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Research Article

Mapping hydrological drought under the CMIP6 climate change scenarios in sub-basin scale: A case study in the upper part of Dong Nai river basin

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Abstract: Hydrological droughts have become more severe due to the compounded effects of climate change and anthropogenic activities. This study aims to assess how climate change could impact hydrological droughts at the sub-basin scale for the Upper Part of Dong Nai (UPDN) river basin. The study used the Soil and Water Assessment Tool (SWAT) to simulate hydrological conditions based on climate change scenarios of SSP2-4.5 and SSP5-8.5 from the CMIP6 projections for the future period of 2030s (2021-2040) and 2050s (2041-2060). The streamflow drought index (SDI) was applied to evaluate the drought severity and frequency. The findings indicate a clear increasing trend in minimum (Tmin) and maximum temperatures (Tmax) relative to yearly rainfall. Under the SSP2-4.5 scenario, yearly rainfall shows a slight increase. However, under the SSP5-8.5 scenario, annual rainfall has a slight increase in the West-Southwest and a decrease in the East-Southeast regions. Rainfall trends show a decrease in the dry season and an increase in the rainy season. The frequency and severity of hydrological droughts can vary between sub-basins. Da Tam, Don Duong, Da Quyn, Da Dang, Dak Nong, Dong Nai 2, and Dak R'Keh are the sub-basins that have more extreme drought conditions compared to the rest of the basins. These results emphasize the need for targeted drought management strategies in the UPDN river basin to build resilience against future climate impacts.

Keywords: Climate change; Mapping hydrological drought; SWAT model; CMIP6; The upper part of Dong Nai river basin; Drought management.

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1. Introduction

Hydrological droughts, characterized by reduced water availability in rivers, lakes, and reservoirs, pose significant challenges to water resource management. These droughts are not merely the result of short-term weather anomalies but are often linked to broader climatic patterns and long-term changes in rainfall and temperature [1, 2]. Climate change scenarios suggest that many regions, including Southeast Asia, are likely to experience more severe drought conditions due to shifts in precipitation patterns and rising temperatures [3]. In addition, drought patterns are also driven by seasonal fluctuations in precipitation, temperature, and other hydro-meteorological conditions [4]. Along with climate change, human-driven activities such as the construction and operation of reservoirs have significantly altered flow patterns [5]. These modifications in flow impact drought conditions by changing the timing and distribution of water availability, thereby exacerbating drought severity and frequency [6, 7].

According to the IPCC, climate change has caused varying increases and decreases in rainfall at high and low latitudes of the Earth [8], and these shifts in precipitation have altered drought conditions. Global climate change scenarios for the future are often based on estimates from General Circulation Models (GCMs). GCMs have relatively coarse resolutions, most of which are around 100km or more [9]. Therefore, it is necessary to suitable downscaling techniques to be able to forecast climate change at the local or regional scale. Up to now, IPCC has six times of accessing and updating climate change scenarios and the most recent was the sixth assessment report (AR6) [10]. Therein, the Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model benchmarking project was used to support the IPCC's AR6 [11]. Compared to the fifth assessment report (AR5) known as Representative Concentration Pathways (RCPs), the AR6 was built based on the Shared Socio-economic Pathways (SSP) approach with 5 main scenarios including SSP1, SSP2, SSP3, SSP4, and SSP5 with respectively name: (i) "Green growth", (ii) "Middle-of-the-road", (iii) "Regional rivalry", (iv) "Inequality" or "A road divided", and (v) "Fossil fuel-based development" [12]. These scenarios are crucial for understanding how different climate futures might influence regional hydrological patterns. In the context of the UPDN river basin, applying CMIP6 scenarios allows for a more precise prediction of hydrological drought risks, offering insights into the spatial and temporal variability of drought across sub-basins.

The upper part of Dong Nai (UPDN) river basin plays a crucial role in the ecological and socio-economic sustainability for the whole Dong Nai river basin. It supports diverse ecosystems, including protected forests and biodiversity hotspots like Cat Tien National Park. The river's natural flow sustains wetlands, fisheries, and agriculture, and maintains the region's ecological balance. Additionally, the UPDN river basin is essential for water supply, energy production, and agriculture. It provides water to millions of people, especially in downstream areas such as Ho Chi Minh City. The basin also hosts major hydropower plants, such as the Dong Nai hydropower system (2, 3, 4, 5), which supplies a significant portion of the region's energy needs. However, rapid urbanization, deforestation, and agricultural activities have placed increasing pressure on water resources and ecosystems. These challenges, combined with climate change, have made the basin more vulnerable to extreme events such as droughts and floods, threatening both its ecological integrity and socio-economic sustainability. Previous studies have primarily focused on basin-wide assessments [13–16], often overlooking the drought impacts for sub-basin. Mapping hydrological drought at the sub-basin scale is crucial for identifying areas most at risk and implementing effective mitigation strategies. Therefore, understanding the impacts of climate change on droughts, especially hydrological droughts following the spatial and temporal aspects at the sub-basin scale, in the UPDN river basin is essential for effective adaptation and mitigation strategies.

This study aims to map hydrological drought across the sub-basins of the UPDN river basin under the CMIP6 climate scenarios SSP2-4.5 and SSP5-8. The comprehensive analysis has been employed by integrating GIS, remote sensing (RS), and the Soil and Water Assessment Tool (SWAT) model, which has been widely used for climate change impacts on hydrology and droughts [4, 13, 14, 17, 18]. In addition, the frequency and intensity of drought events has also analyzed following temporal and spatial distribution in the sub-basin scale. The findings could offer valuable insights for regional water resource management, particularly in planning for drought resilience and adaptation under the conditions of ongoing climate change.

2. Materials and Methods

2.1. Study area

The Dong Nai river basin, the longest inland river in southeastern Vietnam, extends over 586 km and encompasses a catchment area of approximately 36,530 km², spanning across ten provinces and Ho Chi Minh City. This region is a significant economic hub, accounting for approximately 48% of Vietnam's gross domestic product in 2022 [19]. The basin has over 200 irrigations and hydropower reservoirs, regulating nearly 6 billion cubic meters of water. It also has a hydropower capacity of around 3,000 MW. The forest cover rate of the whole basin is about 28%, but it is mainly located upstream in the provinces of the Central Highlands. Hence, this study focuses on the UPDN basin, which spans an area of 11,036 km², with 70% situated in Lam Dong province compared to 30% of the rests of Dak Nong, Binh Phuoc, Dong Nai, and Binh Thuan provinces [20]. The characteristics of the UPDN river basin and its 18 sub-basins are detailed in Table 1 and Figure 1.

Table 1. Properties of the UPDN river basin's sub-basins.

No.	ID	Sub-basin	Main reservoir	Sub-basin mean elevation (m)	Land use (the largest area % first)	IYRES	CHP (MW)	RES_EVOL $(10^4 m^{4-})$	Area (km²)
1	DN1	Da Nhim	Da Nhim	1500	Forest, perennial agri.	1965	240	16500	729
2	DN2	Da Tam	Tuyen Lam	1321	Forest, annual agri.	1987	-	2785	227
3	DN3	Don Duong	-	1141	Forest, annual agri.	-	-	-	372
4	DN4	Da Quyn	Dai Ninh	978	Forest, annual agri.	2008	300	31977	562
5	DN5	Suoi Vang	Dankia	1550	Forest, perennial agri.	1998	4.6	90	314
6	DN6	Da Dang	Da Dang	987	Forest, industrial crops	2016	34	760	1283
7	DN7	Dong Nai 2	Dong Nai 2	907	Perennial crops, forest	2013	70	28100	332
8	DN8	Dong Nai 3	Dong Nai 3	847	Forest, perennial agri.	2011	180	169010	495
9	DN9	Dong Nai 4	Dong Nai 4	714	Forest, perennial agri.	2012	340	33210	159
10	DN10	Dak Nong	Dak R'tih	757	Perennial crops, forest	2011	144	13710	1120
11	DN11	Dong Nai 5	Dong Nai 5	637	Forest, perennial agri.	2014	150	10633	592
12	DN12	Dak R'Keh	Dak Sin	567	Perennial crops, forest	2015	28	1609	321
13	DN13	Dong Nai 6	-	372	Forest, perennial agri.	-	-	-	483
14	DN14	Cat Tien	-	285	Forest, perennial agri.	-	-	-	773
15	DN15	Da Teh	Da Teh	414	Forest, perennial agri.	1990	-	2400	630
16	DN16	Da Huoai	Dam B'ri	592	Forest, perennial agri.	2013	75	5630	909
17	DN17	Ta Lai	-		Perennial crops, rice	-	-	-	431
18	LN1	La Nga	Dai Nga	140	Perennial crops, forest	2015	10	46	1304
All of the UPDN									11036

*CHP is the capacity of hydropower plants (MW); YRES is the year the reservoir became operational; RES_EVOL is the quantity of water needed to raise the reservoir to the emergency spillway $(10^4 m^4)$; agri. is agriculture).

The UPDN river basin is subdivided into 18 sub-basins across two tributaries including the main tributary of the UPDN river basin and the sub-tributary La Nga river basin [21]. The main tributary has 17 sub-basins (from DN1 to DN17) terminating at the Tri An reservoir. The sub-tributary has just one sub-basin (LN1) ending at the Dami hydropower reservoir. The basin's terrain ranges from the Lang Biang plateau (1,300-2,000 above sea level) in the North, through the Di Linh plateau (700-1,000 m) in the center, to a transitional zone with elevations of 200-500 m in the South-Southwest. The region experiences a tropical monsoon climate varying with terrain elevation with a rainy season from May to November and a dry season from December to April of the following year. The average annual rainfall was nearly 2500 mm. The average annual temperature was approximately 22°C. Total rainfall accounts for approximately 87% in the rainy season compared to 13% in the dry season. The total flow in the basin is about 18.5 billion cubic meters, and the rainy season accounts for approximately 85% compared to only 15% in the dry season [22]. These distinct seasonal rainfall patterns play a critical role in the occurrence of hydrological droughts. During the dry season, reduced precipitation and high evaporation rates can significantly lower river flows and water levels in reservoirs, intensifying drought conditions. Conversely, during the rainy season, heavy rainfall can lead to uneven water distribution, leaving some areas more prone to flooding.

