Evaluation of drought features in the Dakbla watershed, Central Highlands of Vietnam

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Abstract:

The drought impacts in the Dakbla watershed were assessed based on a combination of hydrological modeling and drought indices. Three drought indices, the Standardized Precipitation Index (SPI), Standardized Soil Moisture Index (SSI), and Streamflow Drought Index (SDI) were utilized to evaluate the drought features of meteo-hydrology and agriculture. The results indicated that these indices are well adapted to the local conditions, especially the 12-month time scale. Evaluations of drought features on the watershed scale could provide more specific information regarding drought risk than regional-scale/district-level assessments, because a watershed is a hydrologically fundamental unit to consider water resources management. Additionally, evaluations of drought impacts using the SSI, SPI showed longer and higher trends than those using the SPI and SDI in terms of drought duration and frequency. Considering the spatial distribution of drought frequency, the areas predominated by agricultural land in the target watershed had higher drought risk. Thus, assessment of agricultural droughts along with meteo-hydrological droughts is extremely important to support realistic local drought management strategies by considering water availability, water balance, and soil characteristics, especially in specific agricultural areas.

KEYWORDS hydrological modeling; drought indices; drought features; watershed scale assessment; agricultural activities; mountainous region

INTRODUCTION

Drought is an insidious natural phenomenon occurring when the levels of rainfall are lower than what is considered normal. If drought lasts for a long time, the environment and people’s activities in their daily life, industry, and agriculture will be affected significantly because of water scarcity. A long-lasting drought impacted Southeast Asian countries based on a precipitation deficit inherited from 2019 and an insufficient start to the monsoon season the following year (Barbosa et al., 2020). Agriculture is the sector that is most affected by droughts followed by industrial, and domestic water supply. Over the past 30 years, approximately 80% of the economic impact of drought is absorbed by agriculture in Southeast Asia (The Economic and Social Commission for Asia and the Pacific and The Association of Southeast Asian Nations: ESCAP and ASEAN, 2020). In the 2015–2016 drought events, the total rice production reached the lowest level since 2000, with a decreased value of 27 million tonnes (ESCAP and ASEAN, 2020). The food and feed demands of human beings were impacted by the prolonged droughts. With slower onset, repeated or persistent conditions of low or moderate intensity, droughts are known as extensive risks compared with other intensive risks such as earthquakes and cyclones. They are highly localized hazards and occur with a significant impact on largely dispersed populations over longer timescales (ESCAP and ASEAN, 2020). Nevertheless, the impacts of drought are different depending on the meteo-hydrological and agricultural characteristics of each region. If decision makers are unable to deal with local-scale drought impacts, this leads to the implementation of less effective drought planning policies and water resource management strategies in the future. Hence, drought is becoming a noticeable phenomenon, especially in Southeast Asian countries.

The Central Highlands of Vietnam are one of the most sensitive regions to El Niño effects, which have a tropical monsoon climate (CGIAR Research Program on Climate Change, Agriculture and Food Security-Southeast Asia: CCAFS-SEA, 2016). Rainfall in the dry season was normally only 10–15% of that of the whole year in this region (Vietnam Academy for Water Resources: VAWR, 2012). In the strong drought events such as 2004–2005, 2010, and 2015–2016 events, prolonged droughts occurred across a large area. The rainfall was 30–50% lower than the average of many years from 2000 to 2016. Thus, the area irrigated directly from irrigation projects was only 30% of the cultivated area (Directorate of Water Resources: WRD, 2016). The water volume of irrigation reservoirs in the Central Highlands fell to 10–50% of their designed capacity in early April 2016 (CCAFS-SEA, 2016). Furthermore, the rapid expansion of urbanization and agricultural activities along with drought conditions has led to severe stress on water resources. As a result, food security issues have worsened in this region, where poverty rates are high (Grosjean et al., 2016).

