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Assessment of hydro-climatological drought conditions for Hong-Thai Binh river watershed in Vietnam using high-resolution model simulation

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Abstract:

Understating hydro-climatological conditions in a transboundary is always challenging because of issues in sharing available data among riparian countries. The present study has explored the hydro-climatological drought conditions over Hong-Thai Binh river watershed (H-TBRW) based on the downscaled rainfall and reproduced streamflow by the state-of-the-art coupled regional hydroclimate model. The standardized precipitation index (*SPI*) and streamflow drought index (*SDI*) indicators are used to define the climatological and hydrological drought conditions, respectively. Both *SPI* and *SDI* are derived from the precipitation and streamflow data reproducibility for the H-TBRW during 1950-2015. The results demonstrate a slight increasing trend in both climatological and hydrological conditions. Over the H-TBRW, results reveal that the Da and Thao rivers strongly expect drought conditions; meanwhile, the remaining rivers are very likely to experience similar drought conditions as in the past.

Keywords: **coupled WEHY-HCM model, drought, Standardized Precipitation Index, Streamflow Drought Index.**

Classification number: **5.2**

Introduction

In the monsoon regions, though annual mean rainfall is high, the rainfall distribution is quite distinct between the seasons. The rainy season often accounts for 70-90% of the annual mean rainfall [1]. Under a changing climate, increases in surface temperature tend to accelerate evapotranspiration processes, causing greater water vapour in the air that subsequently results in more precipitable water. However, increased precipitation is mostly distributed in the wet season; meanwhile, the dry season is very likely to be drier (e.g., [2, 3]). In other words, droughts are intensifying and are causing adverse impacts on lives, water resources, agriculture, and food security.

Conventional assessments of trend and variability of droughts were mostly conducted using ground hydro-meteorological observation (e.g., [4, 5]) or combined observation and model simulations [6]. It is known that the existing ground observation networks in developing countries are quite scattered and are extremely short on record length. This situation diminishes studies of drought conditions, especially the investigation of spatial variation of droughts across transboundary river basins where data are inaccessible or are not shared among the riparian countries. As an extension of the previous work regarding the reconstruction and evaluation of changes in hydrologic conditions over a transboundary region [7], this study will further capture the trend and variability of droughts in the past climate (1950-2015). The work will be based on the simulations derived from a regional climate model coupled with a physically based hydrology model for the H-TBRW, the portion lying in the territory of Vietnam of the Red river. Some well-known drought indices are employed to detect the trend and variability of both meteorological and hydrological drought conditions. These indices are calculated for a range of time scales as addressed in the literature (e.g., [3, 5]) in order to provide a choice of index appropriate for different meteorological, agricultural and hydrological applications.

Methodology, study area, and data

Hydro-meteorological drought indicators

Droughts often cause impacts over a widespread area

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during a long period of time; these are commonly referred to as social, economic, and social impacts. It is widely accepted that droughts are defined in terms of meteorological, hydrological, agricultural, and socioeconomic conditions. However, this study considers only the first two terms, and drought indices are calculated solely based on precipitation and streamflow data as described in the following paragraphs.

Standardized Precipitation Index (SPI): precipitation and evapotranspiration are primary variables controlling the formation and persistence of drought conditions. However, it is quite difficult to estimate evapotranspiration rates, so drought climatology studies have used mostly data on precipitation. Among the available indices in the literature used to identify meteorological drought condition - for example, Palmer drought severity index [8], crop moisture index [9], and surface water supply index [10] - the standardized precipitation index (*SPI*) has been widely accepted for drought assessment studies (e.g., [11-14]). The SPI is formulated to estimate the precipitation deficit for multiple time scales, *i*, which indicate drought conditions throughout the watershed.

SPI is simply defined as the ratio of the difference of precipitation from the mean for a specified time period over the corresponding standard deviation determined from past records as expressed in equation 1 below:

$$SPI_i = \frac{P_i - \overline{P_i}}{\sigma_i} \quad (1)$$

where *SPI* is standardized precipitation index for time scale i (e.g., 1-, 3-, 6-, 12-, 24-, and 48-month time scales); P_i is precipitation for time scale i; $\overline{P}_i$ is climatological mean precipitation for time scale i; σ_i is standard deviation precipitation for time scale i.

