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Table of Contents

The Ngoc Linh Complex in Central Kon Tum Massif: an exposed remnant of the Early Paleozoic collisional tectonism in East Central Indochina mainland	
<i>Hai Thanh Tran, Truong Tai Nguyen, Hau Vinh Bui, Thanh Xuan Ngo, Monsup Cho, Chi Kim Ngo, Dao Anh Vu, Hiep Huu Nguyen, Binh Van Phan, Hung Quoc Nguyen.....</i>	<i>1</i>
Late Cretaceous Magmatism in the Nui Sam Area (An Giang Province, Southwestern Vietnam): Implications for the Tectono-Magmatic Evolution of the Ankroet Complex	
<i>Bui Vinh Hau, Tran Thanh Hai, Nguyen Truong Tai, Ngo Thi Kim Chi, Phan Van Binh, Vu Anh Dao, Nguyen Huu Hiep, Nguyen Quoc Hung, Ngo Xuan Thanh</i>	<i>10</i>
U–Pb zircon geochronology of meta-diorite in the Vit Thu Lu area, northern Quang Tri, central Vietnam	
<i>Dinh Trong Tuong, Nguyen Quoc Hung, Tran My Dung, Ha Tri Dung, Dang My Cung, Ngo Xuan Thanh</i>	<i>16</i>
Post-collisional extension during the Early Paleozoic in Northeast Vietnam: Evidence from syenitic complex	
<i>Chu Van Dung, Tran My Dung, Ngo Xuan Thanh</i>	<i>23</i>
Zircon U–Pb constraints on episodic magmatism of the Hai Van granitoid complex and implications for the Indosinian orogeny in central Vietnam	
<i>Dinh Trong Tuong, Ngo Xuan Thanh, Tran My Dung Ha Tri Dung</i>	<i>34</i>
Controlling factors on mineralization in the Tram Tau felsic volcanic formation (Tu Le Basin, North Vietnam)	
<i>Tran Thi Huong, Nguyen Hoang, Tran Thanh Hai</i>	<i>42</i>
Distribution and Metamorphic Evolution of REE-bearing Minerals in Metapelitic Rocks of the Nam Co Formation, Song Ma Suture Zone, NW Vietnam	
<i>Bui Vinh Hau</i>	<i>56</i>
Technology for rare earth ore beneficiation in Vietnam	
<i>Thanh Hai Pham.....</i>	<i>63</i>
Structural and tectonic controls on gold mineralization in the northern Kon Tum massif, Vietnam	
<i>Vu Tien Thanh, Nguyen Van Vuong, Luong Thi Thu Hoai</i>	<i>73</i>
Potential for Marine Ion-Adsorption Rare Earth Deposits: Sedimentary Facies Controls in Southwestern Vietnam	
<i>Nguyen Huu Hiep, Phan Van Binh, Tran Thanh Hai, Bui Hoang Bac Bui Vinh Hau, To Xuan Ban, Vu Anh Dao, Vu Thai Linh.....</i>	<i>85</i>
Fluvial geomorphology and weathering crust controls on ion-adsorption rare earth element mineralization in Northwestern Vietnam	
<i>Vu Anh Dao, Dinh Thi Hue.....</i>	<i>93</i>
Tectonic – Geomorphology and its relation to geo-hazards in the Southwest region of Vietnam	
<i>Nguyen Xuan Nam, Tran Thanh Hai, Ngo Thi Kim Chi, Hoang Ngo Tu Do, Vu Anh Dao, Nguyen Xuan Quang.....</i>	<i>100</i>
Grain-size and mineralogical characteristics of surface sediments in the Con Co Island area and their environmental significance	