Utilizing observed data only, it was not possible to evalu-
ate drought features of severity, duration and lag time, and frequency on the watershed scale comprehensively because of the uneven and sparse distribution of observed stations in mountainous regions. Paired catchments, statistical analysis, and hydrological modeling are the popular approaches to assess the impacts of environmental changes on hydrological processes (Li et al., 2009). Among these approaches, hydrological modeling combined with drought indices is more appropriate to evaluate drought impacts and the relationships between different droughts. Historical drought features were analyzed based on different temporal scales which could support policymakers in the short-/middle-/long-term drought planning. Moreover, understanding the spatial distribution of drought features is very essential for sufficient water resources management in particular drought-prone areas. Droughts were assessed all over the world such as Lweendo et al. (2017), Veettil and Mishra (2020), and Bouziyne et al. (2020). In addition, some research discussed the drought impacts in the Central Highlands of Vietnam, such as the evaluation of regional meteorological droughts – the whole Central Highlands (Vu et al., 2015a); local meteo-hydrological droughts – the Dakbla watershed (Vu et al., 2015b); or agricultural drought at the district level – Gia Lai Province (Nga et al., 2019). To evaluate more detailed drought impacts on the watershed scale, a combination of modeling and drought indices is required, particularly in relation to agriculture. The overall objectives of this study are (1) to characterize meteorological (Standardized Precipitation Index: SPI), agricultural (Standardized Soil Moisture Index: SSI), and hydrological (Streamflow Drought Index: SDI) droughts on different temporal scales, and (2) to understand the distribution of historical drought features on each subbasin in the Dakbla watershed.

**MATERIALS AND METHODS**

**Study area**

The Dakbla watershed is one of the main subbasins in the upstream of the Se San River basin. Dakbla River, with an area of 3,507 km², passes through Kon Tum and Gia Lai Provinces, and is located in the Central Highlands of Vietnam (Figure 1). The dry season is from December to April and approximately 15% of the rainfall is concentrated in the dry season. Thus, a consistent lack of rainfall and discharge had some significant impacts on cultivation areas.

As for drought status in the study area, the 2015–2016 drought event was the most prolonged drought event in Vietnam in over 90 years and impacted 52 out of 63 provinces (ESCAP and ASEAN, 2020). A state of emergency was declared in Kon Tum and Gia Lai Provinces in 2015–2016 due to a drought event that presented a high level of danger. This drought event affected 228.5 km² of crops (including 56.2 km² of rice) in Gia Lai Province (Gia Lai Department of Agriculture and Rural Development: GLDARD, 2016). Additionally, 42.0 km² of crops (including 13.7 km² of rice) were destroyed in Kon Tum Province (Kon Tum General Statistics Office: KTGSO, 2016).

**Methods**

Reproduction of river discharge and estimation of soil water content

The Soil and Water Assessment Tool (SWAT) was utilized to simulate the river discharge and soil water content in the target watershed. A detailed description of the hydrological modeling is given in Text S1, and shown in Table S1.

Assessment of drought features

In order to assess drought hazards and to alleviate their impact, severity, duration and lag time, and frequency (Saeid and Faezeh, 2017) were chosen as the drought fea-

![Figure 1. Location of the Dakbla watershed](image-url)


EVALUATION OF DROUGHT FEATURES

Reproducibility of river discharge

Detailed information regarding calibrated parameters and modeling performance are described in Text S2, and shown in Table SII and Figure S1.

Temporal variation of historical drought features

Drought severity

Drought events have a tight relationship with El Niño events (Food and Agriculture Organization: FAO, 2014). Droughts that occurred in Vietnam in the El Niño years were reported in FAO (2014), CCAFS-SEA (2016), Phong and Chinh (2017), and William et al. (2019). There were severe droughts in 2004–2005, 2010, and 2014–2016, and moderate droughts in 2002–2003 and 2006–2007. Our results confirmed that, in the Dakbla watershed, the extreme drought events appeared after the impact of strong El Niño events in the same year as the events. There were nine drought events from 2001 to 2018, in which the 2004–2005, 2010, and 2014–2016 periods experienced severe droughts, while there were moderate droughts in the 2002–2003 and 2006–2007 periods, as shown in Figure 2.

The changes in drought severity in the shorter time scales were more sensitive than those in the longer time scales (McKee et al., 1993). The drought events had a clustering tendency and lasted a long time, leading to a longer duration of drought spells over the longer time scales (Zhao et al., 2014), such as the 2004–2005 and 2015–2016 drought events. In some special cases, the SPI indicated precipitation spells that were insufficient to relieve agricultural and hydrological droughts. This is reflected in the non-recovery of the SSI and SDI, such as SSI-3 and SDI-3 in the 2002–2003 period. The recovery of the SPI to above normal levels was more frequent than for the SSI and SDI (Shukla and Wood, 2008).