The *SPI* is computed by fitting a probability density function to the frequency distribution of precipitation summed over the time scale of interest. *SPI* values can be greater (positive) or less (negative) than the climatological mean precipitation. Table 1 below depicts categorical *SPI* values reflecting drought classifications from extremely wet to dry conditions.

Table 1. Drought classification by *SPI* value (modified after [5]).

State	*SPI* value	Category	*SPI* value	Category
	Positive		*Negative*	
1	2.00 or more	Extreme wet	0 to -0.99	Mild drought
2	1.50 to 1.99	Severe wet	-1.00 to -1.49	Moderate drought
3	1.00 to 1.49	Moderate wet	-1.50 to -1.99	Severe drought
4	0 to 0.99	Mild wet	-2.00 or less	Extreme drought

Streamflow Drought Index (SDI): similar to *SPI*, the *SDI* was developed to explore the water resources conditions of the watershed based on the information of cumulative streamflow volumes for reference periods, as expressed in equation 2 [15]:

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \quad i = 1, 2, \ldots; j = 1, 2, \ldots 12; k = 1, 2, 3, 4 \quad (2)$$

where $V_{i,k}$ denotes the cumulative streamflow volume for the i-th hydrological year and the k-th reference period, k = 1 for October-December, k = 2 for October-March, k = 3 for October-June, and k = 4 for October-September.

Based on cumulative streamflow volumes $V_{i,k}$, the *SDI* is defined for each reference period k of the i-th hydrological year as follows:

$$SDI_{i,k} = \frac{V_{i,k} - \overline{V_k}}{\sigma_k} \quad i = 1, 2, \ldots; k = 1, 2, 3, 4 \quad (3)$$

where V_k and σ_k are the mean and the standard deviation of cumulative streamflow volumes of reference period k as these are estimated over a long period of time, respectively. By this definition, *SDI* values are also categorized into five states of hydrological conditions of the watershed as presented in Table 2.

Table 2. Drought classification by *SDI* value (modified after [15]).

State	*SPI* value	Category	*SPI* value	Category
	Positive		*Negative*	
1	Greater than zero	Non-drought	0 to -0.99	Mild drought
2			-1.00 to -1.49	Moderate drought
3			-1.50 to -1.99	Severe drought
4			-2.00 or less	Extreme drought

Study area

The Red river is categorized among the five major transboundary river systems in Southeast Asia and flows from Yunnan province in Southwest China through northern Vietnam to the Gulf of Tonkin (Fig. 1). The Red river covers a drainage area of 169,020 km^2, of which 48% is in China's territory, 51% is in Vietnam's territory, and only 1% is in Laos' territory. The H-TBRW is named for the downstream portion of the Red river basin in Vietnam. The H-TBRW covers 26 provinces and cities (including Hanoi and Hai Phong), with a total population of 30 million.

As it is located in a tropical region, the H-TBRW is strongly influenced by the tropical monsoon climate. Average annual precipitation is spatially distributed in a wide range over the river basin (from 700-2,100 mm in China to 1,200-4,800 mm in Vietnam). The rainy season is from April through October, representing 85-90% of the total annual rainfall, and the dry season is from November to April representing only 10-15% of the total annual rainfall. With regard to water availability, the river basin produces 136 km^3/year, of which 83 km^3 (61%) is generated in Vietnam's territory.

Fig. 1. Map of the Red river basin (left) and the H-TBRW comprising five main tributaries in Vietnam (right).

Precipitation and streamflow data reproducibility

Due to transboundary issues, information about precipitation and streamflow in the portions beyond the border of Vietnam is not available to the public. Attempts have been made to cover this problem through the provision of reanalysis products. One of the recent precipitation products is APHRODITE - Asian Precipitation Highly Resolved Observational Data Integration Towards the Evaluation - providing gridded daily precipitation over the Asia monsoon region from 1951 to 2015. APHRODITE has advantages for studies of water resources. However, it is worth noting that APHRODITE is a reanalysis product based on historical measurement of precipitation, so it is not able to offer some type of quantitative projection in the future. In addition, featured with 0.25-degree grid cells, APHRODITE is considered a coarse spatial resolution product that diminishes water resources studies at local scales.