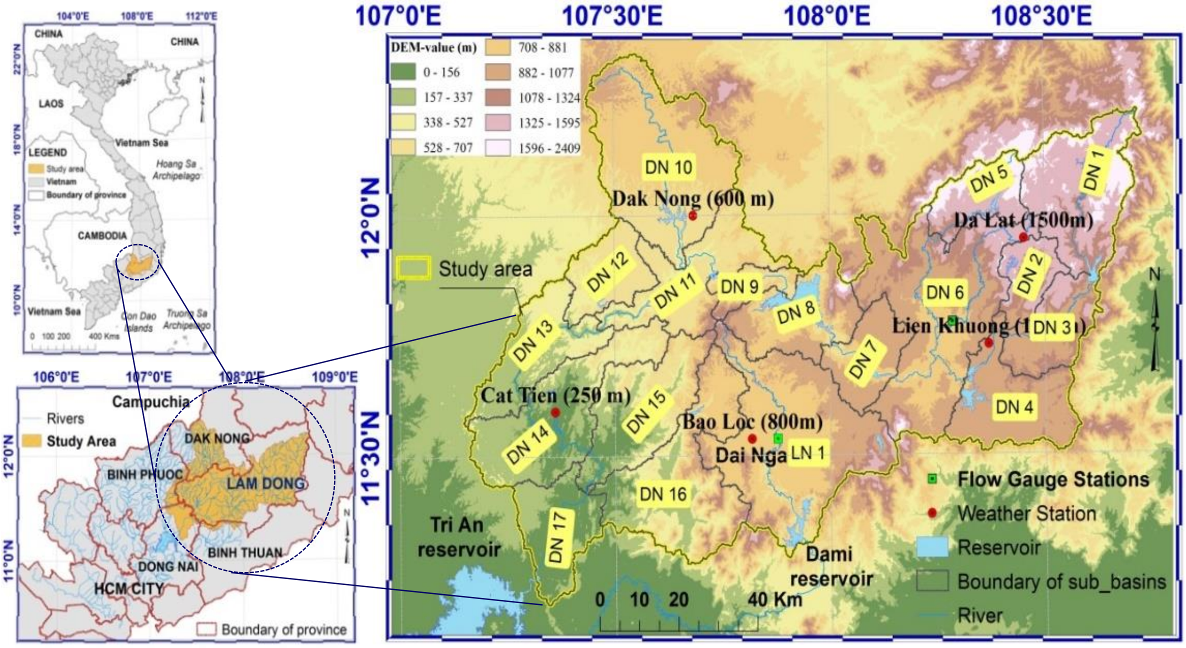

Figure 1. Location of the study area and its sub-basins based on DEM.

2.2. Methodology

The methodological framework for this study is illustrated in Figure 2.

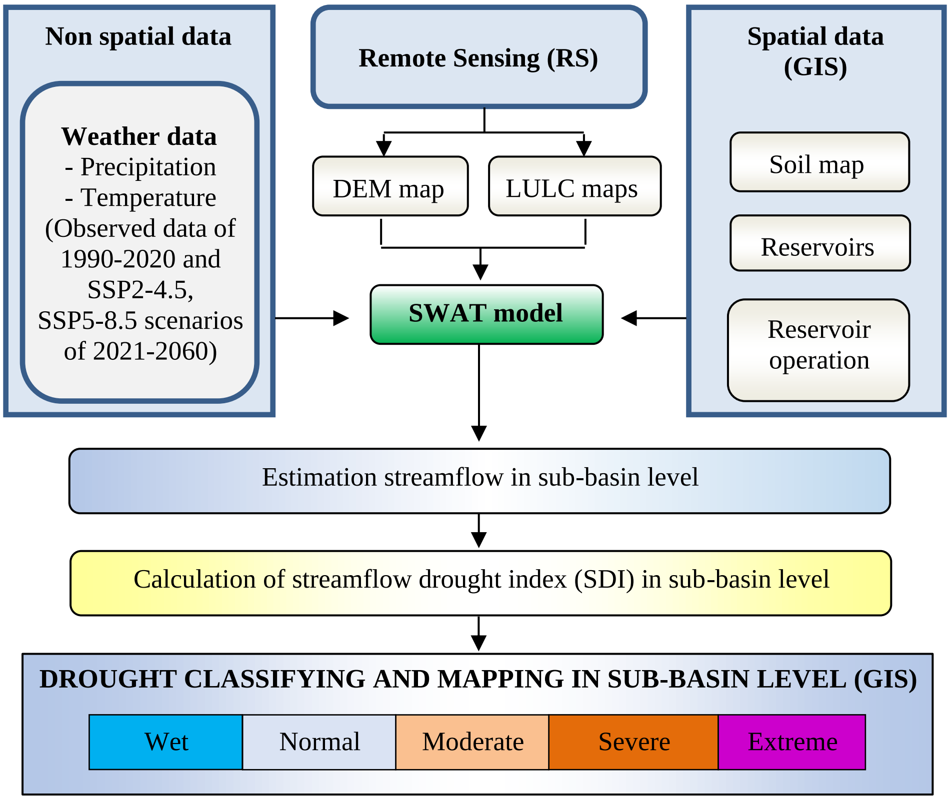

Figure 2. Flowchart of the methodology used for mapping hydrological drought.

2.2.1. Data collection and input preparation

a) Hydro-meteorology data collection

Daily rainfall and temperature data (T_{max}, T_{min}) in the past for the 30-year period (1990-2020) serving as input for the SWAT model as well as for comparison and evaluation purposes have been collected at 5 stations, including Da Lat (1509 m), Lien Khuong (1100 m), Bao Loc (800 m), Dak Nong (600 m), and Cat Tien (300 m) with corresponding altitudes in the areas of about 1,500 m, 1,100 m, 800 m, 600 m and 250 m, as shown in Table 2. These data have been gathered from local management agencies (Department of Natural Resources and Environment of Lam Dong Province, Highland Regional Hydro-meteorological Center). The distribution of these 5 monitoring stations is evenly dispersed across the basin with different elevations, so they can cover the climatic conditions of the study region. Information on the monitoring stations is shown in Table 1 and Figure 1.

Table 2. Descriptions of meteorological monitoring stations in the basin.

No	Name of the monitoring station	Station altitude (m)	Height of zone (m)	Longitude	Latitude
1	Da Lat station	1509	1500	108.45	11.95
2	Lien Khuong Station	939	1100	108.37	11.73
3	Bao Loc Station	840	800	107.82	11.54
4	Dak Nong Station	631	600	107.68	12.00
5	Cat Tien	250	300	107.36	11.59

b) Climate change scenarios in the future

Selecting appropriate General Circulation Models (GCMs) is crucial for enhancing downscaled result accuracy and optimizing computational resources. Five GCMs available in the CMIP6_VN dataset, namely EC-Earth3-Veg, EC-Earth3, CanESM5, HadGEM3-GC31-LL, and CNRM-CM6-1-HR, were chosen based on their suitability and effectiveness for the region [23, 24]. These models were downscaled using the Bias Corrected Spatial Disaggregation (BCSD) method, resulting in a spatial resolution of 10×10 km (~ 0.1°×0.1°) and daily temporal resolution [25, 26]. These climate data are available at: http://remosat.usth.edu.vn/~thanhnd/Download/dat_GEMMES_WP1.

As mentioned above, the Shared Socioeconomic Pathways (SSP) approach in CMIP6 is more up-to-date than the previous CMIP5's Representative Concentration Pathways (RCPs), offering better accuracy in rainfall and temperature projections [8, 11, 18, 25, 27]. The SSP2-4.5 and SSP5-8.5 scenarios from CMIP6 represent "moderate" and "extreme" emissions, respectively, and are recommended by the IPCC to quantify varying levels of greenhouse gas emissions and associated socioeconomic factors [18]. Therefore, the study utilizes climate change scenarios of SSP2-4.5 and SSP5-8.5 to project future hydrological drought conditions for this study. Climate projections are analyzed in the future period of 2021-2060 for minimum temperature, maximum temperature and precipitation. Hydrologic droughts are more deeply assessed periods of the 2030s (2021-2040) and the 2050s (2041-2060). To facilitate localized analysis at specific monitoring stations and to input prepare for SWAT model, datasets in "netCDF.NC" were converted to point data ("Excel.xls") by using ArcGIS's "Multidimension Toolbox".

c) Operation of reservoirs

Reservoirs play an important role in the region's water management, as depicted in Figure 1 and detailed in Table 1. To evaluate the impact of reservoir operations on drought conditions, key reservoir characteristics such as hydropower capacity, operational start year, storage volume etc. were collected from the local Departments of Industry and Trade (DIT) and Agriculture and Rural Development (DARP). Current and future operations are established according to the inter-reservoir operation procedures for the Dong Nai river basin, as stipulated in Decision No. 1895/QD-TTG [28]. Furthermore, the maintenance of minimum environmental flows downstream of reservoirs follows Circular 64/2017/TT-BTNMT [29].

2.2.3. Setup SWAT model

a) SWAT model description

The Soil and Water Assessment Tool (SWAT) is a hydrological model founded on physical principles, designed by Jeff Arnold for the USDA-ARS [30]. It partitions a watershed into sub-watersheds and Hydrological Response Units (HRUs), linking them through stream networks. SWAT operates in two phases: the land phase, which calculates water, sediment, nutrient, and pesticide loads from each HRU, and the routing phase, which tracks these quantities through the channel network to the watershed outlet. The model uses the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (1)$$

where SW_t is the final soil water content; SW_0 is the initial soil water content on day i; t is the time (days); R_{day} is the amount of precipitation on day i; Q_{surf} is the amount of surface runoff on day i (mm H_2O); E_a is the amount of evapotranspiration on day i; w_{seep} is the amount of water entering the vadose zone from the soil profile on day i; Q_{gw} is the amount of return flow on day I (all water units are in mm H_2O).

