project (https://cordex-ea.climate.go.kr/cordex). The selected climate projections were obtained from four regional climate models (RCMs) (HadGEM3-RA, SNU-MM5, RegCM4 and YSU-RSM) to transfer climatic information from the HadGEM2-AO GCM outputs driven by the RCP 8.5 (high emission) scenario to regional scale. The RCP 8.5 scenario was selected for this study because it is representative of the largest impacts of climate change based on the assumption of highest greenhouse gas emission scenario, which is suitable to the drought studies (Leng *et al.*, 2015). Furthermore, the results came out from an assessment of climate change impact for the near future period of 2016–2040 would be interested by decision makers. The details of the four RCMs used in this study shown in Table 2 are presented in Park *et al.* (2016) and Um *et al.* (2017).

Before using the RCM outputs, it is recommended that correcting the RCM outputs is an important step in most of climate change impact studies (Chen *et al.*, 2013). In this study, the delta change method was applied for this correction procedure. This method was selected, because it has been widely used and quite simple in generating a wide range of climate scenarios in various hydrological studies under climate change impacts (Khoi and Suetsugi 2012; Leng *et al.*, 2015; Huyen *et al.*, 2017; Kamali *et al.*, 2017, etc.). Basically, it corrects the RCM-simulated climate time series in the baseline and future periods by adding the differences between observed and simulated climate data (Teutschbein and Seibert, 2013). An addition method is applied to time series of daily temperature and the ratio method is applied to time series of daily precipitation.

Table 2 Description of the four RCMs used in this study

Model	HadGEM3-RA	SNU-MM5	RegCM4	YSU-RSM
Description	Hadley centre global environment model version 3-RA	Mesoscale model version 5	Regional climate model version 4	Regional spectral model
Horizontal resolution	0.44°	50 km	50 km	50 km
Vertical levels	Hybrid-60	σ-18	σ-24	σ-22
Dynamic framework	Non-hydrostatic	Hydrostatic	Non-hydrostatic	Hydrostatic

Results and discussion

Calibration and validation of the SWAT model

The SUFI-2 method is applied to perform a sensitivity analysis of 19 hydrological parameters in the SWAT model. Figure 2 illustrates these parameters with their *t*-value and *P*-values statistics which present a quantity and significance of their sensitivities. A higher absolute value of *t*-test refers to be more sensitive while a *P*-value of 0 measures more significant (Abbaspour, 2015). Out of the hydrological parameters considered for the sensitivity analysis, the curve number for moisture condition II (CN2), base flow alpha factor (ALPHA_BF), channel effective hydraulic conductivity (CH_K2), and Manning's value for the main channel (CH_N2) were found to be the most four sensitive parameters in the study region. These parameters were used for the SWAT model calibration in simulating streamflow. Table 3 shows the final calibrated values of the selected hydrological parameters for the study area.

The SWAT flow simulations were calibrated against the daily flow data from 1982 to 1990 and validated from 1991 to 2009 at the Giang Son, Duc Xuyen, Cau 14, and Ban Don gauging stations, as shown in Fig. 3 and Table 4. The figures indicate that SWAT could capture and reproduce the daily streamflow in the Srepok River Basin during the calibration and validation periods. Additionally, the values of R^2, E_{NS}, and PBIAS are within the ranges of 0.77–0.90, 0.52–0.76 and −14 to 7% for the calibration period, and 0.71–0.87, 0.53–0.73 and −6 to 5% for the validation period, respectively. These statistical indices demonstrated a good agreement between the simulated and observed streamflow for daily simulation based on the criterion of model performance suggested by Moriasi *et al.* (2015). However, the model was not able to draw the peak-flow and low-flow. This could be due to the absence of temporal and spatial variations of storm in the CN2 method (Chu and Shirmohammadi, 2004). Another reason is that the SWAT model uses the models of plant growth and land-use that were developed for temperate areas (Tan *et al.*, 2017). It is suggested that these models should be revised to the tropical regions.

Additionally, the simulated and observed streamflow were compared on a monthly scale. According to the assessment criteria suggested by Moriasi *et al.* (2015), the statistical indices shown in Table 4 suggested a satisfactory agreement in estimating the monthly streamflow. It is easy to recognize that the performance of SWAT model in the validation period (1991–2009) seems to be better than in the calibration period (1982–1990). This

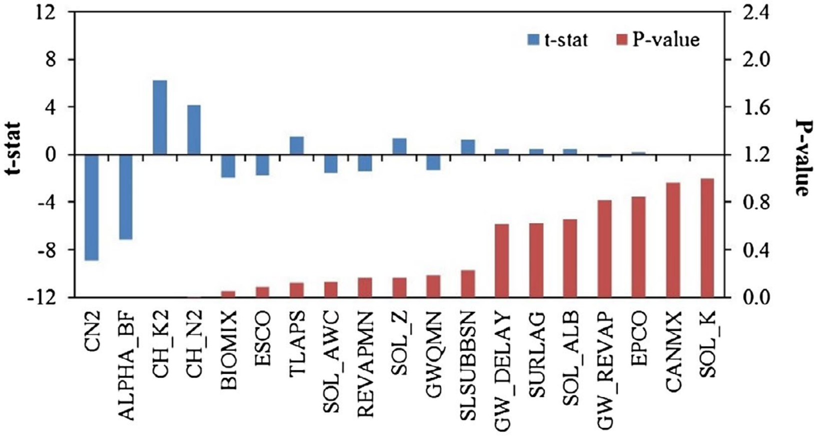
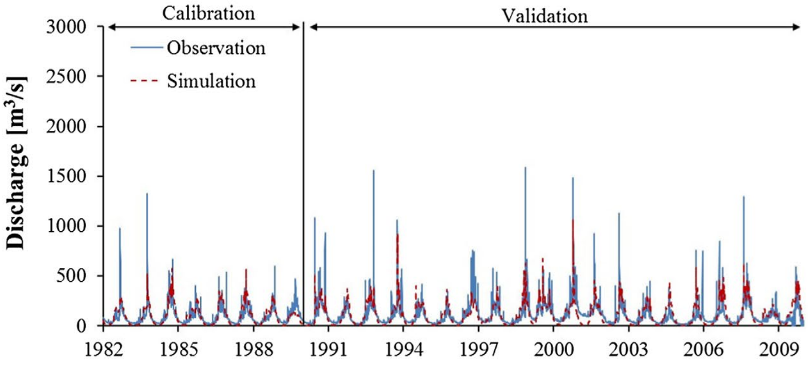