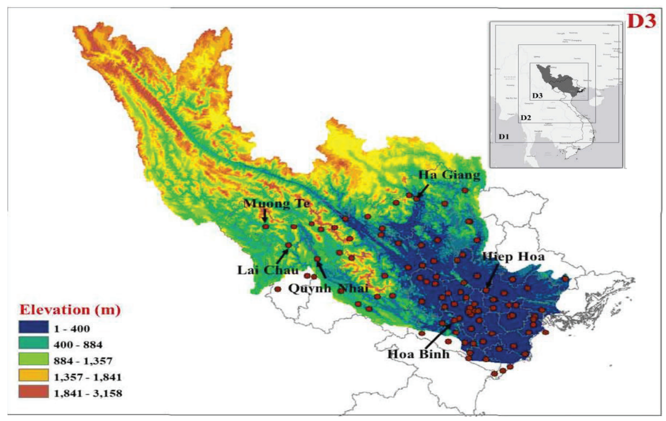

Fig. 2. Cascading computational domains of the downscaling model and location of observation sites in the H-TBRW (modified after [7]).

As a result, high spatial and temporal resolution atmospheric and streamflow data - which were already reconstructed and verified for the entire Red river basin for period 1950-2015 [7, 16] - are employed in this study to derive hydro-meteorological drought indices.

The high-resolution atmospheric and streamflow data are a dynamic downscaling product reproduced using a coupled regional hydroclimate model, or simply referred to as the WEHY-HCM [7, 16]. Atmospheric conditions were reproduced using weather research forecast (WRF) simulations. The WRF simulations were originally nested in the coarse resolution (1.25-degree) reanalysis data, ERA-20C, which were developed by the European Centre for Medium Range Weather Forecasts. These simulations were performed for a domain (D1) with a spatial resolution of 81 km. The WRF simulations were then further refined through cascading domains of 27 km (D2) and 9 km (D3), respectively, as illustrated in Fig. 2. The WRF provided simulation outputs every three hours. The simulated rainfall was then aggregated into larger temporal scales (e.g., daily or monthly time series) for model verification. Results illustrated that the simulated rainfall for the historical period 1975-2006 over the H-TBRW is comparable to the observed precipitation datasets either derived from direct point measurement or the APHRODITE product. Detailed model verification can be seen in the literature [7].

With regard to streamflow data reproducibility, the downscaled precipitation is used to drive the Watershed Environmental Hydrology Model (WEHY) for hydrologic simulations in the H-TBRW. The WEHY is a physically based hydrologic model that is developed based on actual physical processes and information from the model computational unit areas throughout the watershed domain [16]. The model was also designed for coupling regional climate models (e.g., the WRF model) through its land surface component. In addition, the model parameters are nearly calibration-free because they are estimated based on actual physical information of the catchment such as topography, soil, and land use/cover. Therefore, it illustrates advantages for the assessment of water resources in scattered observation catchments.

The WEHY model setup for the H-TBRW was realized in the literature [16]. For a short description, the entire H-TBRW was divided into computational units (or sub-basins) based on similarity in topography and land surface information. Runoff is generated from the dynamic interaction of hillslope flow and channel routing. The monthly discharges at Yen Bai station were employed for model calibration and validation. Model performance statistics exhibited agreement between the monthly simulated and observed discharges. Nash Sutcliffe Efficiency Coefficients of 0.87 and 0.86 were obtained for the model calibration and validation, respectively. Relative errors in runoff volume were less than 5%. These indicate a reasonable reproduction of the monthly discharges for the H-TBRW and useful application for further assessment of hydrologic conditions over the Red river basin.

Results and discussion

Climatological drought conditions over H-TBRW

In general, droughts last from a couple of months to a few years. This study attempts to understand climatological drought conditions corresponding to the time scales of one, three, six, nine, 12, and 24 months. The previous study [7] revealed a reasonable agreement of the reproduced monthly precipitation over the H-TBRW with the APHRODITE product. However, this study again performs the verification of *SPI* derived from the reproduced precipitation data against those determined using rain-gauge measurements. The verification is conducted on a sub-basin average basis. As illustrated in Fig. 1, the H-TBRW is delineated into five sub-catchments, namely, Da, Thao, Lo-Gam, and Upper Thai Binh sub-catchments, and the Red river delta. Available observed precipitation data during the period from 1975 to 2006 are employed for the *SPI* verification.