<i>Phan Van Binh, Hoang Van Long, Le Anh Thang, Vu Anh Dao, Nguyen Huu Hiep, Nguyen Quoc Hung, Bui Vinh Hau, Vo Thi Cong Chinh, Nguyen Thi My Hanh</i>	108
Shoreline change assessment on Phu Quoc Island using Satellite Remote Sensing and the Digital Shoreline Analysis System (DSAS)	
<i>Ngo Thi Kim Chi, Tran Thanh Hai, Bui Minh Quan, Bui Vinh Hau, Phan Van Binh, Vu Anh Dao, Nguyen Xuan Quang</i>	117
Geological characteristics of karst and their relationship to underground karst collapse in Quang Ninh province	
<i>Nguyen Xuan Nam, Nguyen Dinh Tuan, Doan Thi Ngoc Huyen</i>	124
Retaining Structures Using Gabion System: Case Examples to be Applied Further in Mining Engineering Projects	
<i>Phan Van Binh, Vu Anh Dao, Bui Vinh Hau, Nguyen Xuan Nam, Vo Thi Cong Chinh, Nguyen Thi Minh Thu</i>	138
Geological hazards at the main dam of Dap Troi reservoir, Ninh Binh Province, Vietnam	
<i>Ban To Xuan</i>	150
The erosion and accretion at Day River mouth, Vietnam	
<i>Ban To Xuan</i>	161
Spatio-temporal variation of agricultural drought based on SMAPI evaluation toward supporting water resources management in the Red River Basin	
<i>Nguyen Hoang Hiep, Nguyen Lan Huong, Tran Thi Phuong Linh, Vu Anh Dao</i>	179
Landslide hotspot identification by instance-based learning: A comparison of k-nearest neighbour and the entropy-based distance algorithm (Kstar)	
<i>Minh Nhut Dao, Quoc Phi Nguyen, Duong Van Hoa</i>	188
Performance of stochastic inversion approaches of groundwater flow and heat transport modeling in parameter estimation	
<i>Doan Thi Thanh Thuy, Nguyen Hoang Hiep, Nguyen Bach Thao, Vu Thu Hien</i>	203
Environmental Issues of Rare Earth and Critical Mineral Mining in Vietnam	
<i>Quoc Phi Nguyen, Thi Mai Hoa Phan, Thi Cuc Nguyen, Quang Minh Nguyen, Van Binh Nguyen, Trung Thanh Dao, Minh Nhut Dao, Ha Tuan Anh, Khanh Phuong Mai</i>	210
Application of the remote sensing ecological index (RSEI) to assess ecological quality in Coal mining areas of Quang Ninh province, Viet Nam	
<i>Nguyen Thi Cuc, Phan Thi Mai Hoa, Nguyen Anh Hoa, Nguyen Van Bin</i>	219
Environmental vulnerability assessment for sustainable mining using GIS based AHP - VIKOR approach: A Case Study of Ha Quang, Cao Bang District, Vietnam	
<i>Phan Thi Mai Hoa, Nguyen Quoc Phi, Nguyen Thi Cuc</i>	230
Assessment of Hydrodynamic Changes Induced by Dredging and Sand Mining in Tra Ly Estuary for Sustainable Resource Management	
<i>Vu Thi Lan Anh, Nguyen Thi Hoa, Nguyen Thi Hong, Tran Thi Ngoc, Vu Van Ngoc, Nguyen Cham Anh, Nguyen Thi Thuy Hien, Phan Thi Mai Hoa</i>	246

Spatio-temporal variation of agricultural drought based on SMAPI evaluation toward supporting water resources management in the Red River Basin

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ABSTRACT

This study investigated the drought situation in the Red River Basin (RRB) using the Soil Moisture Anomaly Percentage Index (SMAPI), which is derived from soil moisture content, one of the outputs of the VIC (Variable Infiltration Capacity) hydrological model. Throughout the 10-year evaluation (2005-2014), the soil moisture content in the Red River Delta (RRD) remains relatively stable and is higher than in other regions in RRB. However, the spatial-temporal variation of the SMAPI drought index indicates that a greater number of areas in the Northeast experienced severe drought compared to those in the Northwest and the RRD, particularly during the dry season. Conversely, the Northwest primarily exhibited dry and mildly wet conditions.