Fig. 2. Sensitivity of parameters using the SUFI-2 method. [Colour figure can be viewed at wileyonlinelibrary.com]

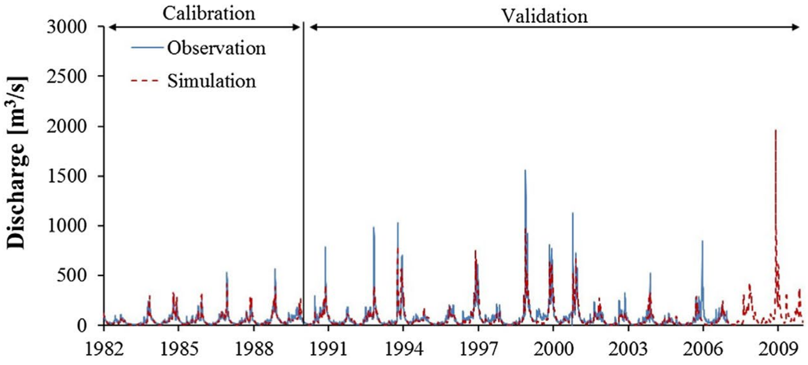
Table 3 SWAT model parameters and their calibrated values for flow simulation

Parameter	Description of parameter	Initial range	Calibrated value
*v*_ALPHA_BF	Baseflow alpha factor	0~1	0.30
*v*_CH_K2	Channel effective hydraulic conductivity	−0.01~500	257
*v*_CH_N2	Manning's values for the main channel	−0.01~0.3	0.07
*r*_CN2	Curve number for moisture condition II	−0.50~0.25	−0.43

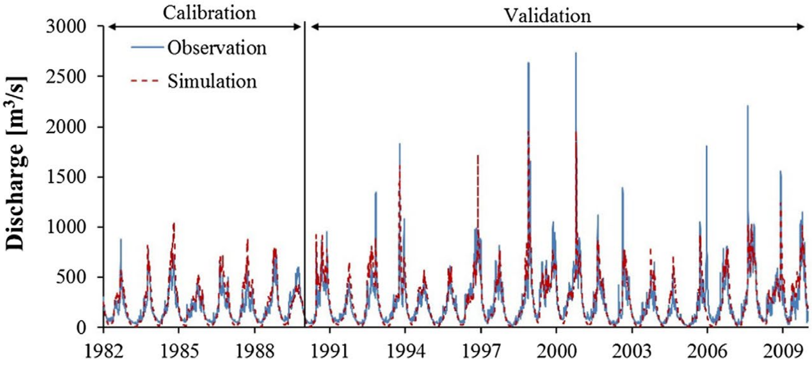
v = parameter value is replaced by given value.
r = parameter value is multiplied by (1 + a given value).



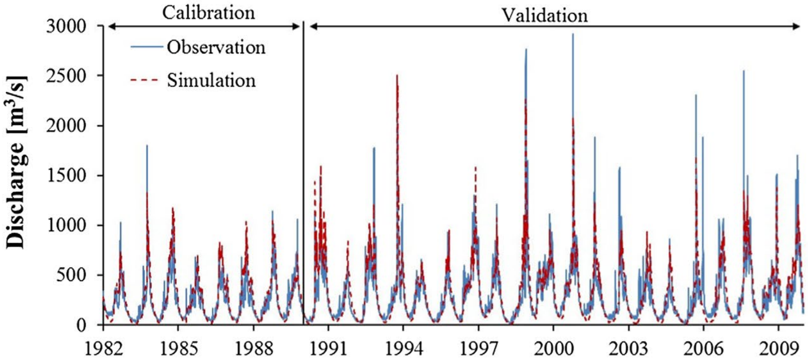
(a) Duc Xuyen station



(b) Giang Son station



(c) Cau 14 station



(d) Ban Don station

Fig. 3. Comparison plots of observed and simulated streamflow for the calibration period (1982–1990) and validation period (1991–2009). [Colour figure can be viewed at wileyonlinelibrary.com]

Table 4 SWAT model performance in the streamflow simulation for four stream gauges within the Srepok River Basin

		Calibration period (1982–1990)			Validation period (1991–2009)		
Station	Time scale	R^2	E_{NS}	PBIAS (%)	R^2	E_{NS}	PBIAS (%)
Duc Xuyen	Daily	0.77	0.52	–2	0.71	0.53	2
	Monthly	0.88	0.64	–2	0.84	0.65	2
Giang Son	Daily	0.89	0.76	7	0.87	0.73	5
	Monthly	0.93	0.84	7	0.89	0.78	5
Cau 14	Daily	0.90	0.60	–12	0.85	0.71	–3
	Monthly	0.93	0.62	–12	0.92	0.83	–3
Ban Don	Daily	0.90	0.61	–14	0.87	0.73	–6
	Monthly	0.94	0.66	–14	0.93	0.83	–6

can be explained using the land-use types in 2003 for the calibration and validation periods. Generally, the results obtained from calibration and validation of streamflow in the Srepok River Basin are similar to the previous studies conducted in the Central Highlands of Vietnam (Vu *et al*., 2015; Huyen *et al*., 2017).