- Dataset

Essential datasets for the SWAT model include Digital Elevation Model (DEM), soil and Land Use/Land Cover (LULC) maps, and weather data [30]. This study utilized a 12.5-meter resolution DEM that was downloaded from the NASA website: https://urs.earthdata.nasa.gov/users/new. This website provides access to a broad range of Earth observation data, including DEM, satellite imagery, and climate data. The LULC map was inherited from 2020 classified Landsat OLI-TIRS images with seven categories WATR, URML, AGRR, FRSE, FRST, PINE, and AGRC [20, 31]. Historical daily rainfall and temperature data from 1990 to 2020 from five weather stations (Bao Loc, Da Lat, Lien Khuong, Cat Tien, and Dak Nong) were used to input for the SWAT model. Monitoring flow at Thanh Binh, Dai Nga, and Tai Lai gauges in the same period of 1990-2020 were used to calibrate and validate the SWAT model. While missing solar radiation, wind speed, and humidity data were auto-generated by SWAT [32]. Future climate projections were derived from CMIP6 scenarios. Table 3 summarizes the datasets for the applied SWAT model.

Table 3. Input data used to simulate and evaluate the SWAT model.

Data	Resolution	Source
Digital Elevation Model (DEM) map	12.5 m	Downloaded from the NASA website: https://urs.earthdata.nasa.gov/users/new
Soil map	30 m	Obtained from the local Department of Natural Resources and Environment (DONRE)
LULC	30 m	Landsat OLI-TIRS images in 2020, downloaded from the website: http://earthexplorer.usug.gov
Weather	Five stations	Obtained from 5 weather stations (Lien Khuong, Da Lat, Bao Loc, Cat Tien and Dak Nong)
Streamflow	Three stations	Derived from 3 gauges (Thanh Binh, Dai Nga, and Ta Lai)

- Model evaluation

The SWAT model could be evaluated by using several key indices such as the coefficient of determination (R^2), Nash-Sutcliffe efficiency (ENS), the Root Mean Square Error (RMSE) and Percent Bias (PBIAS). In this study, R^2 and ENS were specifically chosen for evaluation due to their strong relevance in assessing model performance in hydrology. The R^2 provides a clear measure of the proportion of variance explained by the model, while

ENS effectively captures the model's predictive accuracy in relation to observed data. Together, these indices offer a comprehensive view of the model's performance, essential for validating its reliability in simulating hydrological processes. R^2 ranges from 0 to 1, with 1 indicating a perfect simulation. ENS ranges from -∞ to 1, with values above 0.5 considered satisfactory; values from 0.5-0.65, 0.65-0.75, and 0.75-1.0 are acceptable, good, and very good, respectively [33]. Streamflow data from 1990-2020 from Dai Nga, Thanh Binh, and Ta Lai gauges were used for the model calibration and validation. Calibration used data from 1990-2000, and validation used data from 2001-2010. The SUFI-2 algorithm, a suitable method implemented in SWAT-CUP 2012 and ArcGIS 10.2 [34], was used for these steps of model calibration and validation. Notably, the missing meteorological data such as solar radiation, wind speed, and humidity can impact model performance by introducing bias or reducing the accuracy of simulations. However, the auto-generation method employed by SWAT is appropriate as it uses established algorithms and relationships to estimate these missing variables based on available data, thereby maintaining the integrity of the model outputs.

2.2.2. Drought indices

The temporal variation in hydrological drought can differ across various time scales, including short-term (1 or 3 months), medium-term (6 months), and long-term (12, 24, and 48 months) accumulation periods. The medium-term time scale of 6 months (SPI6, SDI6) is appropriate for portraying hydro-meteorological regimes and is suitable for monitoring hydro-meteorological drought [35]. Thus, this study uses the streamflow drought index in a 6-month scale (SDI6) for assessing hydrological drought in the UPDN river basin due to its effectiveness, as popularly applied by previous research [14, 17, 35]. Monthly streamflow data in the future periods of the 2030s (2021-2040) and 2050s (2041-2060) were calculated using the DrinC software, a tool widely adopted in drought research [36, 37], and freely accessed at the website: (https://drought-software.com). Drought classifications are based on SDI values as follows: Drought classifications are based on SDI values as follows: SDI ≥ 2.0: Extremely wet; 1.5 ≤ SDI < 2.0: Very wet; 1.0 ≤ SDI < 1.5: Moderately wet; -1.0 ≤ SDI < 1.0: Normal; -1.5 ≤ SDI < -1.0: Moderate drought, -2.0 ≤ SDI < -1.5: Severe drought, SDI ≤ -2.0: Extreme drought [14, 38].

3. Results and discussions

3.1. Performance evaluation of the SWAT model

The SWAT model was calibrated and validated by using simulated and observed flows from 1990-2000 and 2001-2010, respectively. The hydrological stations were selected based on their geographic distribution, data availability, and representativeness of the UPDN river basin. Thanh Binh and Dai Nga stations, located upstream, and Ta Lai, downstream, were chosen to capture the natural flow patterns across different sections of the basin. Additionally, the data from these stations during the selected periods of 1990-2000 for calibration and 2001-2010 for validation were considered reliable and minimally impacted by anthropogenic activities (hydropower operation). This ensured stable hydrological conditions, allowing for accurate and robust model calibration and validation. The study used the Sequential Uncertainty Fitting, version 2 (SUFI-2) method for model calibration and verification, as it typically yields good results [34]. The SUFI-2 method efficiently narrows parameter ranges with few iterations, making it ideal for complex models like SWAT [14, 18], where capturing variability and reducing uncertainty are crucial for accurate streamflow predictions. The SWAT model's performance was assessed by using R^2 and ENS statistical values, both of which exceeded 0.70 (Table 4). These values demonstrate the model's good suitability based on criteria in previous studies [33, 39]. Therefore, it can be concluded that the SWAT model is appropriate for predicting streamflow in the UPDN river basin. Accordingly, it can be reliably used to project the impacts of hydrological drought conditions in the sub-basin scale for the study area in the future.

Table 4. The values of R^2 and NSI in the calibration and validation periods of the SWAT model.

Gauging station	Calibration		Validation	
	R^2	NSI	R^2	NSI
Thanh Binh	0.810	0.757	0.811	0.809
Dai Nga	0.812	0.780	0.781	0.809
Ta Lai	0.731	0.712	0.771	0.759

3.2. Projected changes in minimum, maximum temperature, and precipitation

Figure 3 illustrates the yearly average trends of minimum temperature (T_{min}), maximum temperature (T_{max}), and precipitation from 2021 to 2060. These trends are based on ensemble means from five selected Global Climate Models (GCMs) under the SSP2-4.5 and SSP5-8.5 scenarios for five areas: Da Lat (DL), Lien Khuong (LK), Bao Loc (BL), Dak Nong (DN), and Cat Tien (CT). The results show that T_{max} and T_{min} have similar increasing trends across the entire UPDN river basin, with nearly parallel trend lines. Both SSP2-4.5 and SSP5-8.5 scenarios indicate a more pronounced increase in yearly mean T_{min} and T_{max} compared to yearly precipitation. The temperature increases of the SSP5-8.5 scenario project higher from 0.5°C to 1.0°C compared to the SSP2-4.5 scenario across the UPDN river basin.

Under the SSP2-4.5 climate change scenario, the temperature increases in Da Lat, Lien Khuong, Bao Loc, Dak Nong, and Cat Tien are approximately 0.80°C, 0.81°C, 0.82°C, 0.83°C, and 0.84°C for T_{max}, and 0.75°C, 0.75°C, 0.76°C, 0.76°C, and 0.77°C for T_{min}, respectively. Figure 4 (a1, a2) illustrates the spatial distribution of these temperature increases. Under the SSP5-8.5 climate change scenario, both T_{min} and T_{max} show similar increasing trends from 2021 to 2060 across all areas. The increases in T_{min} at Da Lat, Lien Khuong, Bao Loc, Dak Nong, and Cat Tien are approximately 1.21°C, 1.22°C, 1.24°C, 1.27°C, and 1.29°C. Meanwhile, the values for T_{max} are 1.20°C, 1.23°C, 1.26°C, 1.28°C, and 1.32°C, respectively. The spatial distribution of temperature increase is less in the East-Northeast regions compared to the South-Southwest regions, as Figure 4 (b1, b2).

Regarding rainfall factors, the SSP2-4.5 scenario graph and trend function in Figure 3 show no clear increasing or decreasing trend for yearly rainfall from 2021 to 2060. The results show a distinct upward trend in both minimum (T_{min}) and maximum (T_{max}) temperatures compared to vague and unclear fluctuation trends in annual rainfall. These findings are also consistent with previous reports [2, 17, 18, 40, 41]. The average rainfall across the UPDN river basin during this period is 2138 mm. Under the SSP5-8.5 scenario, the average annual rainfall is 2096 mm, lower than the SSP2-4.5 scenario. Specifically, under the SSP2-4.5 scenario, the rainfall in Da Lat, Lien Khuong, Bao Loc, Dak Nong, and Cat Tien is approximately 1692 mm, 1688 mm, 2490 mm, 2462 mm, and 2359 mm respectively. Under the SSP5-8.5 scenario, these values are 1633 mm, 1631 mm, 2447 mm, 2438 mm, and 2331 mm respectively. Similar to temperature factors, the spatial distribution of yearly rainfall increase in East-Northeast regions is less pronounced than in South-Southwest regions under the SSP2-4.5 scenario. Moreover, under the SSP5-8.5 scenario, Da Lat, Lien Khuong, and Bao Loc show yearly rainfall decrease trends ranging from -6.73% to -1.23% per year. Meanwhile, Dak Nong and Cat Tien regions show yearly rainfall increase trends ranging from 1.53% to 7.03% per year, as shown in Figure 4 (b3). The relative stability of annual rainfall under the SSP2-4.5 and SSP5-8.5 scenarios suggests that water availability may not fluctuate drastically throughout the years, allowing for more consistent irrigation practices and crop management strategies. However, the distribution of rainfall involves uncertainty [25, 42], so stakeholders must remain vigilant in monitoring rainfall patterns to adapt to potential shifts in climate conditions.

