Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 12 No 8, 3851 doi: 10.2166/wcc.2021.255

Assessment of climate change impact on water availability in the upper Dong Nai River Basin, Vietnam

D. N. Khoi[a,b,c], V. T. Nguyen[d,*], T. T. Sam[b], N. T. H. Mai[a,c], N. D. Vuong[e] and H. V. Cuong[f]

[a] Faculty of Environment, University of Science, 227 Nguyen Van Cu Street, Dist. 5, Ho Chi Minh City 700000, Vietnam
[b] Institute for Computational Science and Technology, Ho Chi Minh City 700000, Vietnam
[c] Vietnam National University Ho Chi Minh City, Linh Trung Ward, Thu Duc Dist., Ho Chi Minh City 700000, Vietnam
[d] Department of Civil and Environmental Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-744, Korea
[e] Southern Institute of Water Resources Research, 658 Vo Van Kiet Street, Dist. 5, Ho Chi Minh City, Vietnam
[f] The Key Laboratory of River and Coastal Engineering, Vietnam Academy for Water Resources, Hanoi, Vietnam
*Corresponding author. E-mail: vnguyen@snu.ac.kr

ABSTRACT

On a global scale, climate change is projected to have detrimental impacts on water availability. This situation will become more severe owing to accumulated impacts of climate change and anthropogenic activities. This study aims to investigate climate change impact on water availability in the upper Dong Nai River Basin using the Soil and Water Assessment Tool (SWAT) and Water Evaluation and Planning (WEAP) models. Future rainfall scenarios were downscaled from five different general circulation models under RCP4.5 and RCP8.5 using the Long Ashton Research Station Weather Generator (LARS-WG) tool. Under the climate change impact, annual river discharge in the study region is generally projected to have upward trends in the future, except for the near-future period of the 2030s under RCP4.5. In addition, dry-seasonal river discharge is expected to be increased in the future. Considering the baseline condition of water use, there was an annual water shortage of approximately 32.9×10^3 m^3, which mostly occurred in the dry season from January to March. Climate change may reduce the water shortage in the study region ranging from 7.0 to 30.1% in the future. Under the combined impacts of climate change and increasing water demand, the water shortage will vary from −18.6 to 6.0% in the future. The results can provide valuable insights to implement appropriate future water resources planning and management in the study region.

Key words: climate change, SWAT, water availability, water shortage, WEAP

HIGHLIGHTS

- Lack of knowledge about climate change impacts on water availability in the study region.
- Water shortage caused by aggregated impacts of future climate change and increase in water demand.
- Provide valuable insights to implement appropriate future water resources planning and management.

1. INTRODUCTION

Climate change is one of the uppermost challenges and has ranked as the second-highest risk to livelihoods as stated in the Global Risk Report in 2021 (WEF (World Economic Forum) 2021). Climate change results in temperature rise and precipitation variation, which consequently affects the hydrological cycle. River discharge is a major indicator of water availability for agricultural, domestic, and industrial sectors, and the alterations in hydrological processes may pose a threat to water quantity and quality, including water scarcity and flooding (Ficklin *et al.* 2018). The threat can be more severe in the future as the global water consumption has tripled over the past 60 years from 1,400 km^3/year in 1950 to 4,200 km^3/year in 2010 (UNESCO and UN-Water 2020). Specifically, the global water demand for all water-use purposes is likely to increase up to 50% by 2050 compared to the reference condition with the occurrence probability of water scarcity in some regions of the world (Boretti & Rosa 2019). Therefore, the assessment of the potential impacts of climate change on water availability is pivotal, especially in regions where the socioeconomic and ecological systems are greatly vulnerable to climate and water scarcity.