Consequently, the results from calibration and validation steps show a good agreement between simulations and observations. This confirms that the SWAT model is a reliable tool, and it can be used for further investigation of the climate change impacts on regional hydrology in the Srepok River Basin.

Historical features of the droughts

The drought in the Srepok River Basin is becoming more frequent with the adverse effects on social economy and agriculture. The calculation results for the period 1983–2015 using the SPI, SSWI and SRI indices with the 1-, 3-, 6- and 12-month accumulation periods were shown in Fig. 4. It shows that the drought events in terms of meteorological, hydrological agricultural aspects happened quite often during the years 1983, 1990, 1992, 1995, 1998, 2005, 2013 and 2015. It seems that the severe and extreme drought events happen associated with the El Niño events, since the strong El Niño events also occurred during the years of 1982–1983, 1997–1998 and 2014–2015; and moderate El Niño events occurred during the years of 1995–1996 and 2002–2003 (CCAFS-SEA, 2016).

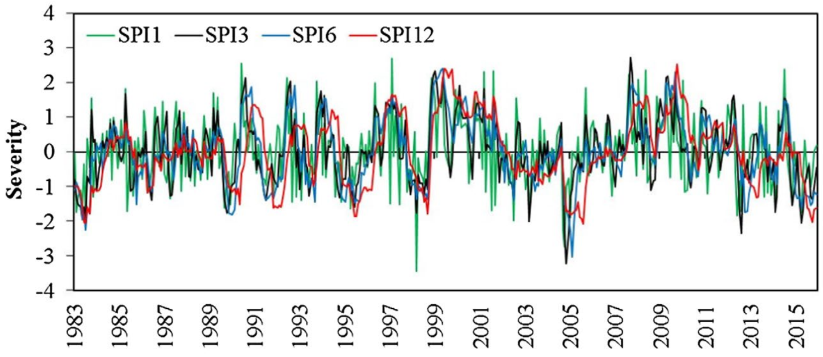
As shown in Fig. 4, the SPI, SRI and SSWI indices produced a same trend in terms of severity and timing of the droughts. Table 5 presents the correlation values of SPI with SRI and SSWI for the periods of 1-, 3-, 6- and 12-month accumulation. The table demonstrated that the meteorological drought have stronger correlations with the hydrological and agricultural droughts in the longer accumulation periods. For instance, the correlation coefficients of SPI versus SRI reduced from 0.91 for the 12-months accumulation period to 0.87, 0.75 and 0.58 for the 6-, 3- and 1-month accumulation periods. Similarly, the R^2 values of SPI versus SSWI dropped from 0.86 for the 12-months accumulation period to 0.84, 0.80 and 0.74 for the 6-, 3- and 1-month accumulation periods, respectively. Another finding is that the hydrological drought has a month lag time, while the agricultural drought does not have lag time from the meteorological drought (Table 6). Additionally, the spatial distribution of the frequency of SPI, SRI and SSWI as shown in Fig. 5, indicates that the western region of the basin is the most vulnerable to hydro-meteorological droughts and the northern region is the most vulnerable to agricultural drought.

Climate change scenarios

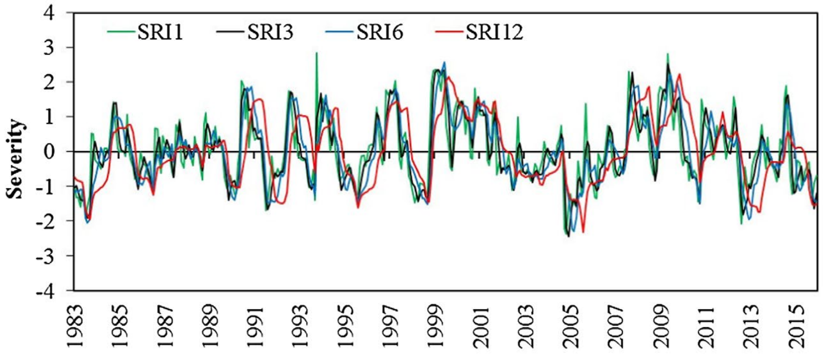
As mentioned previously at section ‘Climate change scenarios’, the RCP 8.5 emission scenario has been selected from four RCMs (HadGEM3-RA, SNU-MM5, RegCM4 and YSU-RSM). Figure 6 illustrates the shift in annual distribution of temperature and precipitation with the uncertainty range of 5 and 95 percentile bounds for the 2030s (2015–2030) relative to the baseline period (1980–2005). The temperature is projected to increase in the future, with an increase in around 1.08°C (within the range of 0.96–1.25°C). Besides that, the future precipitation is predicted to decrease by 4.52% (within the range of –10.84 to –2.05%). Regarding seasonal change, the dry-seasonal and wet-seasonal precipitation decrease by 4.84% (the range of –7.62 to 0.38%) and 4.44% (–13.37 to –1.87%), respectively.