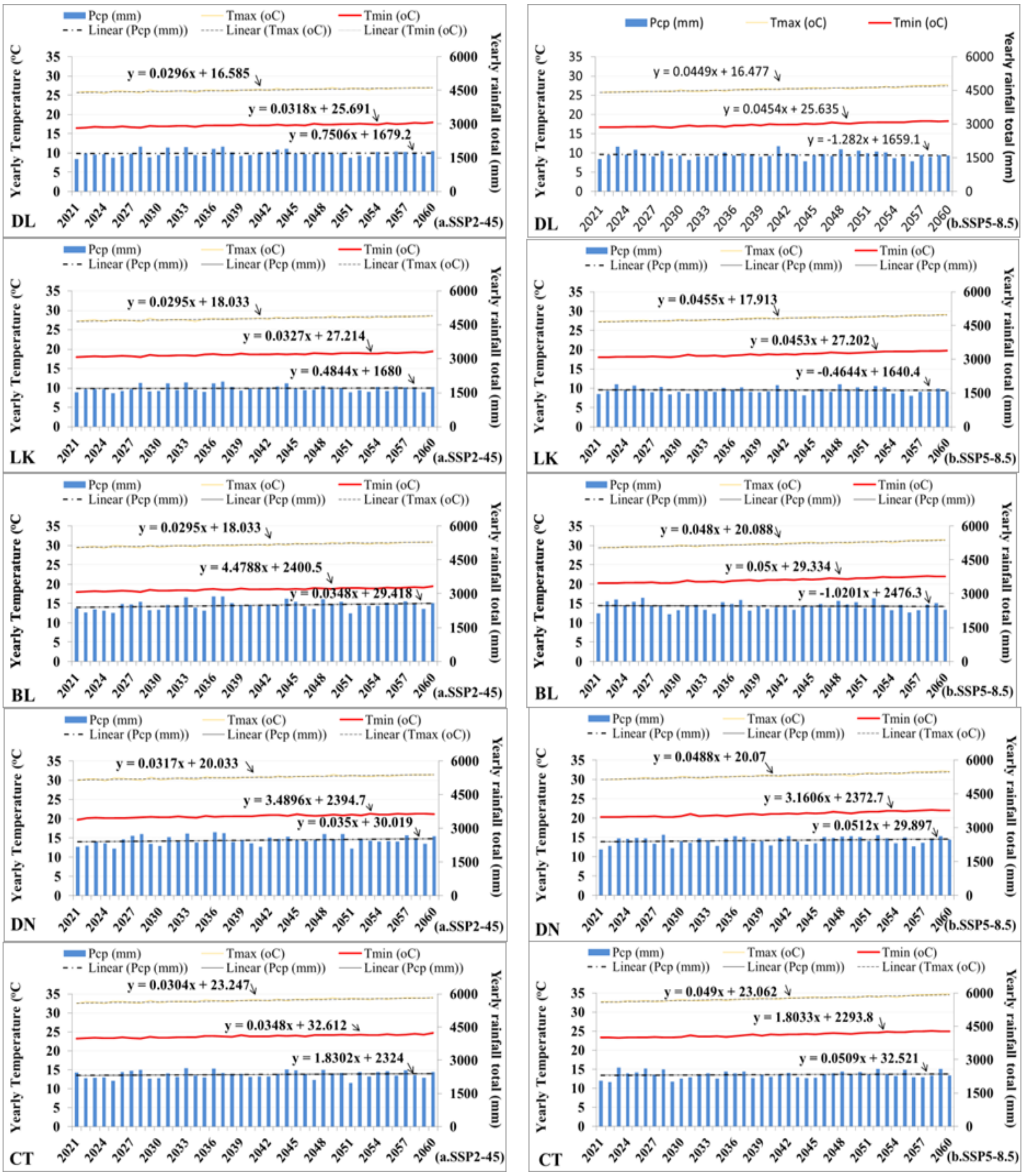

Figure 3. Projected changes in yearly minimum temperature, maximum temperature, and precipitation in the period of 2021-2060 in Da Lat (DL), Lien Khuong (LK), Bao Loc (BL), Dak Nong (DN), Cat Tien (CT): (a) SSP2-45 scenario; (b) SSP5-8.5 scenario.

Because rainfall volumes and changes significantly impact drought conditions [1], this study analyzed rainfall in more detail to assess its effect on drought in the basin. Average monthly precipitation for 2021-2060 was examined in two periods: 2021-2040 (near future) and 2041-2060 (mid-century), under SSP2-4.5 and SSP5-8.5 scenarios. This analysis provides crucial information for developing short-term and long-term adaptation strategies. Figure 5 shows changes in average monthly rainfall for the 2030s and 2050s under the SSP2-4.5 scenario, compared to the 1990-2020 historical period. Monthly rainfall tends to increase from mid-rainy season to the early dry season (August to December). Conversely, monthly rainfall tends to decrease from the mid-dry season to the early rainy season (February to May) for both SSP2-4.5 and SSP5-8.5 scenarios. These results are also similar to the previous study in Ca river, a basin located in North Central Vietnam with a climate divided into four distinct seasons (autumn, winter, spring, and summer), the spring MAM (March, April, May) precipitation in the future could be decreased, while the autumn (September, October, November: SON) precipitation could be increased [41, 43]. Clearly, the trend of increasing and decreasing rainfall in the study area has the distinctly dry-rainy seasonal characteristics of the Central Highlands region.

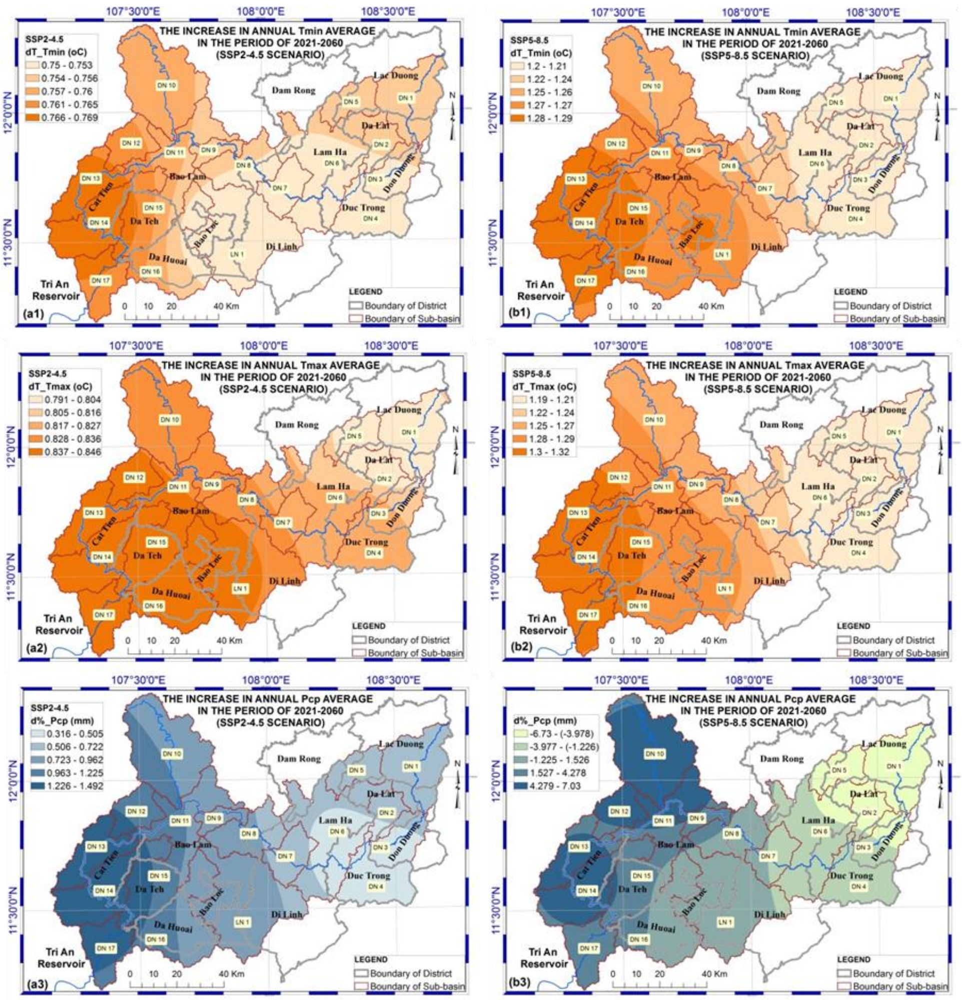

Figure 4. Spatial changes and trends in (1) annual minimum temperature average (T_{min}, °C), (2) annual maximum temperature average (T_{max}, °C) and (3) annual precipitation (P%, mm) in the period of 2021-2060 in the UPDN river basin: (a) SSP2-4.5 scenario; (b) SPP5-8.5 scenario.

Compared with the SSP2-4.5 scenario, the average monthly rainfall of the SSP5-8.5 scenario is more erratic and unpredictable. In the period 2022-2041, rainfall decreases in the dry season months including January, February, April, May, June, and July. While rainfall increases in the months of September, October, November and December. In the period 2041-2060, rainfall decreases in February, March, April, May, and June but increases in the months of January, June, August, September, October, November, and December. Thus, the SSP5-8.5 scenario can cause irregular monthly rainfall changes, no longer following the seasonal pattern (dry season and rainy season) in the basin.