Keywords: SMAPI, soil moisture, Variable Infiltration Capacity, Red River Basin

1. Introduction

Drought in Vietnam is a phenomenon that requires attention and monitoring due to the escalating effects of climate change. Drought has caused substantial effects on minor water sources and the operation of hydropower plants, which are among the primary energy sources in our country today. Continuous and precise monitoring, evaluation, and forecasting of drought are urgent and essential activities that contribute to the establishment of a database system for the management of water resources, irrigation, and agricultural production. The Red River Delta region, characterized by its extensive delta formation, exhibits a substantial water demand. In 2010, statistics from the provinces and cities in the Red River Delta region indicated that the total water demand for the area was 12.1 billion m³. The agricultural sector received the largest share, constituting 71.8% of the total demand, while urban water supply accounted for 5.7%, industry for 5.1%, and the service, tourism, and transport sectors collectively for approximately 9%. Since 2003, the Red River Basin has experienced persistent large-scale drought, resulting in significant degradation of water resources, while the demand for water for domestic, agricultural, and industrial purposes continues to rise. Given the escalating and detrimental effects of climate change and drought on economic and social activities, conducting research, assessments, and forecasts to deliver early warnings and implement drought prevention strategies is an urgent imperative, yielding direct advantages for societal well-being. The utilization of sophisticated instruments such as modeling, satellite remote sensing, and Geographic Information Systems (GIS) can yield numerous advantages and address the constraints in spatial and temporal scope inherent in conventional monitoring techniques, particularly in drought assessment and forecasting, as well as in water resource management

overall (Hiep et al., 2018, 2023; Huong et al., 2023; Luong et al., 2021a, 2021b).

Despite numerous global studies utilizing drought indices associated with soil moisture, research in this domain concerning Vietnamese river basins remains significantly constrained. A significant impediment to research on drought indices associated with soil moisture in Vietnamese river basins is the absence of a soil moisture parameter monitoring network (Luong et al., 2021a). Recent studies have utilized remote sensing satellite imagery and modeling tools to evaluate drought conditions in various river basins in Vietnam (Tran et al., 2017, 2019). Specifically, Vu et al., (2013) employed the TDVI temperature drought index derived from MODIS imagery to evaluate drought conditions in the Red River Delta from 2000 to 2012. Nevertheless, MODIS satellite imagery was exclusively acquired during a specific timeframe in February each year, thereby precluding the analysis of agricultural drought evolution over time in the Red River Delta. This study assesses the distribution and evolution of soil moisture parameters and the SMAPI agricultural drought index in the Red River Basin utilizing the Variable Infiltration Capacity (VIC) model. This study employs the SMAPI agricultural drought index, which has been extensively utilized to evaluate drought conditions in river basins globally. This study analysis the variation of SMAPI on the spatial distribution and temporal of the Red River Basin.

2. Material and methods

2.1. Study area

The Red River Basin encompasses an area of approximately 169000 km², with 50.3% situated in Vietnam, 48.8% in China, and 0.9% in Laos. The Red River Basin is located in northern Vietnam, with geographical coordinates of 20°00' to 21°80' North latitude and 105°30' to 107°00' East longitude. The topography of the Red River Basin inclines from northwest to southeast. Mountainous terrain predominates in the eastern and northern upper regions, gradually diminishing towards the east. The river traverses in a northwest-southeast direction at an average elevation of 1090 m (**Figure 1a**). The mountainous region along the Vietnam-Laos border features numerous peaks exceeding 1800 meters.

2.2. Hydrological modeling

The VIC model is a macroscale and semidistributed hydrological model that works on a grid cell system (Liang et al., 1994; Liang et al., 1996). It can solve equations for the balance of water and energy to figure out several hydrological parameters such as runoff, soil moisture, infiltration, and evapotranspiration at each grid cell following the time interval simulation. Another word, the VIC model needs four main types of information to work well: (1) topography, (2) meteorological forcing data (e.g., precipitation, maximum and minimum air temperature, and wind speed), (3) land cover and land use data, and (4) soil properties.