This study first attempted to test the *SPI* derived from the reproduced precipitation using the Nash Sutcliffe Efficiency Coefficient, which can suggest the agreement in time and severity level of drought conditions of the *SPI*. A test was conducted for the Da river sub-catchment over a period of five years (1990-1994). Results reveal that the simulated *SPI* and that obtained using observation data are quite similar, as seen in Fig. 3. Performance statistics are presented in Table 3 and reveal encouraging results. However, it is noted that similar *SPI* verification is quite challenging for the remaining sub-catchments because rainfall remains an unpredictable variable among the others simulated by the WRF model. It is understood as the uncertainties of the model structure, parameterization schemes, boundary, and initial conditions. In general, most model simulations tend to provide information about a climatological trend rather than a precise simulation of an event magnitude and the time it occurs. In addition, ground observation sites are quite scattered, leading to substantial errors for area rainfall estimates. It is noted that the calculated *SPIs* considering rainfall as a gamma distribution variable outperform those calculated considering rainfall as a normal distribution variable that tends to underestimate the drought conditions [17].

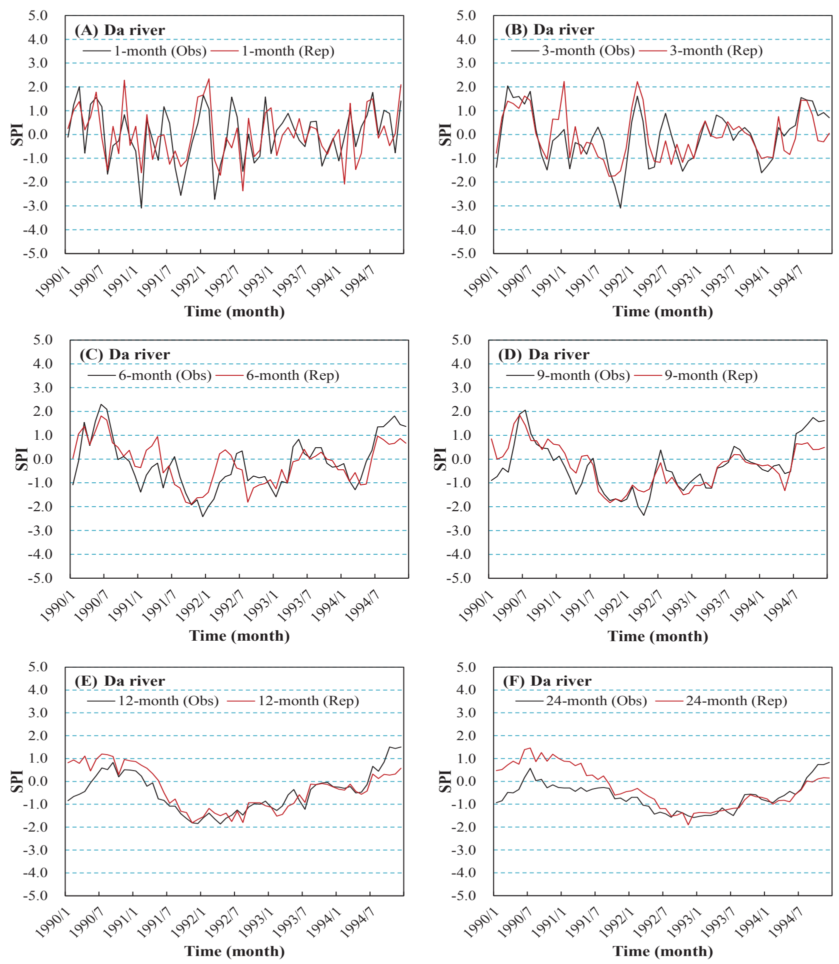

Fig. 3. Verification of SPIs for the Da river sub-catchment with different time scales: (A) 1-month; (B) 3-month; (C) 6-month; (D) 9-month; (E) 12-month; and (F) 24-month.

Table 3. Statistics of *SPI* verification for Da sub-catchment.