The correlation among three drought indices was assessed (Table I). A 12-month time scale was selected to demonstrate the drought features in the target area because of the presence of the highest correlation among the drought indices for this time scale compared to others. The R² values were 0.82 for the SPI–SSI correlation and 0.89 for the SPI–SDI correlation over the 12-month time scale. The 6-month time scale could also be used, although the correlation evaluation was lower than the 12-month time scale. The correlation among these indices over the 6-month time scale was 0.81 for the SPI–SSI correlation and 0.84 for the SPI–SDI correlation.

Drought duration and time lag

Agricultural drought had a longer duration than the other types of drought. Drought duration of each drought event during the 2001–2018 period was shown in Table SIII. The total drought months (indices ≤ –1) among drought events in this period of SPI-12, SSI-12, and SDI-12 were 32, 39, and 34 months, respectively. Agricultural drought followed the pattern of meteorological drought without a time lag, whereas there was a one-month time lag between meteorological and hydrological droughts. The correlation among these indices is shown in Table I. Besides rainfall, the length of the lag time depends on other variables, as a...
basin’s morphological conditions contribute to discharge formation (Kamali et al., 2017). Hydrological drought happened later than meteorological drought, which could be based on the buffering function of the soil layers and the groundwater system to meteorological drought (Zhao et al., 2014).

Drought frequency

The drought frequency of the three indices was calculated by the number of drought months from moderate to extreme drought (indices ≤ −1) in total dry months (indices < 0) of 18 target years as shown in Figure 3. The SSI-12 showed the highest percentage of drought months with a value of 38.2%, which was evaluated higher than by utilizing the SPI and SDI. In SPI-12 and SDI-12, the percentage of drought months occupied 37.0% and 32.6% in total dry months, respectively. It is obvious that drought impacts regarding soil moisture could not be evaluated if only the SPI and SDI were used. Thus, the use of multiple indices in drought assessment is essential to provide comprehensive support for policymakers in the development of realistic local drought policies, especially for agriculture.

Spatial distribution of historical drought features

The spatial distribution of the 12-month time scale drought frequency from 2001 to 2018 is shown in Figure 4. The drought tendency increased, following the north–south and east–west directions. The highest meteorological

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Table I. The correlation $R^2$ between SPI and SSI or SDI for the 0-, 1-, and 2-month lag periods. Bold values represent the highest correlation between SPI and SSI or SDI (3-, 6-, 12-month time scales)

| Time lag | $R^2$ of SPI and SSI | $R^2$ of SPI and SDI |
|----------|----------------------|----------------------|
|          | SPI-3 vs. SSI-3      | SPI-6 vs. SSI-6      | SPI-12 vs. SSI-12 | SPI-3 vs. SDI-3 | SPI-6 vs. SDI-6 | SPI-12 vs. SDI-12 |
| 0 months | **0.70**             | **0.81**             | **0.82**          | 0.74           | 0.84           | 0.89           |
| 1 month  | 0.48                 | 0.67                 | 0.69              | **0.76**       | **0.85**       | **0.91**       |
| 2 months | 0.11                 | 0.47                 | 0.54              | 0.35           | 0.67           | 0.70           |

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Figure 2. Drought severity for the SPI, SDI, and SSI (3-, 6-, 12-month time scales). The inward tick of each year starts from September. The years and duration of the El Niño events were referred from FAO (2014), CCAFS-SEA (2016), Phong and Chinh (2017), and William et al. (2019)
The importance of drought evaluation in agriculture in the Central Highlands of Vietnam

Droughts in the Central Highlands have been assessed in previous studies. The SPI was frequently chosen to evaluate meteorological droughts in these publications because of its simplicity, and only precipitation was used for assessment at the regional scale (Vu et al., 2015a) or district level (Nga et al., 2019). It is difficult to consider drought impacts on hydrology and agriculture when using only the SPI for developing irrigation systems and water resource management strategies, which requires using a combination of modeling and other indices such as the SSI and SDI. Vu et al. (2015b) assessed droughts in the target area, finding a tight correlation between SPI and SDI, without considering agricultural drought. In addition, although the agricultural drought impacts were also evaluated by a modeling approach in the different river basins (Dak Lak Province) of the Central Highlands by Sam et al. (2019), the relationship between drought-prone areas and agricultural land was not indicated.