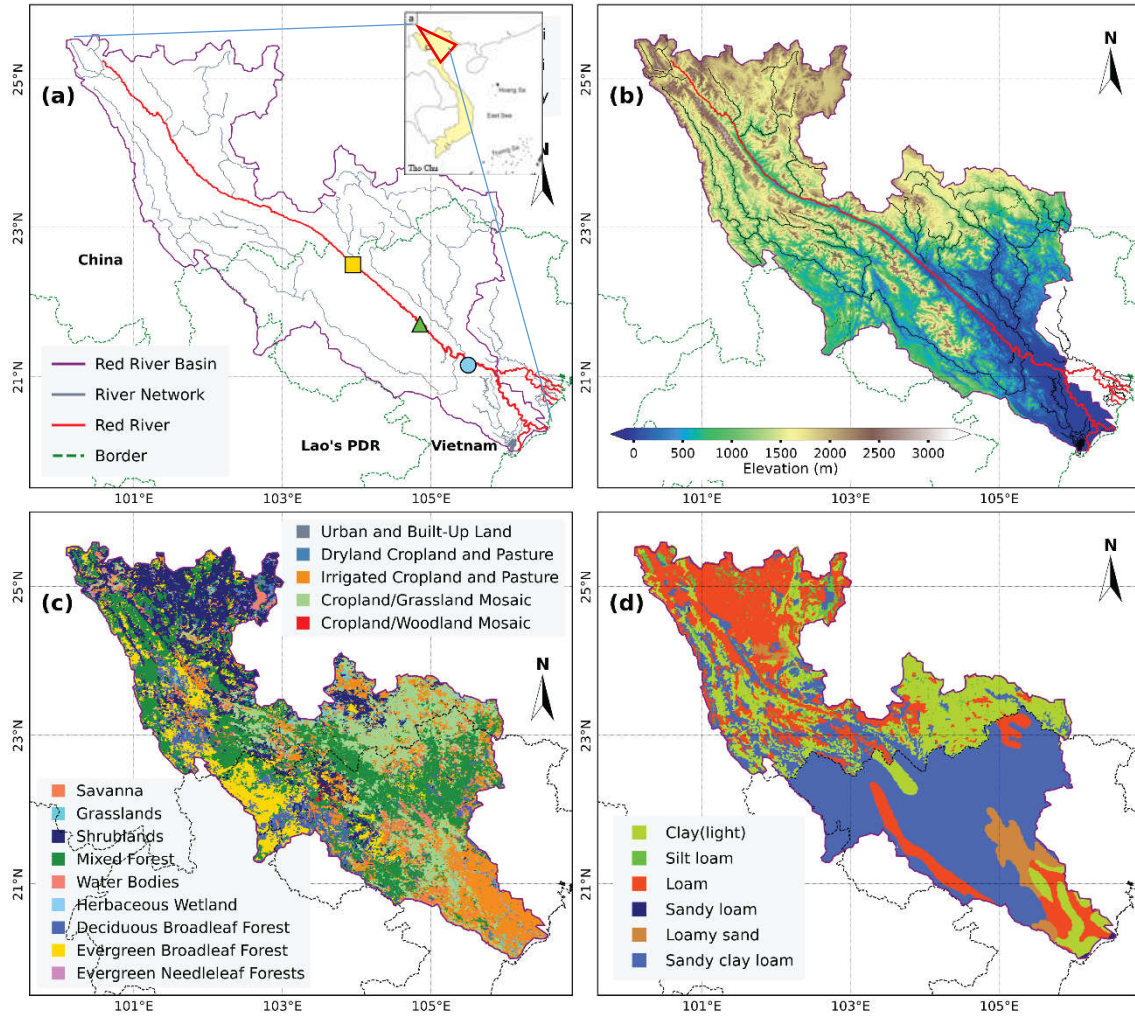


Figure 1. (a) Study map area and river network of the Red River Basin, (b) Map of elevation with main river, (c) Land cover properties, and (d) Soil types.

2.3. Datasets

This study used topographical, meteorological, land cover and vegetation, and soil type data from various sources to feed the VIC model for the RRB.

This study created a 90m-resolution Digital Elevation Model (DEM) for the RRB using NASA's Shuttle Radar Topographic Mission (SRTM) data. Figure 1b shows that the DEM estimated RRB's elevation as 71 to 3269 m above sea level. ArcGIS generated the RRB river network (Figure 1a) from the SRTM DEM. The meteorological data, including rainfall, air temperature, and wind speed, were collected US NCEI (<https://gis.ncdc.noaa.gov/maps/>) from 2005-2014. Land cover properties were obtained from the USGS as shown in Figure 1c. The VIC model relies on vegetation data (LAI data) from NASA's Terra satellite's MODIS (Moderate Resolution Imaging Spectroradiometer) with a spatial resolution of 0.1°. ArcGIS software and Extraction by Mask tool were used to create the RRB mask with 0.1-degree spatial resolution for LAI data processing. LAI data from raster images was extracted to feed vegetation libraries and parameter files, which the VIC hydrological model needs. Finally, this study used the FAO soil type database (<http://www.fao.org/>) as shown in Figure 1d. This study will calibrate its model using soil type database key parameters including $b_{infiltration}$, D_s , D_{s_max} , and W_s (Liang et al., 1994). Our prior research (Hiep et al., 2018; Huong et al., 2023) meticulously delineated the appropriate parameters of the VIC model to assess the goodness of

fit between estimated and observed streamflows. This study utilized the VIC model's simulation outputs to extract a simulated soil moisture dataset for the 10-year period from 2005 to 2014, which was employed to calculate SMAPI over the RRB.