Generally, under the influence of climate change, the results show that in both SSP2-4.5 and SSP5-8.5 scenarios, rainfall tends to increase in the rainy season months and decrease in the dry season months, especially in the last months of the dry season and the early rainy season (from April to May). It can be predicted that climate change will cause droughts and floods to become more and more unusual in the near future in the basin. Therefore, to effectively mitigate the risk of extreme drought events during the dry season, managers and policymakers must implement proactive measures focused on prevention and preparedness. Upgrading reservoirs and improving irrigation efficiency are essential for optimizing water management and ensuring that agricultural and domestic needs are met during times of water scarcity.

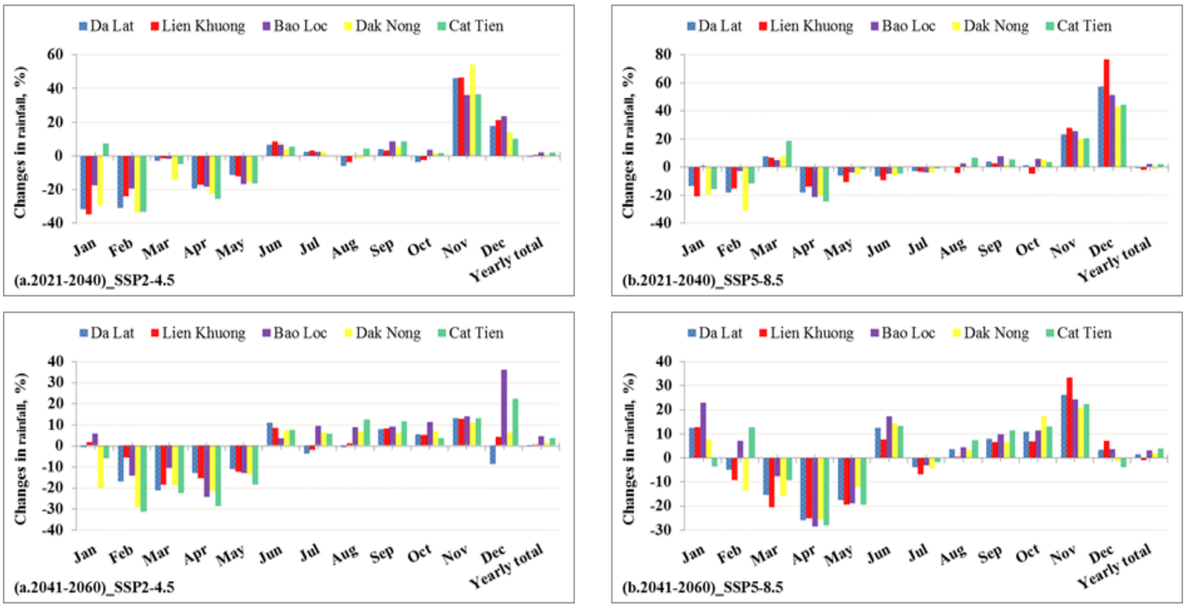

Figure 5. Projected changes in monthly and yearly rainfall mean in Da Lat, Lien Khuong, Bao Loc, Dak Nong, and Cat Tien in the period of 2021-2040 and 2041-2060: (a) SSP2-4.5 scenario; (b) SSP5-8.5 scenario.

3.3. Projected changes in the hydrological droughts

3.3.1. Drought frequency analysis

The frequency of hydrological drought for 18 sub-basins ranked from the highest to the lowest for the period 2021-2040 and 2041-2060 according to the SSP2-4.5 scenario is shown by the bold values in the “Sum of D” column in Table 5. The spatial distribution of hydrological drought (SDI6) for the two periods 2021-2040 and 2041-2060 for the two scenarios SSP2-4.5 and SSP5-8.5 on the UPDN river basin is shown in Figure 6. In general, in the basin, the normal condition (NC) is still the most common, accounting for over 67% compared to the rest being drought (D) and wet condition (WC). At the same time, there is a relatively equal balance between wet (WC) and drought (D) in the basin, which reflects the current reality in the basin, which is local drought and flooding all appear in the basin. Overall, UPDN river basin, wet condition (WC) is 10.5% vs. 11.0% of D over 2021-2040 and 16.5% of WC vs. 15.6% of D over 2041-2060 for the SSP2-4.5 scenario. These figures for the SSP5-8.5 scenario are 14.6% of WC and 15.6% of D in 2021-2040 and 16.3% of WC and 14.7% of D in 2041-2060, respectively. Furthermore, for the SSP2-4.5 scenario, the period 2041-2060 has a higher frequency of drought than the period 2021-2040 (15.6% compared to 11.0%). At the same time, in the near future period 2021-2040, the SSP5-8.5 scenario has a higher frequency of drought than SSP2-4.5 (15.6% compared to 11.0%). However, in the period 2041-2060, the frequency of drought does not differ much between these two scenarios with 15.6% of SSP2-4.5 compared to 14.7% of SSP5-8.5. This is also consistent with the average monthly rainfall forecast for the period 2041-2060 of these two scenarios shown in Figure 5.

At the sub-basin level, according to the SSP2-4.5 scenario, in the period 2021-2040, the three sub-basins with the highest frequency of hydrological drought (SDI6) are respectively

Dong Nai 4 (DN 9), Dong Nai 3 (DN 8) in Di Linh, Bao Lam districts of Lam Dong province and Dak Nong (DN 10) in Dak Glong district, Gia Nghia city of Dak Nong province with corresponding values of 13.6%, 13.2%, and 13.2%. During the period 2041-2060, the three sub-basins Da Huoai (DN 16) in Da Huoai district, La Nga (LN 1) in Di Linh district, and Don Duong (DN 3) in Don Duong district of Lam Dong province will have a high frequency of occurrence. Hydrological drought (SDI6) is the highest with corresponding values of 18.75%, 17.9%, and 17.4%. However, the sub-basin with extreme drought (ED) status belongs to DN2 (Da Tam) in Duc Trong district, DN6 (Da Dang) in Lam Ha district and DN 3 (Don Duong) in Don Duong district for the period 2021-2040 and DN 10 (Dak Nong), DN 12 (Dak R'Keh) of Dak Glong district, Gia Nghia city of Dak Nong province and DN 1 (Da Nhim) in Don Duong district, as italic values shown in Table 5. Therefore, in the future, there needs to be adaptive solutions for these areas where extreme drought (ED) occurs.

Table 5. Ranking from the highest to the lowest the frequency of hydrological drought according to sub-basins under the SSP2-4.5 scenario.

No.	**The near future period of 2021 - 2040**								**Mid-century period of 2041 - 2060**							
	ID	**WC**	**NC**	**Drought (D)**			**Sum of D**	**Total**	**ID**	**WC**	**NC**	**Drought (D)**			**Sum of D**	**Total**
				MD	**SD**	**ED**						**MD**	**SD**	**ED**		
1	DN 9	11.1	75.3	10.2	3.4	0.0	**13.6**	100	DN 16	16.6	64.7	13.2	2.6	3.0	**18.7**	100
2	DN 8	11.1	75.7	9.4	3.8	0.0	**13.2**	100	LN 1	17.0	65.1	9.8	6.4	1.7	**17.9**	100
3	DN 10	9.4	77.4	11.9	1.3	0.0	**13.2**	100	DN 3	16.6	66.0	9.4	6.0	2.1	**17.4**	100
4	DN 16	15.7	71.5	11.9	0.9	0.0	**12.8**	100	DN 6	17.4	66.4	10.2	3.0	3.0	**16.2**	100
5	*DN 2*	8.1	79.1	10.6	1.3	*0.9*	**12.8**	100	DN 7	17.4	66.4	9.8	3.4	3.0	**16.2**	100
6	*DN 6*	11.5	75.7	6.0	6.4	*0.4*	**12.8**	100	DN 8	17.0	67.2	8.9	4.3	2.6	**15.7**	100
7	DN 7	11.5	75.7	6.0	6.4	0.4	**12.8**	100	DN 9	16.6	67.7	8.5	4.3	3.0	**15.7**	100
8	DN 11	10.2	77.0	10.6	2.1	0.0	**12.8**	100	*DN 10*	16.6	67.7	9.8	1.7	*4.3*	**15.7**	100
9	LN 1	14.9	72.8	11.9	0.4	0.0	**12.3**	100	DN 17	18.3	66.0	8.9	3.8	3.0	**15.7**	100
10	DN 4	12.3	75.3	6.4	5.5	0.4	**12.3**	100	DN 4	17.0	67.7	8.9	4.7	1.7	**15.3**	100
11	DN 12	9.4	78.7	8.5	3.0	0.4	**11.9**	100	*DN 12*	17.0	67.7	9.4	1.7	*4.3*	**15.3**	100
12	DN 13	9.8	79.6	9.4	1.3	0.0	**10.6**	100	*DN 1*	13.6	71.5	8.1	3.0	*3.8*	**14.9**	100
13	DN 14	8.9	80.4	9.8	0.9	0.0	**10.6**	100	DN 11	17.0	68.1	6.4	6.0	2.6	**14.9**	100
14	DN 15	8.9	80.4	9.4	1.3	0.0	**10.6**	100	DN 5	15.3	70.2	8.5	4.7	1.3	**14.5**	100
15	DN 17	8.9	80.4	10.2	0.4	0.0	**10.6**	100	DN 13	17.9	67.7	6.4	5.5	2.6	**14.5**	100
16	*DN 3*	11.5	79.1	6.4	2.1	*0.9*	**9.4**	100	DN 14	17.9	67.7	6.4	5.1	3.0	**14.5**	100
17	DN 1	8.9	85.1	5.1	0.4	0.4	**6.0**	100	DN 15	17.9	67.7	6.4	5.1	3.0	**14.5**	100
18	DN 5	6.8	92.8	0.4	0.0	0.0	**0.4**	100	DN 2	10.2	75.7	8.9	4.3	0.9	**14.0**	100
For the UPDN		10.5	78.4	8.6	2.3	0.2	**11.0**	100		16.5	67.8	8.8	4.2	2.7	**15.6**	100

(*) ID: identification; WC: wet condition; NC: normal condition; MD: moderate drought; SD: severe drought; ED: extreme drought; D: drought condition.