A noticeable finding in this study is that the watershed-scale evaluation of drought features can provide more specific information compared to regional-scale/district-level assessments. The evaluation of drought issues within the context of a drought mitigation plan was comprehensively conducted using multiple indices. The number of months, ranging from a moderate to severe drought level, occupied between 25 and 35% of the total dry months from our evaluation of three indices, which indicated a higher risk than the result of Vu et al. (2015a) using only the SPI for regional assessment (approximately 20%).

Another important finding is that the drought frequency using the SSI was higher than when utilizing the SPI and SDI. In addition, the drought duration of the SSI was longer than that of the others and there was no time lag between the SPI and SSI. This means drought will affect agriculture significantly when meteorological drought occurs. As for the spatial distribution of the 12-month time scale drought frequency, the northeastern part of the target area was not captured well by the SPI and SDI. Additionally, the southwestern area is a more exposed, drought-prone area with predominantly agricultural land (paddy fields), leading to...
higher drought vulnerability in these areas, especially with regard to agricultural drought. Thus, the importance of agricultural drought assessment was emphasized along with meteo-hydrological drought.

**Contribution to future drought mitigation in the Central Highlands of Vietnam**

The inefficiency of irrigation systems is a significant obstacle in the Central Highlands of Vietnam. Until 2018, there were 492 irrigation units in Kon Tum Province and 344 units in Gia Lai Province. The irrigation efficiency was less than 60% and 70% of the designed irrigation capacity in Kon Tum and Gia Lai Provinces, respectively (Kon Tum Department of Agriculture and Rural Development: KTDARD, 2018; GLDARD, 2019). Combined with severe climate conditions, the low irrigation efficiency dramatically affects local agricultural production.

Short-term strategies were implemented by the local government each year to mitigate drought issues and water shortages (Kon Tum People’s Committee, 2019). There were no inter/long-term policies for drought before 2020 in this area. In 2020, the “Project on drought management in Kon Tum Province during the 2021–2030 period” was started to mitigate the impacts of prolonged droughts for agriculture, which involved building a set of tools for drought management and promoting irrigation infrastructure investment (Kon Tum People’s Committee, 2020). By using the SWAT and multiple drought indices, this study showed that different drought features can be indicated for meteo-hydrology and agriculture on the watershed scale with different temporal and spatial distributions. Thus, it is considered that this methodology can support policymakers in irrigation system planning by considering local water resource availability, and/or suggesting crop conversion strategies for local farmers in the area.

**CONCLUSIONS**

Three indices SPI, SSI, and SDI were utilized to evaluate the drought features in the Dakbla watershed. The main findings are summarized as follows:

- Extreme drought events appeared in the same year as strong El Niño events in the study area, from the result of drought severity evaluation.
- The total drought months (indices ≤ –1) in the 12-month time scale, according to the SSI, was evaluated as 39 months, which is longer than the evaluation of the SPI by 7 months and that of the SDI by 5 months.
- Agriculture is affected immediately when meteorological drought occurs due to the fact that there is no time lag between the SPI and SSI.
- The drought frequency between moderate and extreme drought levels was 38.2% in the SSI-12, which is higher than in the SPI-12 and SDI-12.
- The 12-month time scale drought frequency was spatially represented by the SSI in more detail than by the SPI and SDI, particularly for the northeastern areas. The areas with higher drought risk were found in the southwest, which is predominated by agricultural land.

Understanding the drought features of meteo-hydrology and agriculture is important in mountainous areas. Drought impacts should be considered alongside other phenomena in the context of climate changes in the future. The Dakbla watershed plays an extremely crucial role as the upstream of the Se San River basin. Assessments of the impacts of drought will enable policymakers to mitigate the adverse effects of local-scale drought and contribute to the development of regional policies.

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**SUPPLEMENTS**

Text S1. Hydrological modeling

Text S2. The calibrated parameters and modeling performance

Text S3. Limitation and recommendation

Figure S1. Simulated and observed river discharges at the Kon Tum station in the calibration period (2000–2009) and validation period (2010–2018)

Table S1. Input data information for the SWAT

Table SII. Eight sensitive parameters selected by the SUFI-2 algorithm and their ranges for the parameter value optimization. The calibrated values are used for modifying the original values in the SWAT by relative changes

Table SIII. The drought duration, minimum and maximum drought severity of drought events recorded by SPI-12, SSI-12, and SDI-12 during a 2001–2018 period (indices ≤ –1)

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