2.4. Soil Moisture Anomaly Percentage Index (SMAPI)

The standard precipitation index (SPI) and Palmer drought severity index (PDSI) have been used in many studies to measure drought severity. According to Zhai et al., (2010), decreased precipitation and other water balance factors caused basin-scale droughts. In agriculture, soil moisture is more important than precipitation because it affects crop growth at different stages (Narasimhan and Srinivasan, 2005). Four indices are commonly used to study agricultural drought: SMI, CDI, CMI, and SMAPI. The CDI is estimated from satellite-based measurements of crop ecological and physiological responses to drought over a short time, while the SMI measures soil relative dryness as a percentage of field capacity. The SMI and CDI are better for drought analysis in small areas with specific soils and crops. The CMI is the sum of evapotranspiration deficit and soil demand, a byproduct of PDSI, assuming that land use, land cover, and vegetation are evenly distributed across the climatic zone, which may not reflect the studied region's conditions. The SMAPI, developed for regional agricultural drought characterization (Wu et al., 2011), is better for this study. SMAPI definition:

$$\text{SMAPI} = (\text{SoilMois} - \text{SoilMois}^*) \times (\text{SoilMois}^*)^{-1}$$

Where, SoilMois and SoilMois* represent the current simulated daily soil moisture and mean soil moisture of the study period, respectively, using the standard VIC mode diagnostic of evapotranspiration.

The classification of SMAPI values was made following the approach by Luong et al., (2021), including the codes to represent different drought/wet levels as SMAPI values range from -0.5 to +0.5 following the high and low risk drought, respectively.

3. Results and discussion

3.1 Variation of SMAPI in monthly

The monthly distribution of the Soil Moisture Anomaly Percentage Index (SMAPI) across the Red River Basin demonstrates a pronounced seasonal cycle associated with regional monsoon dynamics and topographic variability. During the dry-season months (November in the previous year to March next year), negative SMAPI values dominate the Northern and Northwestern mountainous regions, indicating persistent soil moisture deficits, while localized positive anomalies are observed in the southeastern deltaic areas, suggesting relatively wetter-than-normal conditions likely influenced by lowland hydrological retention and irrigation activities.

A gradual transition toward near-normal soil moisture conditions emerges during May - September, particularly across the central basin, reflecting the onset of pre-monsoon rainfall and increasing soil moisture recharge in the wet season. Peak wet-season conditions occur from July to August, when positive anomalies expand across much of the basin, especially in central and western regions, corresponding to intensified monsoon precipitation and enhanced infiltration processes. In the late transitional season (April and October), spatial heterogeneity increases, with renewed negative anomalies in the northern uplands and persistent positive anomalies in the southeastern delta region, indicating differential moisture retention related to

elevation and drainage characteristics. Overall, the observed SMAPI patterns highlight strong seasonal and spatial controls on soil moisture variability, emphasizing the influence of monsoonal rainfall regimes, basin topography, and downstream hydraulic buffering on hydrological conditions within the basin.