Analysis of the SSP5-8.5 scenario reveals significant spatial and temporal variations in hydrological drought frequency across the study area. For the period 2021-2040, Da Huoai (DN 16), La Nga (LN 1), and Cat Tien (DN 14) are the highest frequency of hydrological drought sub-basins, with respective values of 20.0%, 19.6%, and 17.9%. The period of 2041-2060 shows Ta Lai (DN 17), Da Huoai (DN 16), and La Nga (LN 1) are the highest drought sub-basins with frequencies at 18.3%, 17.0%, and 17.0%, respectively. Notably, the occurrence of extreme drought conditions does not necessarily correlate with overall drought frequency. For the 2021-2040 period, extreme drought events are predominantly observed in DN4 (Da Quyn), ND7 (Dong Nai 2), and DN6 (Da Dang). In contrast, the 2041-2060 period sees a geographical shift in extreme drought occurrences, with ND10 (Dak Nong), ND4 (Da Quyn), and DN3 (Don Duong) being the most severely affected. These findings, as illustrated in Table 6, underscore the complex spatial dynamics of hydrological drought in the region and highlight the importance of sub-basin scale analysis in drought management strategies.

Table 6. Ranking from the highest to the lowest the frequency of hydrological drought according to sub-basins under the SSP5-8.5 scenario.

No.	The near future period of 2021 - 2040								Mid-century period of 2041 - 2060							
	ID	WC	NC	Drought (D)			Sum of D	Total	ID	WC	NC	Drought (D)			Sum of D	Total
				MD	SD	ED						MD	SD	ED		
1	DN 16	18.7	61.3	10.2	8.5	1.3	**20.0**	100	DN 17	17.4	64.3	14.0	4.3	0.0	**18.3**	100
2	LN 1	16.6	63.8	11.5	6.4	1.7	**19.6**	100	DN 16	15.7	67.2	9.8	7.2	0.0	**17.0**	100
3	DN 14	18.7	63.4	12.3	4.3	1.3	**17.9**	100	LN 1	18.3	64.7	10.6	6.4	0.0	**17.0**	100
4	DN 15	18.7	63.4	12.3	3.8	1.7	**17.9**	100	DN 15	16.2	67.7	11.9	4.3	0.0	**16.2**	100
5	DN 13	18.3	63.8	10.2	6.8	0.9	**17.9**	100	DN 14	16.2	67.7	11.1	5.1	0.0	**16.2**	100
6	DN 12	15.3	67.2	9.8	4.7	3.0	**17.4**	100	DN 12	17.9	66.8	8.9	3.4	3.0	**15.3**	100
7	DN 11	18.7	65.1	9.4	4.7	2.1	**16.2**	100	*DN 10*	17.4	67.2	9.4	2.6	*3.4*	**15.3**	100
8	DN 17	17.4	66.4	11.5	3.4	1.3	**16.2**	100	DN 13	19.1	65.5	9.8	5.1	0.4	**15.3**	100
9	DN 9	14.5	69.4	9.8	4.7	1.7	**16.2**	100	DN 11	19.1	66.0	10.2	4.7	0.0	**14.9**	100
10	DN 8	14.0	70.6	9.4	3.8	2.1	**15.3**	100	DN 7	15.3	70.6	6.8	4.7	2.6	**14.0**	100
11	*DN 4*	11.5	73.6	9.4	1.7	*3.8*	**14.9**	100	DN 8	17.0	68.9	8.1	3.8	2.1	**14.0**	100
12	DN 2	12.8	73.2	8.5	3.4	2.1	**14.0**	100	DN 9	16.6	69.4	8.1	4.7	1.3	**14.0**	100
13	*DN 7*	10.6	75.3	8.5	1.7	*3.8*	**14.0**	100	DN 6	14.5	71.9	6.4	4.7	2.6	**13.6**	100
14	*DN 6*	11.1	75.3	7.7	1.7	*4.3*	**13.6**	100	DN 1	14.5	72.3	6.0	5.5	1.7	**13.2**	100
15	DN 3	12.3	74.5	6.8	4.7	1.7	**13.2**	100	*DN 4*	14.5	72.3	6.0	3.8	*3.4*	**13.2**	100
16	DN 1	12.3	74.5	7.7	3.4	2.1	**13.2**	100	*DN 3*	14.9	72.3	5.5	4.3	*3.0*	**12.8**	100
17	DN 5	10.2	77.9	6.8	3.4	1.7	**11.9**	100	*DN 2*	14.5	73.2	5.5	3.4	*3.4*	**12.3**	100
18	DN 10	12.3	77.0	8.1	0.4	2.1	**10.6**	100	DN 5	14.5	73.2	5.5	5.5	1.3	**12.3**	100
For the UPDN		14.7	69.8	9.4	4.0	2.2	**15.6**	100		16.3	69.0	8.5	4.6	1.6	**14.7**	100

(*) ID: identification; WC: wet condition; NC: normal condition; MD: moderate drought; SD: severe drought; ED: extreme drought; D: drought condition.

3.3.2. Spatial variability of drought

The spatial and temporal variability of drought conditions within the basin is influenced by a complex interplay of factors, including climate change scenarios, precipitation patterns, sub-basin distribution (upstream and downstream), and hydroelectric plant operations. Under the SSP2-4.5 scenario, drought frequency exhibits a higher prevalence in the sub-basins situated in the East-Northeast upstream region of the basin (Figure 6a). These areas, as previously analyzed, receive comparatively less precipitation than the West-Southwest region. Furthermore, hydroelectric projects within the basin exert a significant influence on drought conditions, particularly in cases of extreme drought (ED). Two noteworthy hydroelectric projects that divert water to external basins warrant particular attention: (1) Da Nhim hydrologic plant with a capacity of 120MW transfers approximately 0.7 billion m^3 of water to the Cai river basin in Phan Rang province, situated between DN1 (Da Nhim) and DN3 (Don Duong); and (2) Dai Ninh hydrologic plant with a capacity of 160MW diverts approximately 1.3 billion m^3 of water to the Luy river basin in Binh Thuan province, located between DN4 (Da Quyn) and DN6 (Da Dang). These projects have a substantial impact on the hydrological drought conditions within the basin. Of particular note, the watersheds DN3 (Don Duong) and DN6 (Da Dang), which are situated downstream of these water-diverting hydroelectric projects, exhibit a higher frequency of extreme drought (ED) conditions compared to other sub-basins. Consequently, these two watersheds should be accorded priority in drought prevention and mitigation efforts within Lam Dong province.

Analysis of the drought conditions under the SSP5-8.5 scenario reveals a higher frequency of drought events in the downstream regions of the basin (DN 15, DN16, DN17) compared to the upstream areas (Figure 6b). Paradoxically, wet conditions (WC) also exhibit greater prevalence in the downstream regions. This dichotomy suggests that the SSP5-8.5 scenario introduces a higher degree of unpredictability in both drought and flood occurrences relative to the SSP2-4.5 scenario. The total annual precipitation does not significantly differ between the two scenarios however there are substantial variations in monthly rainfall patterns between dry and wet seasons. Consequently, the temporal and spatial distribution of hydrological drought conditions varies markedly between the SSP2-4.5 and SSP5-8.5 scenarios, and therefore there will be a difference in the spatial distribution of drought in the basin.

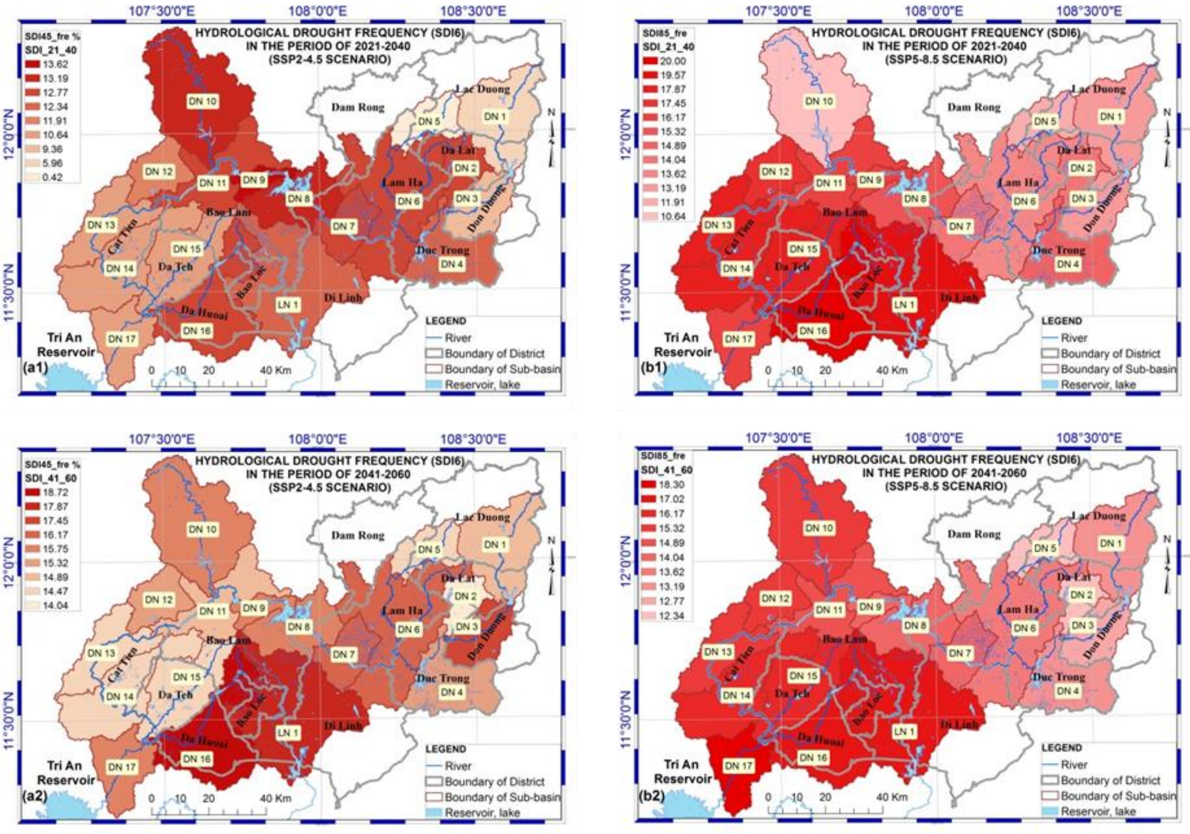

Figure 6. The spatial frequency of hydrological drought according to sub-basins level in the period of (1) 2021-2040 and (2) 2041-2060: (a) SSP2-45 scenarios; (b) SSP5-8.5 scenarios.