Impacts of climate change on streamflow and soil water content

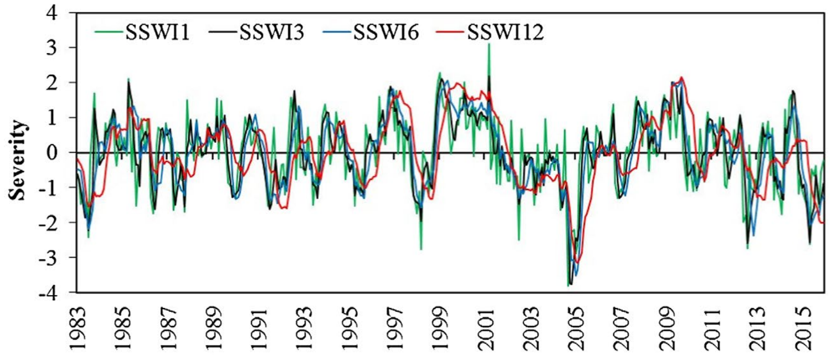
Figure 7 presents the changes in monthly streamflow and soil water content (SW) with the uncertainty range of 5 and 95‰ bounds under the effects of projected climate change. Soil water content (SW) is also investigated in this study, as it plays an important role for agricultural activities. The annual streamflow and SW are expected to be decreased by 11.92% (within the range of –26.53 to



(a) SPI – meteorological drought



(b) SRI – hydrological drought



(c) SSWI – agricultural drought

Fig. 4. SPI (a), SRI (b) and SSWI (c) with 1-, 3-, 6- and 12-month accumulation for the Srepok River Basin. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 5 Correlation coefficient (R^2) between drought indices for different accumulation periods in the Srepok River Basin.

	SRI1	SRI3	SRI6	SRI12	SSWI1	SSWI3	SSWI6	SSWI12
SPI1	**0.48**	0.34	0.28	0.12	**0.74**	0.47	0.36	0.24
SPI3	0.40	**0.75**	0.61	0.34	0.57	**0.80**	0.62	0.44
SPI6	0.32	0.56	**0.87**	0.59	0.46	0.64	**0.84**	0.62
SPI12	0.11	0.31	0.57	**0.91**	0.23	0.40	0.62	**0.86**

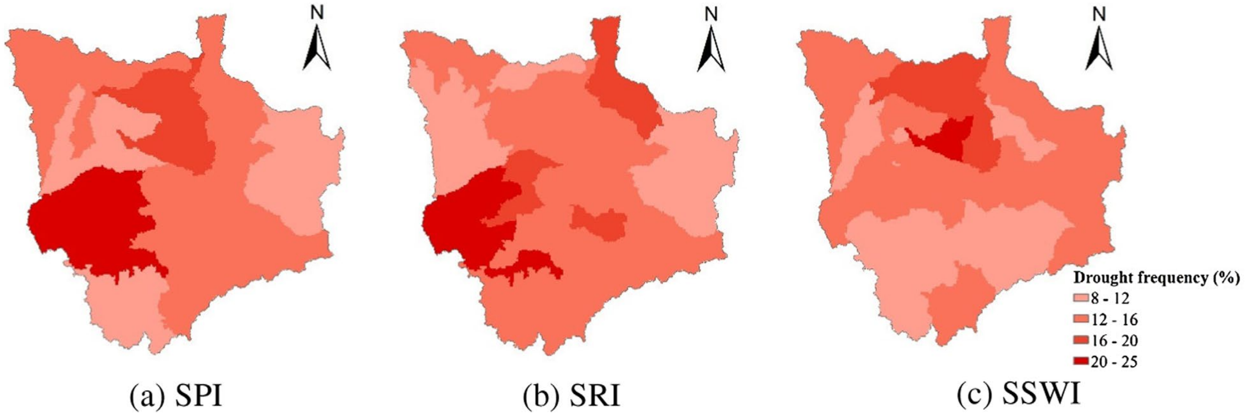
Bold values indicate the highest R^2 values of SPI with SRI and SSWI.

–9.76%) and 6.04% (–9.35 to –4.09%), respectively. The decreases in annual streamflow and SW could be attributed to decrease in precipitation and increase in evapotranspiration because of temperature rise in the future. It clearly shows that the responses of SW and streamflow to climate change occur in the same direction. In the case of seasonal change, the dry-seasonal and wet-seasonal streamflow considerably decrease by 13.17% (–16.52 to –6.33%) and 11.64% (–28.70 to –9.48%), respectively. As regards SW, it

Table 6 Correlation coefficient (R^2) of SPI with SRI and SSWI for different lag times in the Srepok River Basin.

		Lag time					
Time scales		0 month	1 month	2 month	3 month	4 month	5 month
1 month	SPI versus SRI	0.48	**0.61**	0.44	0.34	0.22	0.19
	SPI versus SSWI	**0.74**	0.34	0.33	0.21	0.15	0.17
3 month	SPI versus SRI	0.75	**0.86**	0.76	0.57	0.39	0.30
	SPI versus SSWI	**0.80**	0.73	0.59	0.41	0.31	0.23
6 month	SPI versus SRI	0.87	**0.93**	0.88	0.79	0.66	0.52
	SPI versus SSWI	**0.84**	0.82	0.76	0.65	0.53	0.40
12 month	SPI versus SRI	0.91	**0.95**	0.92	0.86	0.78	0.70
	SPI versus SSWI	**0.86**	0.85	0.81	0.75	0.68	0.61

Bold values indicate the highest R^2 values of SPI with SRI and SSWI.