Sub-catchment	Nash Sutcliffe Efficiency Coefficient					
	1-month	*3-month*	*6-month*	*9-month*	*12-month*	*24-month*
Da river	0.37	0.58	0.65	0.69	0.56	NA

NA: not applicable.

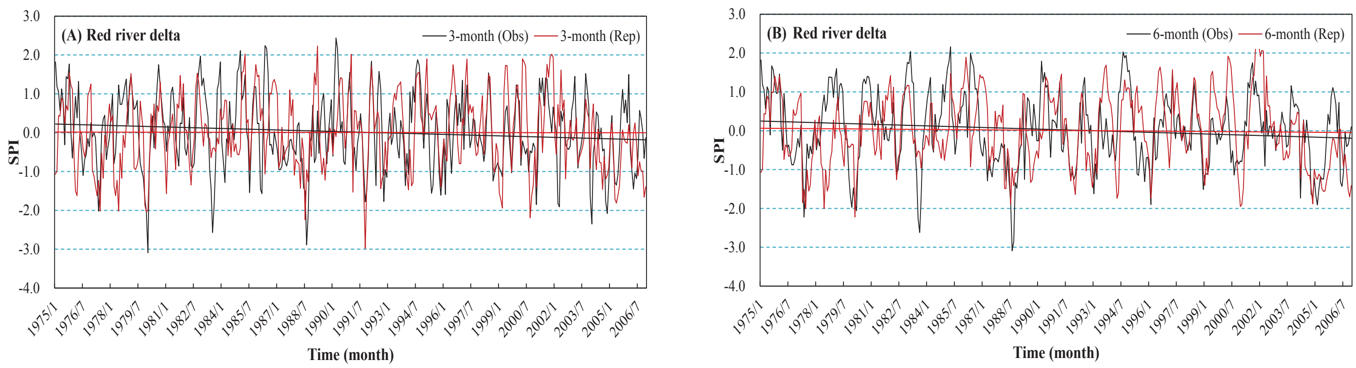

Fig. 4. Verification of *SPI* trend for the Red river delta with time scales: (A) 3-month; (B) 6-month.

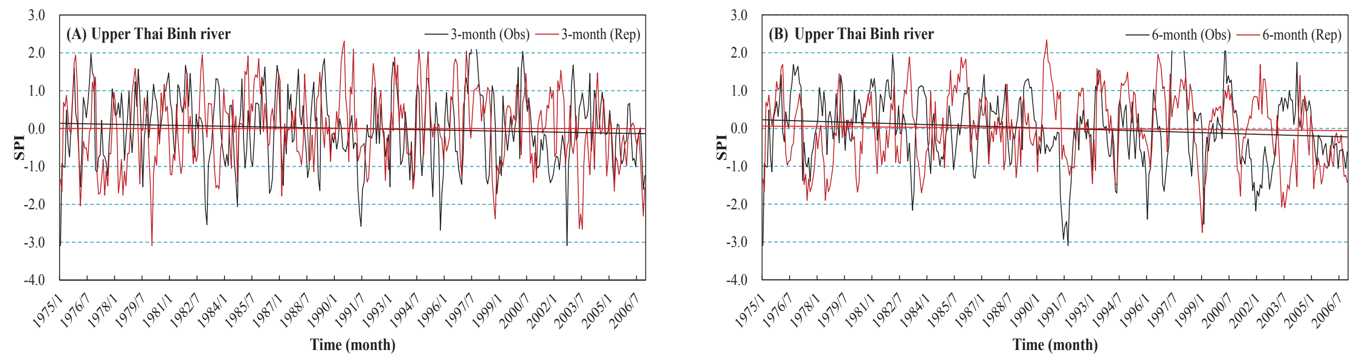

Fig. 5. Verification of *SPI* trend for the Upper Thai Binh river sub-catchment with time scales: (A) 3-month; (B) 6-month.

Table 4. Number of severe drought events simulated by model versus actual observation during 1975-2006 in Red river delta and Upper Thai Binh river sub-catchment.