3.4. Changes in hydrological drought in future scenarios compared to the historical period

The results of calculating historical hydrological drought are based on monitoring data from three hydrological stations in the basin, including Thanh Binh in the Da Dang sub-basin (ND6), Dai Nga in the La Ngai sub-basin (LN1), and Ta Lai in the Ta Lai sub-basin (DN17). Streamflow data spanning the 30-year period (1990-2020) were utilized to calculate SDI6 for the Thanh Binh and Ta Lai stations. While streamflow data of the 24-year period (1990-2014) were employed for the Dai Nga station, because the Dai Nga station has not operated normally since 2014 due to the water diversion caused by the Dai Nga hydropower plant. Overall, for both the historical and future periods, the NC (normal conditions) still predominates, accounting for more than 63%, compared to the WC (wet conditions) and D (drought) (Table 7). Additionally, the percentage of D and WC is nearly equal, reflecting the climate characteristics of the UPDN basin, which has a five-month dry season (December to April), followed by a seven-month rainy season (May to November). However, under the influence of climate change, extreme drought (ED) is projected to occur more frequently in the future. For example, at Thanh Binh, the ED occurrence was 1.6% during the historical period 1990-2020, compared to 3.0% for the period 2041-2060 under the SSP2-4.5 scenario, and 6.4% under the SSP5-8.5 scenario. At Ta Lai, ED accounts for 4.1% during 1990-2020, rising to 11.5% under the SSP2-4.5 scenario and 14.0% under the SSP5-8.5 scenario for the period 2041-2060, respectively.

Table 7. Comparison of the frequency of hydrological drought historical observation to future predictions at three Thanh Binh, Dai Nga, and Ta Lai gauges under the SSP2-4.5 and SSP5-8.5 scenarios.

Scenarios	Periods	WC	NC	Drought (D)			Sum of D	Total
				MD	SD	ED		
Thanh Binh gauge								
History	1990 - 2020	13.6	73.3	7.4	4.6	1.6	**13.1**	100
SSP2-4.5	2021 - 2040	11.5	75.7	6.0	6.4	0.4	**12.8**	100
	2041 - 2060	17.4	66.4	10.2	3.0	3.0	**16.2**	100
SSP5-8.5	2021 - 2040	11.1	75.3	4.3	1.7	7.7	**13.6**	100
	2041 - 2060	14.5	71.9	2.6	4.7	6.4	**13.6**	100
Dai Nga gauge								
History	1990 - 2020	12.8	76.8	5.0	2.0	3.4	**10.4**	100
SSP2-4.5	2021 - 2040	14.9	72.8	11.9	0.4	0.0	**12.3**	100
	2041 - 2060	17.0	65.1	9.8	6.4	1.7	**17.9**	100
SSP5-8.5	2021 - 2040	16.6	63.8	1.7	6.4	11.5	**19.6**	100
	2041 - 2060	18.3	64.7	0.0	6.4	10.6	**17.0**	100
Ta Lai gauge								
History	1990 - 2020	12.5	73.3	7.4	2.7	4.1	**14.2**	100
SSP2-4.5	2021 - 2040	18.3	66.0	8.9	3.8	3.0	**15.7**	100
	2041 - 2060	17.4	66.4	1.3	3.4	11.5	**16.2**	100
SSP5-8.5	2021 - 2040	17.4	66.4	1.3	3.4	11.5	**16.2**	100
	2041 - 2060	17.4	64.3	0.0	4.3	14.0	**18.3**	100

(*) WC: wet condition; NC: normal condition; MD: moderate drought; SD: severe drought; ED: extreme drought; D: drought condition.

In general, the observed spatial patterns in hydrological drought occurrence within the UPDN river basin can be attributed to a combination of climatic, geographical, and anthropogenic factors. The interplay of these factors results in complex spatial patterns of drought occurrence within the UPDN river basin. The basin's topography has influenced local climate patterns. The distribution of precipitation across the basin is uneven, with certain areas receiving less rainfall than others. For example, the East-Northeast upstream regions with high elevation often experience lower precipitation compared to the West-Southwest areas, contributing to various drought frequency and severity. The presence of hydroelectric plants and water diversion projects has impacted local hydrology. For instance, the Da Nhim and Dai Ninh plants have diverted substantial water to other basins, potentially leading to reduce water availability downstream, especially during dry periods. Hydropower reservoirs upstream can significantly modify the natural flow regime by altering the timing and magnitude of water release. These regulated flows, often designed to meet energy demands, exacerbate drought and flood conditions in downstream sub-basins.

Based on these results, there is a relatively equal balance between wet and drought conditions, reflecting the current reality in the basin, where localized droughts and flooding events frequently occur. These changes in droughts can be reduced by upgrading reservoirs and improving irrigation system efficiency. Moreover, agricultural practices need to adapt to the changing rainfall patterns. Agricultural activities need to shift to more drought-resistant crop varieties, adjust planting schedules, and implement soil moisture management techniques to maintain productivity during drier periods. In addition, the drought mitigation solutions should be prioritized for sub-basins that have high drought frequency and severity such as Da Tam, Don Duong, Da Quyn, and Da Dang.

4. Conclusions

The findings suggest that climate change could lead to more significant increases in temperature than changes in precipitation. In the future, increases in temperature and precipitation are anticipated to vary spatially and temporally across the basin. The trend shows greater temperature and precipitation increases in the West-Southwest than in the

East-Southeast of the basin. Under the SSP2-4.5 scenario, annual rainfall slightly increases in most areas of the basin for the period 2021-2060. However, the SSP5-8.5 scenario projects a slight rainfall decrease in the East-Southeast region and a slight increase in the West-Southwest. Additionally, rainfall tends to decrease in some months of the dry season (February to May) and increase some months of the rainy season (August to December). These changes in rainfall patterns contribute significantly to variations in drought frequency and severity across the basin.

The frequency of drought occurrence varies between the upstream and downstream areas of the basin, depending on climate change scenarios, rainfall distribution, and hydroelectric project operations. According to the SSP2-4.5 scenario, drought frequency is more common at sub-basins located in the upstream part belonging to the East-Northeast of the basin. Conversely, the SSP5-8.5 scenario suggests that the downstream part of the basin (DN 15, DN16, and DN17) experiences more frequent hydrological droughts than the upstream part.

The frequency and severity of droughts can vary between sub-basins. Da Tam (DN2), Don Duong (DN3), Da Quyn (DN2), Da Dang (DN6), Dong Nai 2 (ND7), Dak Nong (DN10), and Dak R'Keh (DN12) are the sub-basins having more frequent extreme drought (ED) conditions compared to the rest of the basins. These sub-basins should be prioritized for drought prevention in the coming years. The research results can provide valuable information for policymakers in planning, management, and sustainable development of the UPDN river basin. These findings highlight the need for targeted adaptive management strategies, such as prioritizing water conservation and storage infrastructure in sub-basins with higher drought frequency and severity, and adjusting hydroelectric project operations to mitigate downstream drought risks.

The study has proposed the useful solution in integrate GIS, remote sensing (RS), and the SWAT model to simulate and analyze the spatiotemporal dynamics of hydrological droughts in the UPDN river basin. However, this study also has some limitations, such as the lack of detailed reservoir operation data. The weather data input for the SWAT model, derived from GCMs with a 10 km × 10 km resolution, can cause uncertainty. Thus, further research should focus on integrating high-resolution climate data and exploring the impacts of land-use changes and human activities on drought dynamics to provide a more comprehensive understanding of future water resource challenges.

Author Contributions: Developed ideas, conceptualized framework, and methodology: P.H., V.L.P.; selected methods, techniques, and processed data: P.H.; wrote the draft article: P.H., L.V.T.; Edited and reviewed the article: V.L.P.

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References

1. Liming, G.; Yaonan, Z. Spatio-temporal variation of hydrological drought under climate change during the period 1960–2013 in the Hexi Corridor, China. *J. Arid. Land* **2016**, *8(2)*, 157–171.
2. Benyoussef, S.; Arabi, M.; Yousfi, Y.E.; Cheikh, B.B.; Abdaoui, A.; Azirar, M.; Mechkirrou, L.; Ouarghi, H.E.; Zegzouti, Y.F.; Boughrous, A.A. Climate Change and Water Resources Management in the Ghis-Nekor Watershed (North of Morocco) – A Comprehensive Analysis Using SPI, RDI and DI Indices. *Ecol. Eng. Environ. Technol.* **2024**, *25(2)*, 196–209.