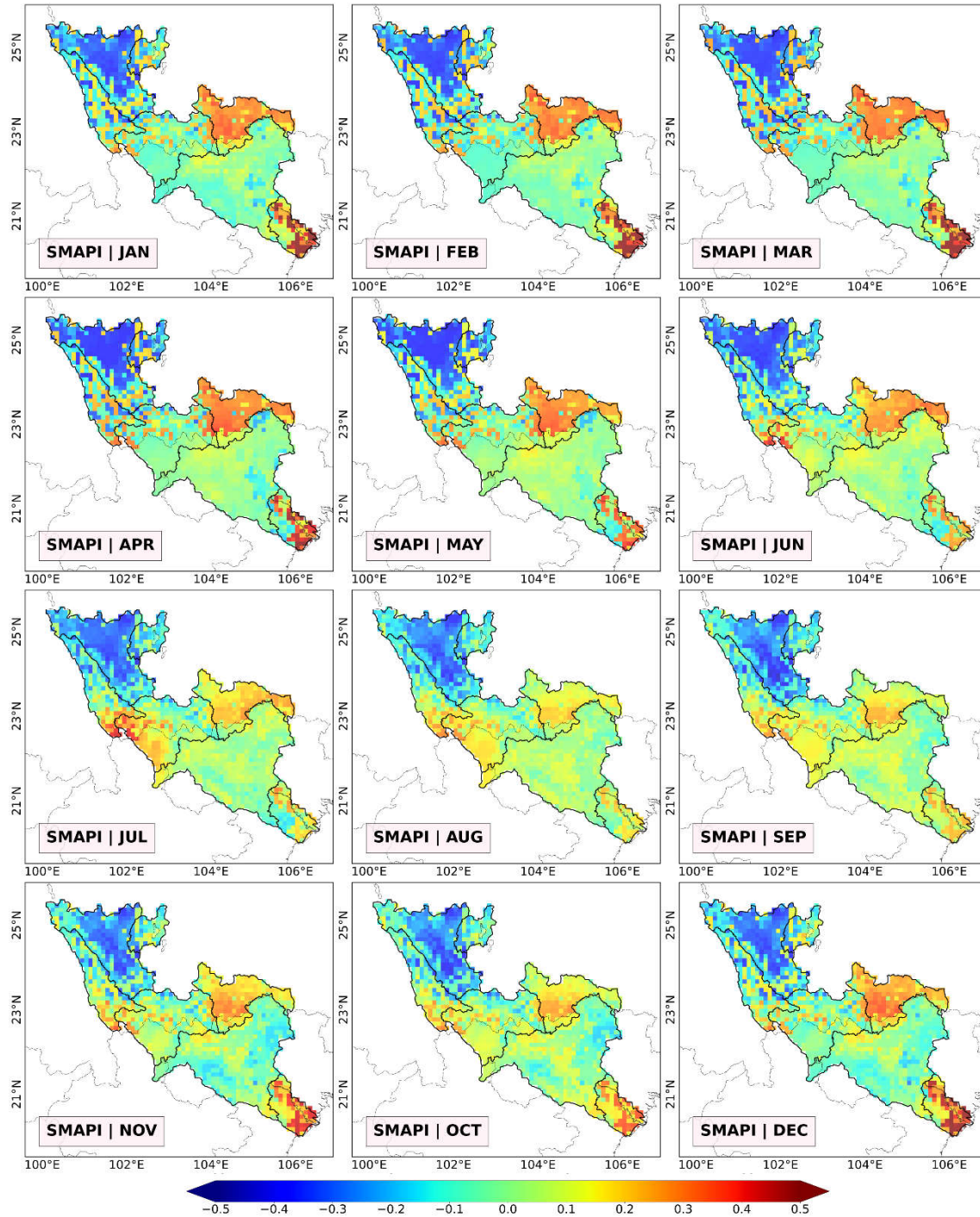


Figure 2. Spatio-temporal variation of SMAPI in monthly of the Red River Basin.

3.2. Variation of SMAPI in seasonal

In previous sections, the spatial and temporal variation of SMAPI was examined following the monthly interval. Herein, we deeply analysis of SMAPI fluctuation in seasons following the hydrodynamics is strongly affected by the monsoon area, including three seasons: dry season (from November last year to March next year), wet season (from May to September), and transitional seasons (April and October) (Luong et al., 2021).

During the dry season (DRY), widespread negative SMAPI values are prevalent in the northern and northwestern mountainous regions, indicating ongoing soil moisture deficits. On the other hand, the southeastern deltaic areas exhibit moderate positive anomalies, indicating a localized retention of moisture due to lowland hydrological conditions. During the wet season (WET), near-normal to positive SMAPI values rise significantly across the central and southern basin. It should be explained that high-rate soil moisture due to increased rainfall by typhoon or tropical storm, and infiltrates directly to soil. However, localized negative anomalies remain in certain parts of the northern highlands, indicating a slower recovery of moisture in elevated terrain. In the transition season (TRA), intermediate moisture conditions dominate much of the basin, with a mix of positive and negative anomalies indicating gradual shifts between dry and wet hydrological regimes. The southeastern delta consistently exhibits higher positive anomalies across all seasons, underscoring its role as a moisture-retentive zone influenced by low elevation and dense river networks. Overall, the seasonal SMAPI patterns illustrate a strong hydroclimatic influence on soil moisture variability, highlighting the combined effects of monsoonal precipitation, terrain elevation, and downstream hydraulic storage on soil moisture dynamics at the basin scale (Hiep et al., 2023, Luong et al., 2021).