Sub-catchment	1-month	3-month	6-month	9-month	12-month	24-month	Average
Red river delta							
Observation	27	20	21	19	26	14	21
Model	35	23	21	16	14	17	21
Absolute relative error (%)	30%	15%	0%	16%	46%	21%	21%
Upper Thai Binh river							
Observation	27	20	21	19	26	14	21
Model	35	23	21	16	14	17	21
Absolute relative error (%)	30%	15%	0%	16%	46%	21%	21%

Thus, the next attempts are focusing on model verification in terms of climatological drought trend and risk. For example, Figs. 4 and 5 illustrate the drought trends (time scales of three and six months) obtained from model simulation versus actual observation during 1975-2006 in the Red river delta and Upper Thai Binh sub-catchment. Results demonstrate that both modelled and observed drought trends are comparable and indicate a slight decrease in droughts. Similar results (not shown) are found for the remaining time scales. Table 4 demonstrates the risk of severe drought conditions (represented by a number of drought events that *SPI* is less than minus-1.5) in the Red river delta and Upper Thai Binh sub-catchment. These results indicate a reasonable performance of the model simulation against observation. On average, the number of severe drought events are well reproduced by the WRF model. However, the model still provides the average absolute relative errors of about 20%.

As a result, climatological drought conditions of various time scales in the H-TBRW are reproduced based on the simulated rainfall for the period 1950-2015, a sufficiently long time scale that is able to reflect the most accurate climatological condition in comparison with such studies as [18, 19], which assessed the drought conditions using shorter periods of time. Fig. 6 illustrates an example of climatological drought conditions with the time scale of six months in the H-TBRW. Results show there has been a slight increase of drought conditions in the Red river delta, Lo-Gam, and Thai Binh sub-watersheds; meanwhile, an intensified implication of drought has been observed for Da and Thao sub-watersheds. It is not revealed in this text; however, in terms of time scales, the drought conditions have been more severe with increased time scales. Table 5 presents the number of climatological severe and extreme droughts in the H-TBRW during 1950-2015. Among the five sub-watersheds, the Red river delta and Upper Thai Binh sub-watershed experienced more severe drought events; however, the Da sub-watershed has observed more extreme drought events.

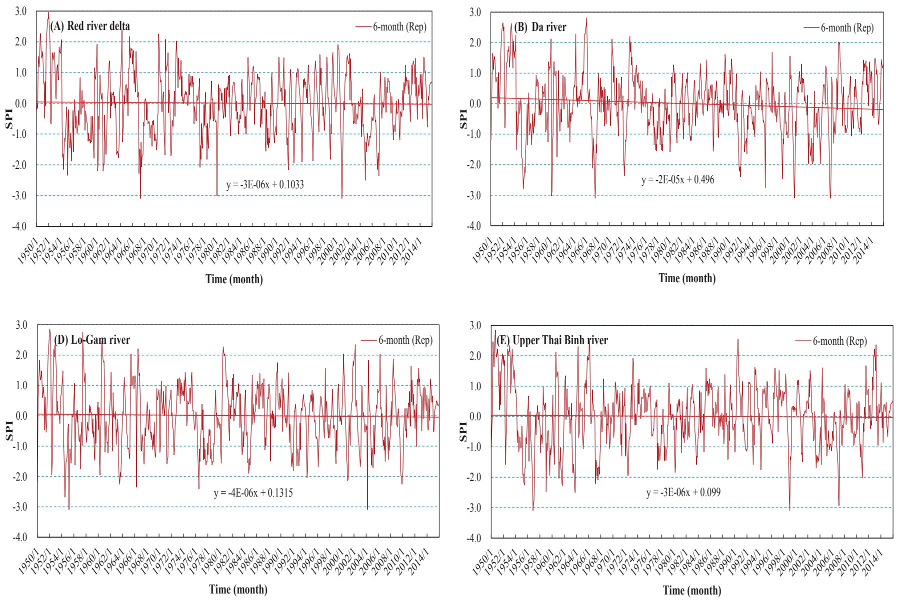

Fig. 6. Climatological drought conditions simulated by model during 1950-2015 for the H-TBRW sub-catchment: (A) Red river delta, (B) Da river, (C) Thao river, (D) Lo-Gam river, and (E) Upper Thai Binh river with the straight lines representing the trend of the drought conditions.

the drought situation in the Thao river is rather stable. The drought situations (not shown) in other rivers are also found to be similar. These trends indicate minor stress on water availability for the water-use sectors in the downstream areas. However, it is noted that the influence of reservoir operation is excluded from the streamflow simulations. Thus, the next effort of this research series will further elaborate this trend of drought as both reservoir operation and projection data are analyzed.