3. Li, Q.; Ye, A.; Wada, Y.; Zhang, Y.; Zhou, J. Climate change leads to an expansion of global drought-sensitive area. *J. Hydrol.* **2024**, *632(130874)*, 1–9.
4. Tri, D.Q.; Dat, T.T.; Truong, D.D. Application of meteorological and hydrological drought indices to establish drought classification maps of the Ba river basin in Vietnam. *Hydrology* **2019**, *6(49)*, 1–20.
5. Ngan, T.T.K.; Khoi, D.N. Analysing the impact of hydropower dams on streamflow in the Be river basin. *VN J. Sci. Technol. Eng.* **2019**, *16(4)*, 35–39.
6. Wu, J.; Chen, X.; Gao, L.; Yao, H.; Chen, Y.; Liu, M. Response of hydrological drought to meteorological drought under the influence of large reservoir. *Adv. Meteorol.* **2016**, *16(2197142)*, 1–11.
7. Langen, S.C.H.; Costa, A.C.; Neto, G.G.R.; Oel, P.R. Effect of a reservoir network on drought propagation in a semi-arid catchment in Brazil. *Hydrol. Sci. J.* **2021**, *66(10)*, 1567–1583.
8. IPCC. Climate Change 2022: Impacts, adaptation and vulnerability - working group II contribution to the sixth assessment report of the intergovernmental panel on climate change. New York, USA, 2022.
9. Thanh, N.D.; Nguyen, M.H.; Pannier, E.; Woillez, M.N.; Drogoul, A.; Huynh, T.P.L.; Le, T.T.; Nguyen, T.T.H.; Nguyen, T.T.; Nguyen, T.A.; Thomas, F.; Truong, C.Q.; Vo, Q.T.; Vu, C.T. Climate change in Viet Nam: Impacts and adaptation. A COP26 assessment report of the GEMMES Viet Nam project. Paris, 2021.
10. IPCC. The physical science basis. New York, USA, 2021.
11. Huong, N.T.; Kim, Y.T.; Kwon, H.H. Evaluation and selection of CMIP6 GCMs for long-term hydrological projections based on spatial performance assessment metrics across South Korea. *J. Water Clim. Change* **2023**, *14(8)*, 2663–2678.
12. Riahi, K.; van Vuuren, D.P.; Kriegler, E.; Edmonds, J.; O'Neill, B.C.; Fujimori, S.; Bauer, N.; Calvin, K.; Dellink, R.; Fricko, O.; Lutz, W. The shared socio-economic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environ. Change* **2017**, *42*, 153–168.
13. Sam, T.T.; Khoi, D.N.; Thao, N.T.T.; Nhi, P.T.T.; Quan, N.T.; Hoan, N.X.; Nguyen, V.T. Impact of climate change on meteorological, hydrological and agricultural droughts in the Lower Mekong River Basin: a case study of the Srepok Basin, Vietnam. *Water Environ. J.* **2019**, *33*, 547–559.
14. Khoi, D.N.; Sam, T.T.; Loi, P.T.; Hung, B.V.; Thinh, N.V. Impact of climate change on hydro-meteorological drought over the Be river basin, Vietnam. *J. Water Clim. Change* **2021**, *12(7)*, 3159–3169.
15. Sarwar, A.N.; Waseem, M.; Azam, M.; Abbas, A.; Ahmad, I.; Lee, J.E.; Haq, F.U. Shifting of meteorological to hydrological drought risk at regional scale. *Appl. Sci.* **2022**, *12(5560)*, 1–14.
16. Mahdavi, P.; Kharazi, H.G. Impact of climate change on droughts: a case study of the Zard river basin in Iran. *Water Pract. Technol.* **2023**, *18(10)*, 2258–2276.
17. Pandhumas, T.; Kuntiyawichai, K.; Jothityangkoon, C.; Suryadi, F.X. Assessment of climate change impacts on drought severity using SPI and SDI over the Lower Nam Phong River Basin, Thailand. *Hydrology* **2020**, *47(3)*, 326–338.
18. Tran, T.-N.-D.; KimDo, S.; Nguyen, B.Q.; Tran, V.N.; Grodzka-Łukaszewska, M.; Sinicyn, G.; Lakshmi, V. Investigating the future flood and drought shifts in the transboundary Srepok river basin using CMIP6 projections. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2024**, *17*, 7516–7529.
19. Vietnam MONRE. Report on general planning of Dong Nai river basin period 2021 - 2030, vision to 2050. Ha Noi, Vietnam, 2023, pp. 1–281.
20. Hung, P.; Trung, L.V.; Vo, P.L. Decision support tool for integrated water resources management based on GIS, remote sensing and SWAT model: A case study in the

upper part of Dong Nai river basin, Vietnam. In Advances in Research on Water Resources and Environmental Systems. GTER 2022. Environmental Science and Engineering, Vo, P.L.; Tran, D.A.; Pham, T.L.; Le Thi Thu, H.; Nguyen Viet, N.; Ed. Springer: Gewerbestrasse 11, 6330 Cham, Switzerland, 2023, pp. 361–388.
21. Jolk, C.; Greassidis, S.; Jaschinski, S.; Stolpe, H.; Zindler, B. Planning and decision support tools for the integrated water resources management in Vietnam. *Water* **2010**, *2*, 711–725.
22. Hung, P. Application of GIS, remote sensing and SWAT in integrated water resources management: A case study in the upper part of Dong Nai river basin. Ho Chi Minh City University of Technology (HCMUT) - Vietnam National University Ho Chi Minh City, Ho Chi Minh City, 2022.
23. Nguyen-Duy, T.; Ngo-Duc, T.; Desmet, Q. Performance evaluation and ranking of CMIP6 global climate models over Vietnam. *J. Water Clim. Change* **2023**, *14(6)*, 1831–1846.
24. Hung, P.; Quyen, N.T.N.; Trung, L.V.; Phu, V.L. Performance evaluation of some CMIP6-GCMs in simulating rainfall and temperature in the upper part of Dong Nai river basin. *VN J. Hydrometeorol.* **2024**, *762*, 47–61.
25. Tran, A.Q.; Ngo, D.T.; Espagne, E.; Trinh, T.L. A 10-km CMIP6 downscaled dataset of temperature and precipitation for historical and future Vietnam climate. *Sci. Data* **2023**, *10(1)*, 1–12.
26. Department of Climate Change, V.N.M. National Climate Change Impacts and Adaptation Final Report. Ha Noi, Vietnam, 2022.
27. Eyring, V.; Bony, S.; Meehl, G.A.; Senior, C.A.; Stevens, B.; Stouffer, R.J.; Taylor, K.E. Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **2016**, *9(5)*, 1937–1958.
28. Vietnam Prime Minister. Decision No. 1895/QD-TTg dated December 25, 2019 on the promulgation of inter-reservoir operating procedures in the Dong Nai river basin. Ha Noi, 2019.
29. Vietnam Ministry of Natural Resources and Environment. Circular 64/2017/TT-BTNMT Regulations on determining minimum flows in rivers, streams and downstream of reservoirs, dams. Ha Noi, Vietnam, 2017, pp. 1–8.
30. Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R. Introduction and history. Soil and Water Assessment Tool Theoretical Documentation Version 2009, Texas Water Resources Institute Technical Report No. 406: Texas A&M University System College Station, Texas 77843-2118, 2011, pp. 6–10.
31. Hung, P.; Le, T.V.; Vo, P.L.; Duong, H.C.; Mostafizurb, R.M. Vulnerability assessment of water resources using GIS, remote sensing and SWAT model – A case study: The upper part of Dong Nai river basin, Vietnam. *Int. J. River Basin Manage.* **2021**, *20*, 1–16.
32. Mango, L.M.; Melesse, A.M.; McClain, M.E.; Gann, D.; Setegn, S.G. Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modeling tudy to support better resource management. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 2245–2258.
33. Moriasi, D.N.; Arnold, J.G.; Liew, M.W.V.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* **2007**, *50(3)*, 885–900.
34. Khoi, D.N.; Thom, V.T. Parameter uncertainty analysis for simulating streamflow in a river catchment of Vietnam. *Global Ecol. Conserv.* **2015**, *4*, 538–548.
35. Padhiary, J.; Patra, K.C.; Dash, S.S. A novel approach to identify the characteristics of drought under future climate change scenario. *Water Resour. Manage.* **2022**, *36*, 5163–5189.

36. Tigkas, D.; Vangelis, H.; Tsakiris, G. DrinC: A software for drought analysis based on drought indices. *Earth Sci. Inf.* **2015**, *8(3)*, 697–709.
37. Tigkas, D.; Vangelis, H.; Proutsos, N.; Tsakiris, G. Incorporating aSPI and eRDI in drought indices calculator (DrinC) software for agricultural drought characterisation and monitoring. *Hydrology* **2022**, *9(100)*, 1–14.
38. McKee, T.B.; Doesken, N.J.; Kleist, J. The relationship of drought frequency and duration to time scales. Proceeding of the 8th Conf. Appl. Climatol. Anaheim Calif. **1993**, pp. 179–184.
39. Can, T.; Xiaoling, C.; Jianzhong, L.; Gassman, P.W.; Sabine, S.; José-Miguel, S.P. Assessing impacts of different land use scenarios on water budget of Fuhe River, China using SWAT model. *Int. J. Agric. Biol. Eng.* **2015**, *8(3)*, 95–109.
40. Wang, L.; Shu, Z.; Wang, G.; Sun, Z.; Yan, H.; Bao, Z. Analysis of future meteorological drought changes in the Yellow river basin under climate change. *Water* **2022**, *14(1896)*, 1–20.
41. Shin, J.Y.; Chien, P.V.; Um, M.J.; Kim, H.; Sung, K. Projection of changes in rainfall and drought based on CMIP6 scenarios on the Ca river basin, Vietnam. *Water* **2024**, *14(1914)*, 1–19.
42. Anaraki, M.V.; Kadkhodazadeh, M.; Morshed-Bozorgde, A.; Farzin, S. Predicting rainfall response to climate change and uncertainty analysis: Introducing a novel downscaling CMIP6 models technique based on the stacking ensemble machine learning. *J. Water Clim. Change* **2023**, *14(10)*, 3671–3691.
43. Tran, A.Q.; Ngo, D.T.; Espagne, E.; Trinh, T.L. A high-resolution projected climate dataset for Vietnam: Construction and preliminary application in assessing future change. *J. Water Clim. Change* **2022**, *13(9)*, 3379–3399.