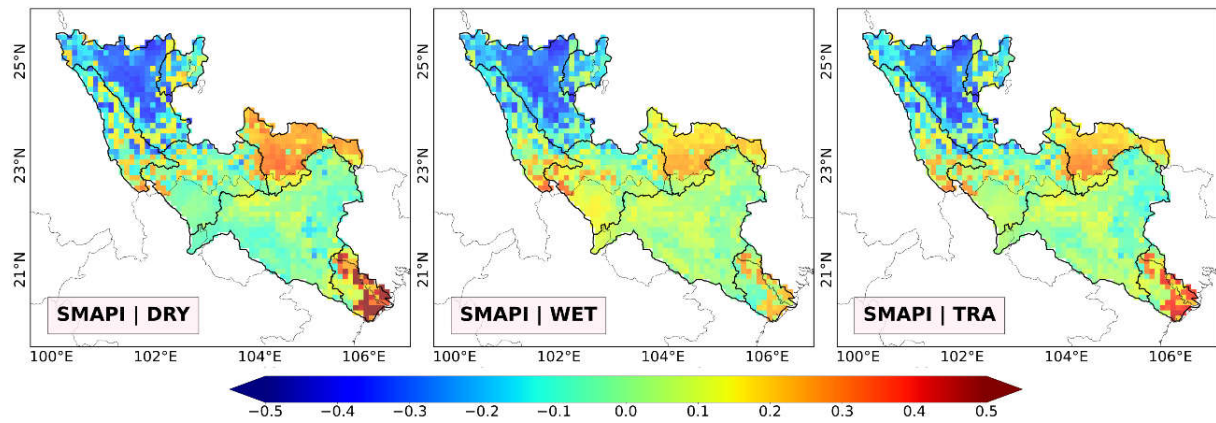


Figure 3. Spatio-temporal variation of SMAPI in monthly of the Red River Basin.

3.3. Variation of SMAPI in yearly

Figure 4 presents a comprehensive, high-resolution spatio-temporal analysis of the SMAPI across the RRB during the period from 2005 to 2014. Throughout the entire 10-year observation windows, the northwestern quadrant of the delineated region is consistently dominated by pronounced negative SMAPI anomalies, with values frequently plunging into the range of -0.3 to -0.5 . It should be explained that this area is a high-potential drought area because this is a highland and high mountain with limited annual precipitation. In stark contrast, the eastern region, especially the extreme southeastern extensions of the study domain, exhibit a remarkably resilient pattern of positive SMAPI anomalies, with index values routinely exceeding the $+0.3$ threshold and frequently peaking near the maximum observable scale limit of $+0.5$, which is denoted by concentrated extremely wet conditions.