Table 5. Climatological severe and extreme drought events simulated by model during 1950-2015 in Red river delta and Upper Thai Binh river sub-catchment.

Sub-catchment	1-month	3-month	6-month	9-month	12-month	24-month	Average
Red river delta							
Severe drought	65	55	53	50	45	54	54
Extreme drought	30	21	15	10	8	27	19
Da river							
Severe drought	54	53	56	48	44	49	51
Extreme drought	20	29	26	25	21	19	23
Thao river							
Severe drought	57	51	50	49	48	37	49
Extreme drought	22	12	15	23	23	14	18
Lo-Gam river							
Severe drought	45	50	57	59	59	45	53
Extreme drought	18	16	13	12	9	12	13
Upper Thai Binh river							
Severe drought	74	58	56	48	47	38	54
Extreme drought	22	21	19	23	20	20	21

Hydrological drought conditions over the H-TBRW

The present study examines hydrological drought conditions based on the reproduced streamflow at various sites in the H-TBRW. The hydrological drought conditions are explored for different time periods. Within this text, Fig. 7 illustrates the hydrological drought trends over the past 65 years at the Da and Thao rivers (Hoa Binh and Yen Bai, respectively). It appears that the hydrological drought in the Da river is becoming slightly severe; meanwhile,

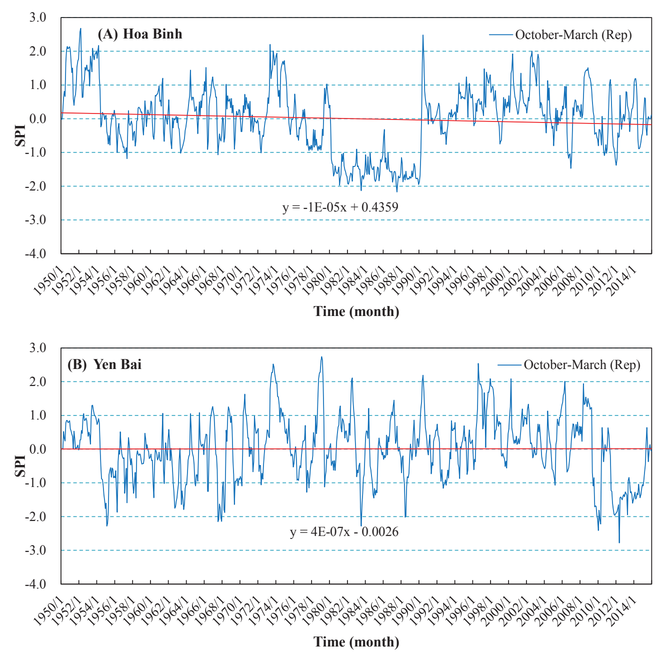

Fig. 7. Hydrological drought conditions (October-March) simulated by model during 1950-2015 for the H-TBRW sub-catchment: (A) Da river (at Hoa Binh), and (B) Thao river (at Yen Bai) representing the trend of the drought conditions.

Conclusions and remarks

Understating hydro-climatological conditions in a transboundary is always challenging because of the insufficient data availability. The present study has explored the hydro-climatological drought conditions over the H-TBRW based on the downscaled rainfall and reproduced streamflow by the state-of-the-art WEHY-HCM model. The results demonstrate a slight increase in trends of both climatological and hydrological conditions (*SPI* and *SDI*). Over the H-TBRW, the Da and Thao rivers are expecting a stronger implication of drought; meanwhile, the remaining rivers are quite likely to experience similar drought conditions as in the past.

It is also noted that there exist model intrinsic uncertainties because of imperfect model structure, parameterization schemes, boundary, and initial conditions. In general, model simulations provide reasonable climatological trends rather than a precise simulation of an event magnitude and the time it occurs. As a result, model bias correction will be still needed for further interpretation of the hydro-climatological drought conditions in such sub-catchments of the H-TBRW.

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