(a) SPI (b) SRI (c) SSWI

Fig. 5. Spatial distribution of the drought frequency in the baseline period for the Srepok River Basin. [Colour figure can be viewed at wileyonlinelibrary.com]

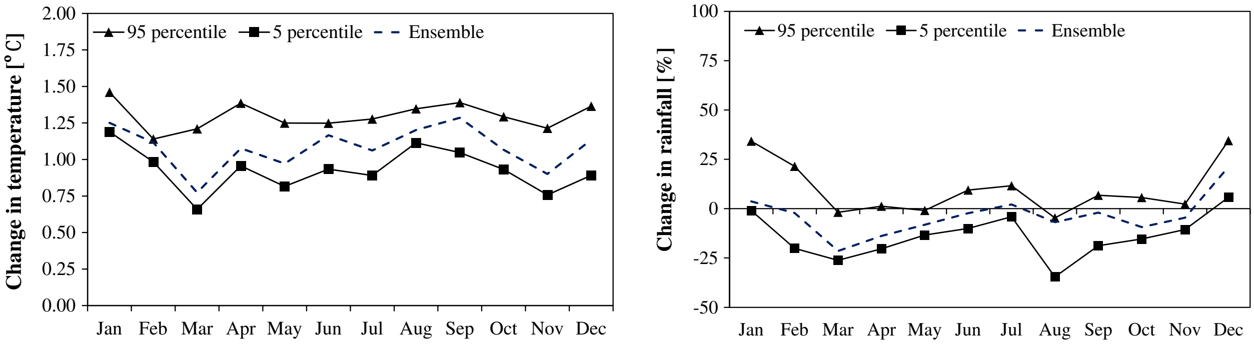


Fig. 6. Monthly changes in temperature and precipitation for the period 2030s. [Colour figure can be viewed at wileyonlinelibrary.com]

is forecasted to be decreased by 4.00% (−8.08 to −2.36%) in the wet season, and 11.55% (−13.61 to −8.76%) in the dry season. A decrease in SW affects significantly on agricultural activities, especially in the dry season. Therefore, more efficient irrigation systems and reservoirs for agriculture should be planned and developed.

Impacts of climate change on the drought characteristics

Under the impact of climate change, the meteorological, agricultural and hydrological drought events increase from 13 to 43%, 14 to 44% and 22 to 40%, respectively. It means

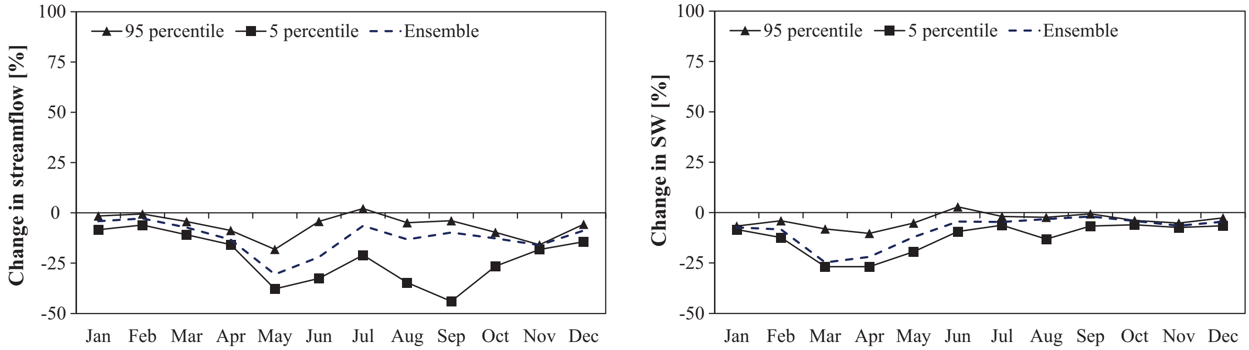
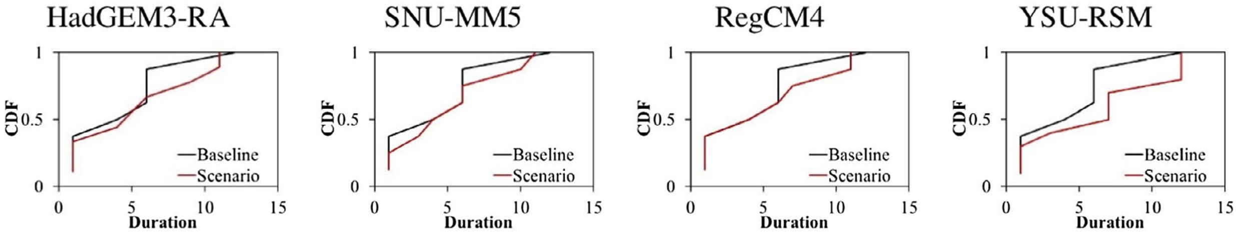
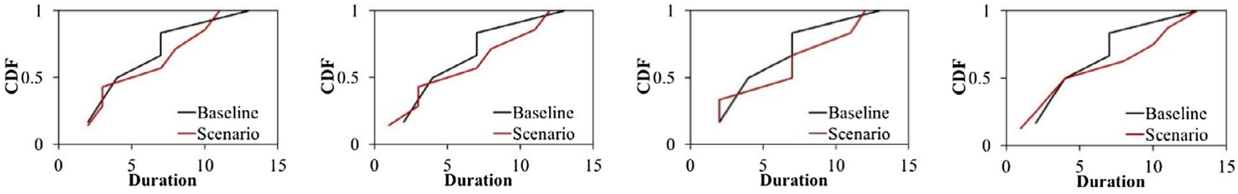