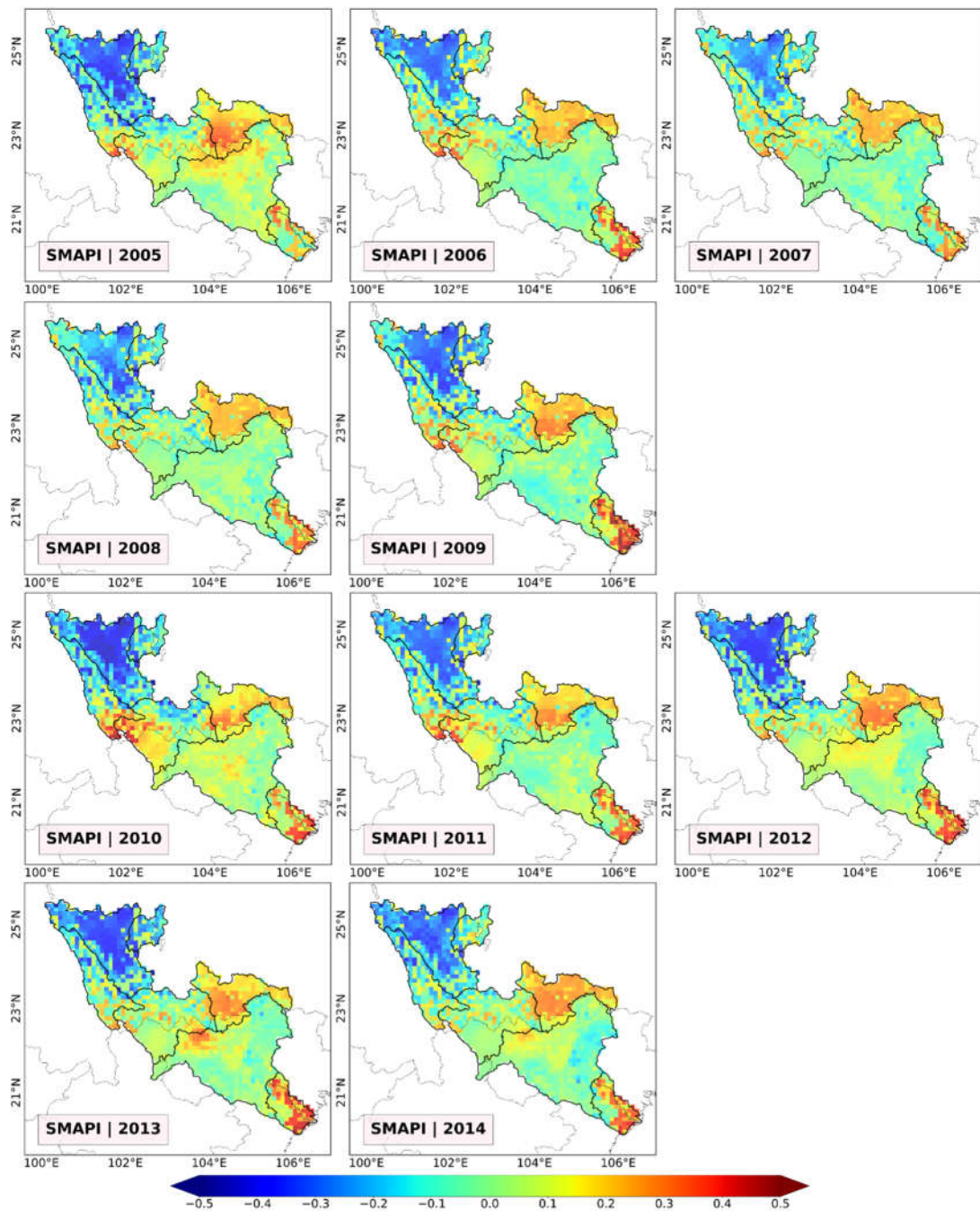


Figure 4. Spatio-temporal variation of SMAPI in yearly of the Red River Basin.

Specifically, The RRD region demonstrates the highest soil moisture levels due to its significant annual precipitation and water transfer from upstream to downstream. The drought conditions decreased significantly after 2009, achieving a peak SMAPI value of 0.5. This improvement is attributed to the enhanced system and flood management facilitated by dams and reservoirs, which have greatly benefited the RRD region.

4. Conclusion

This research utilized the Variable Infiltration Capacity (VIC) hydrological model to simulate soil moisture in the Red River Delta at a resolution of $0.1^\circ \times 0.1^\circ$ from 2005 to 2014. Soil moisture parameters were utilized to compute the SMAP drought index, facilitating the evaluation of drought severity and progression across various regions of the Red River Basin for resource management purposes. Drought maps for various months in the Red River Basin

were generated utilizing a Geographic Information System (GIS) to facilitate the visual evaluation of drought severity and its temporal and spatial progression from 2005 to 2014.

The analysis of spatio-temporal variations in the SMAPI drought index, utilizing soil moisture parameters, indicates that numerous areas in the Northeast region endure more severe drought conditions compared to the Northwest and Red River Delta regions, particularly during the dry season and transitional months. Simultaneously, the Northwest region predominantly encounters moderate drought and mild humidity. In contrast to the Northeast and Northwest regions, the majority of the Red River Delta experiences moderate to highly humid conditions year-round, particularly during the dry season.

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