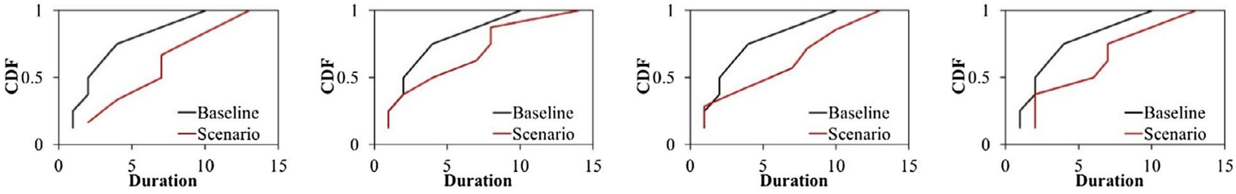
Fig. 7. Monthly changes in streamflow and soil water content (SW) for the 2030s. [Colour figure can be viewed at wileyonlinelibrary.com]



(a) SPI - meteorological drought



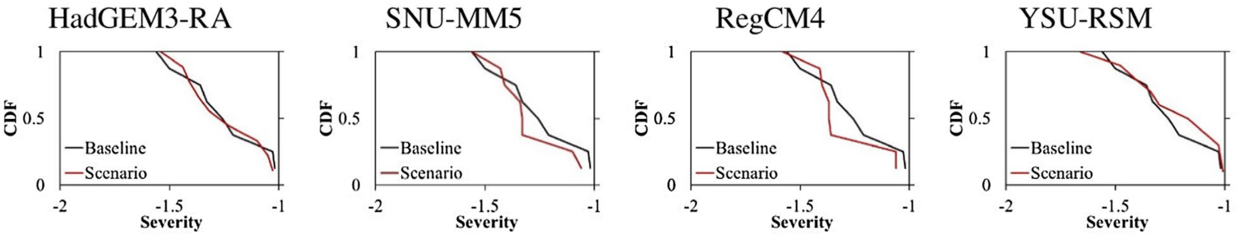
(b) SRI - hydrological drought



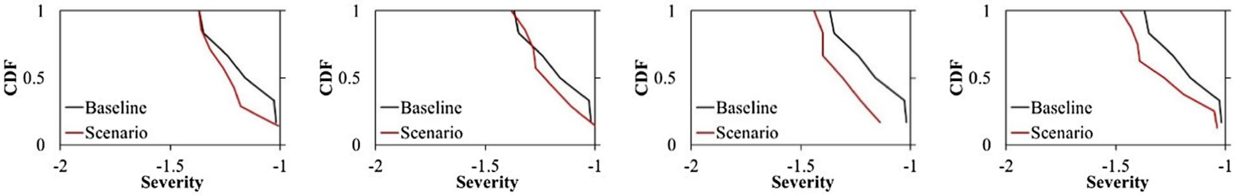
(c) SSWI - agricultural drought

Fig. 8. The cumulative distribution function (CDF) curves of drought duration for the baseline and future periods in the Srepok River Basin. [Colour figure can be viewed at wileyonlinelibrary.com]

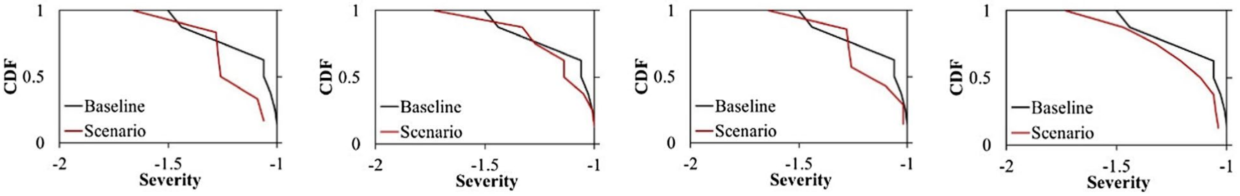
that the drought frequency is predicted to increase in near future for the three drought types. The increases in the drought frequency could be attributed to decreases in precipitation, streamflow and SW. Figure 8 displays the cumulative distribution function (CDF) curves of the drought duration of the study area for the baseline and future periods corresponding to four RCMs. The figure revealed that predicted changes in drought duration present significant variation between RCMs. In general, it is also indicated that a longer duration of the future meteorological, hydrological and agricultural droughts is foreseen. In terms of the longest drought duration, a decrease in the drought duration is anticipated for the meteorological and hydrological droughts. In contrast, the duration of agricultural drought is foreseen to increase in the future. Regarding the future drought severity (Fig. 9), an increase in the drought severity is predicted for the meteorological, hydrological and agricultural droughts based



(a) SPI - meteorological drought



(b) SRI - hydrological drought



(c) SSWI - agricultural drought

Fig. 9. The cumulative distribution function (CDF) curves of drought severity for the baseline and future periods in the Srepok River Basin. [Colour figure can be viewed at wileyonlinelibrary.com]

on all of the four RCMs. Also, the largest drought severity (i.e. the minimum negative values of SPI12, SRI12 and SSWI12) is forecasted to increase for all three drought types throughout the CDF curves.

Discussion

The recurrent droughts are the main disasters in the Central Highlands of Vietnam, frequently occurring in the dry season (November–April). Severe drought events in recent years, including the historical drought during 2015–2016, have caused huge losses to livelihoods and agriculture with intense impacts on agricultural production and freshwater supply in this area (UNDP, 2016). Thus, the study on drought prediction is vital to mitigate its impacts for the Srepok River Basin.

Analysis of the drought characteristics in the past, it indicated a strong relationship between the droughts in the Central Highland of Vietnam and the El Niño phenomenon. This is consistent with the finding of the drought study conducted in Vietnam (Vu-Thanh *et al*., 2014). Another finding is that the correlations of the meteorological drought with the hydrological and agricultural droughts increase as the accumulation periods are increased. The finding here is similar to that of the studies conducted in the Kerkheh River Basin (Kamali *et al*., 2017) and the Vu Gia – Thu Bon River Basin (Vu *et al*., 2017). Hao *et al.* (2018) indicated that SRI and SSWI are less shifting in the monthly time scale than SPI because of an antecedent precipitation deficit that regulates the soil moisture and streamflow. This may delay the effects of meteorological drought on hydrological and agricultural droughts. In addition, Kamali *et al.* (2017) stated the length of time lag varies spatially because it depends on both climate and catchment properties. In this study, we found that a 1-month time lag between hydrological drought and meteorological drought and a 0-month time lag between agricultural drought and meteorological drought were observed in the study area.

Under the climate change impacts, the features of the meteorological, hydrological and agricultural droughts in terms of severity, duration and frequency, are predicted to increase in the near future in the study area. The finding here is agreeing with that of the study in the Lower Mekong River Basin conducted by Thilakarathne and Sridhar (2017). They reported that the 3S (Sesan, Srepok and Sekong Rivers) River Basin are experienced to increases in the severity and duration of the meteorological drought in the future. However, our finding disagrees to that of the study conducted by Vu *et al.* (2015)

in the Dakbla River Basin in the Central Highlands of Vietnam. They indicated decreases in intensity and frequency of the future meteorological and hydrological droughts. The difference is understandable because the climate change scenarios in that study were obtained from the IPCC-AR4 GCM simulations. The last finding of our study is that the climate change impact on meteorological, hydrological and agricultural droughts is different. As shown in Figs 8 and 9, SRI and SSWI are more sensitive to climate change than SPI. The significant changes in SRI and SSWI are attributed to non-linear response of SW and streamflow to climate change (Wang *et al*., 2011). From the result, the agricultural sector is identified to be sensitive to climate change; therefore, adaptation and mitigation to climate change impacts on agriculture and agricultural water management in this region are necessary.

Conclusions

This study investigated the changes in the meteorological, agricultural and hydrological droughts under the impact of climate change in the Srepok River Basin. The major findings can be summarized as follows:

(1) The analysis results of the historical droughts stated meteorological drought (SPI) has a stronger correlation with hydrological drought (SRI) and agricultural drought (SSWI) as the accumulation period is increased. Moreover, a 1-month time lag between SRI and SPI and a 0-month time lag between SSWI and SPI were determined;

(2) Based on climate change scenarios (precipitation and temperature) generated for the period of 2016–2040, the result indicated an increase in temperature and a decrease in precipitation in the near future. Under the climate change impact, the streamflow and soil water content would be decreased significantly in the future; and

(3) The drought characteristics in terms of severity, duration and frequency, are projected to be increased in the near future. Additionally, SSWI and SRI are more sensitive to climate change than SPI. In general, the results obtained in this study could be useful for planning and managing water resources in this region through mitigation and adaptation to climate change impact on drought features.

Acknowledgement

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number ‘105.06-2013.09’. The authors also would like to thank to anonymous reviewers for their very valuable and constructive comments to improve the manuscript.

To submit a comment on this article please go to http://mc.manuscriptcentral.com/wej. For further information please see the Author Guidelines at wileyonlinelibrary.com

References

Abbaspour, K.C. (2015) SWAT-CUP: *SWAT Calibration and Uncertainty Programs – A User Manual*. Eawag: Swiss Federal Institute of Aquatic Science and Technology.

CCAFS-SEA (CGIAR Research Program on Climate Change, A. and F.S.-S.A.). (2016) *Assessment Report: The Drought Crisis in the Central Highlands of Vietnam*. Hanoi, Vietnam.

Chen, J., Brissette, F.P., Chaumont, D. and Braun, M. (2013) Finding appropriate bias correction methods in downscaling precipitation for hydrologic impact studies over North America. *Water Resources Research*, 49, 4187–4205.

Chu, T.W. and Shirmohammadi, A. (2004) Evaluation of the SWAT model’s hydrology component in the piedmont physiographic region of Maryland. *Transactions of the ASAE*, 47, 1057–1073.

Duan, K. and Mei, Y. (2014) Comparison of meteorological, hydrological and agricultural drought responses to climate change and uncertainty assessment. *Water Resources Management*, 28, 5039–5054.

FAO. (2016) *‘El Nino’ Event in Vietnam: Agriculture Food Security and Livelihood Needs Assessment in Response to Drought and Salt Water Intrusion*. Hanoi.

GSO (General Statistics Office). (2015) *Statistical Yearbook of Vietnam*. Hanoi, Vietnam.

von Gunten, D., Wöhling, T., Haslauer, C.P., Merchán, D., Causapé, J. and Cirpka, O.A. (2016) Using an integrated hydrological model to estimate the usefulness of meteorological drought indices in a changing climate. *Hydrology and Earth System Sciences*, 20, 4159–4175.

Hao, Z., Singh, V.P. and Xia, Y. (2018) Seasonal drought prediction: advances, challenges, and future prospects. *Reviews of Geophysics*, 56(1), 108–141. https://doi.org/10.1002/2016RG000549

Huyen, N.T., Tu, L.H., Tram, V.N.Q., Minh, D.N., Liem, N.D. and Loi, N.K. (2017) Assessing the impacts of climate change on water resources in the Srepok watershed, Central Highland of Vietnam. *Journal of Water and Climate Change*, 8(3), 524–534. https://doi.org/10.2166/wcc.2017.135

IPCC. (2013) *The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Kamali, B., Houshmand Kouchi, D., Yang, H. and Abbaspour, K. (2017) Multilevel drought hazard assessment under climate change scenarios in semi-arid regions – a case study of the Karkheh River Basin in Iran. *Water*, 9, 241.

Khoi, D.N. and Suetsugi, T. (2012) Hydrologic response to climate change: a case study for the Be River Catchment, Vietnam. *Journal of Water and Climate Change*, 3, 207–224.

Khoi, D.N. and Thom, V.T. (2015) Parameter uncertainty analysis for simulating streamflow in a river catchment of Vietnam. *Global Ecology and Conservation*, 4, 538–548.

Kim, C.J., Park, M.J. and Lee, J.H. (2014) Analysis of climate change impacts on the spatial and frequency patterns of drought using a potential drought hazard mapping approach. *International Journal of Climatology*, 34, 61–80.

Le, T. and Sharif, H. (2015) Modelling the projected changes of river flow in Central Vietnam under different climate change scenarios. *Water*, 7, 3579–3598.

Leng, G., Tang, Q. and Rayburg, S. (2015) Climate change impacts on meteorological, agricultural and hydrological droughts in China. *Global and Planetary Change*, 126, 23–34.

McKee, T.B., Doesken, N.J. and Kliest, J. (1993) The relationship of drought frequency and duration to time scales. In: *Proceedings of the 8th Conference on Applied Climatology*. Boston. pp. 179–184.

MONRE. (2016) Climate Change and Sea Level Rise Scenarios for Vietnam. Hanoi.

Moriasi, D.N., Gitau, M.W., Pai, N. and Daggupati, P. (2015) Hydrologic and water quality models: performance measures and evaluation criteria. *Transactions of the ASABE*, 58, 1763–1785.

Neitsch, A.L., Arnold, J.G., Kiniry, J.R. and Williams, J.R. (2011) *Soil and Water Assessment Tool Theoretical Documentation Version 2009*. Texas: Texas A&M University.

Park, C., Min, S.-K., Lee, D.-K.D., Cha, D.-H., Suh, M.-S., Kang, H.-S., *et al.* (2016) Evaluation of multiple regional climate models for summer climate extremes over East Asia. *Climate Dynamics*, 46, 2469–2486.

Phan, T.T.H., Sunada, K., Oishi, S. and Sakamoto, Y. (2010) River discharge in the Kone River basin (Central Vietnam) under climate change by applying the BTOPMC distributed hydrological model. *Journal of Water and Climate Change*, 1, 269–279.

Raghavan, S.V., Tue, V.M. and Shie-Yui, L. (2014) Impact of climate change on future stream flow in the Dakbla river basin. *Journal of Hydroinformatics*, 16, 231–244.

Spinoni, J., Naumann, G., Carrao, H., Barbosa, P. and Vogt, J. (2014) World drought frequency, duration, and severity for 1951–2010. *International Journal of Climatology*, 34, 2792–2804.

Tan, M.L., Ibrahim, A.L., Yusop, Z., Chua, V.P. and Chan, N.W. (2017) Climate change impacts under CMIP5 RCP scenarios on water resources of the Kelantan River Basin, Malaysia. *Atmospheric Research*, 189, 1–10.

Teutschbein, C. and Seibert, J. (2013) Is bias correction of regional climate model (RCM) simulations possible for non-stationary conditions? *Hydrology and Earth System Sciences*, 17, 5061–5077.

Thilakarathne, M. and Sridhar, V. (2017) Characterization of future drought conditions in the Lower Mekong River Basin. *Weather and Climate Extremes*, 17, 47–58. https://doi.org/10.1016/j.wace.2017.07.004

Um, M.-J., Kim, Y. and Kim, J. (2017) Evaluating historical drought characteristics simulated in CORDEX East Asia against observations. *International Journal of Climatology*, 37(13), 4643–4655. https://doi.org/10.1002/joc.5112

UNDP. (2016) *Vietnam Drought and Saltwater Intrusion: Transitioning from Emergency to Recovery*. Vietnam: UNDP.

Vu-Thanh, H., Ngo-Duc, T. and Phan-Van, T. (2014) Evolution of meteorological drought characteristics in Vietnam during the 1961–2007 period. *Theoretical and Applied Climatology*, 118, 367–375.

Vu, M.T., Raghavan, V.S. and Liong, S.-Y. (2015) Ensemble climate projection for hydro-meteorological drought over a river basin in Central Highland, Vietnam. *KSCE Journal of Civil Engineering*, 19, 427–433.

Vu, M.T., Vo, N.D., Gourbesville, P., Raghavan, S.V. and Liong, S.-Y. (2017) Hydro-meteorological drought assessment under climate change impact over the Vu Gia-Thu Bon river basin, Vietnam. *Hydrological Sciences Journal*, 62, 1654–1668.

Wang, D., Hejazi, M., Cai, X. and Valocchi, A.J. (2011) Climate change impact on meteorological, agricultural, and hydrological drought in Central Illinois. *Water Resources Research*, 47, https://doi.org/10.1029/2010WR009845.

Wu, H. and Chen, B. (2015) Evaluating uncertainty estimates in distributed hydrological modeling for the Wenjing River watershed in China by GLUE, SUFI-2, and ParaSol methods. *Ecological Engineering*, 76, 110–121.