The potential impacts of climate change on water availability have been studied in many regions of the world (e.g., Hussen *et al.* 2018; Yan *et al.* 2018; Asghar *et al.* 2019). For instance, Dahal *et al.* (2020) investigated the climate change impact on

---

water availability in the Karnali River Basin of Nepalese Himalaya and revealed an increase in future streamflow. Touch *et al.* (2020) evaluated the effect of climate change on water availability in the Pursat River Basin in Cambodia, and the results showed that water availability will decline in the future. Touseef *et al.* (2021) also indicated that precipitation and streamflow may reduce in the future in the Hongshui River Basin in China. In the aforementioned studies, the findings generally revealed that climate change is likely to unequivocally influence water availability, and the climate change impact may vary across regions. In addition, water availability will be influenced by population growth and economic development, which increase the demand for water use (Beck & Bernauer 2011). Together with climate change, the increasing water demand may put immense pressures on water availability resulting in a water shortage crisis in many regions (Alcamo *et al.* 2007; Kifle Arsiso *et al.* 2017).

Vietnam has relatively abundant water resources, which have highly seasonal variation and are unequally distributed across the nation (World Bank 2019). In addition, Vietnam is identified as one of the most vulnerable countries to climate change in the East Asia and Pacific region (IPCC 2018). Climate change will affect the spatio-temporal variations of water availability in this country. Moreover, the increase in water demand due to the population growth and rapid economic development has put a pressure on water resources in recent years. Specifically, the future water demand in Vietnam is estimated to increase by approximately 27.5% from 51 billion m^3 in 2016 to 65 billion m^3 in 2030 (World Bank 2019). Several studies have investigated the impact of projected climate change in some basins of Vietnam with varying results in terms of the magnitude and direction of changes in water availability (Huyen *et al.* 2017; Thang *et al.* 2018; Tram *et al.* 2019). However, very few studies have taken account of water-use scenarios in the future (e.g., Dau *et al.* 2021), which is pivotal for a robust understanding of changes in water availability.

The main objective of the present study was to investigate the impact of climate change on water availability in the upper Dong Nai River Basin (DNRB) in the southern region of Vietnam. The study region plays an important role in ensuring water supply for most economic centers in southern Vietnam. Additionally, there is still no previous investigation on water availability in the upper DNRB in the context of climate change. The finding of this study has significant implications for future sustainable water resources management in the study area.

The manuscript is structured as follows. A specific study region is described in Section 2; this will be followed by the description of methodology in Section 3, whereby all simulation tools used in this study are presented. Results and discussion are illustrated in Section 4. Eventually, the conclusions are mentioned in Section 5.

2. STUDY REGION

The present study is carried out in the DNRB, which is located in the southern region of Vietnam (Figure 1). The basin has a drainage area of approximately 14,700 km^2. The mainstream Dong Nai River originates from the Langbiang Plateau in the Central Highlands and flows into the Tri An reservoir following the northeast-southwest direction. The annual river discharge was nearly 338 m^3/s at the Ta Lai stream gauge and 123 m^3/s at the Phu Hiep stream gauge in the period of 1987–2013. The elevation of the basin varies from 50 to 2,300 m above sea level. The climate is monsoon tropic with two typical seasons: the rainy season from May to October and the dry season from November to April. The mean annual rainfall in the study region was approximately 2,300 mm for the period of 1985–2013. The rainfall ranged from 2,000 mm in the eastern part of the basin to 2,800 mm in the western part. The mean annual temperature was approximately 25.9 °C. This basin has fairly fertile land with nearly 75% of the area covered by basaltic soil, which is suitable for agricultural development; therefore, agriculture is the main economic activity in the basin. The total population of the basin was approximately 2.42 million inhabitants in 2014, and the population growth rate was approximately 1.54% per year during the period of 2010–2014 (GSO 2015). The upper DNRB plays an important role in water supply for domestic and agricultural purposes. Furthermore, this basin provides water for generating hydropower and controlling saltwater intrusion in the downstream Dong Nai River in the dry season.

3. METHODOLOGY

In order to estimate the potential impact of climate change on water availability, the prevalent hydrologic and water allocation models are applied for the evaluation of the impacts of climate change under different scenarios (Hussen *et al.* 2018; Allani *et al.* 2020). In this study, the Soil and Water Assessment Tool (SWAT) model and the Water Evaluation and Planning (WEAP) model were utilized. The modeling framework for the present study is illustrated in Figure 2. The SWAT model was used to simulate river discharge of the study region under different climate change scenarios. The climate

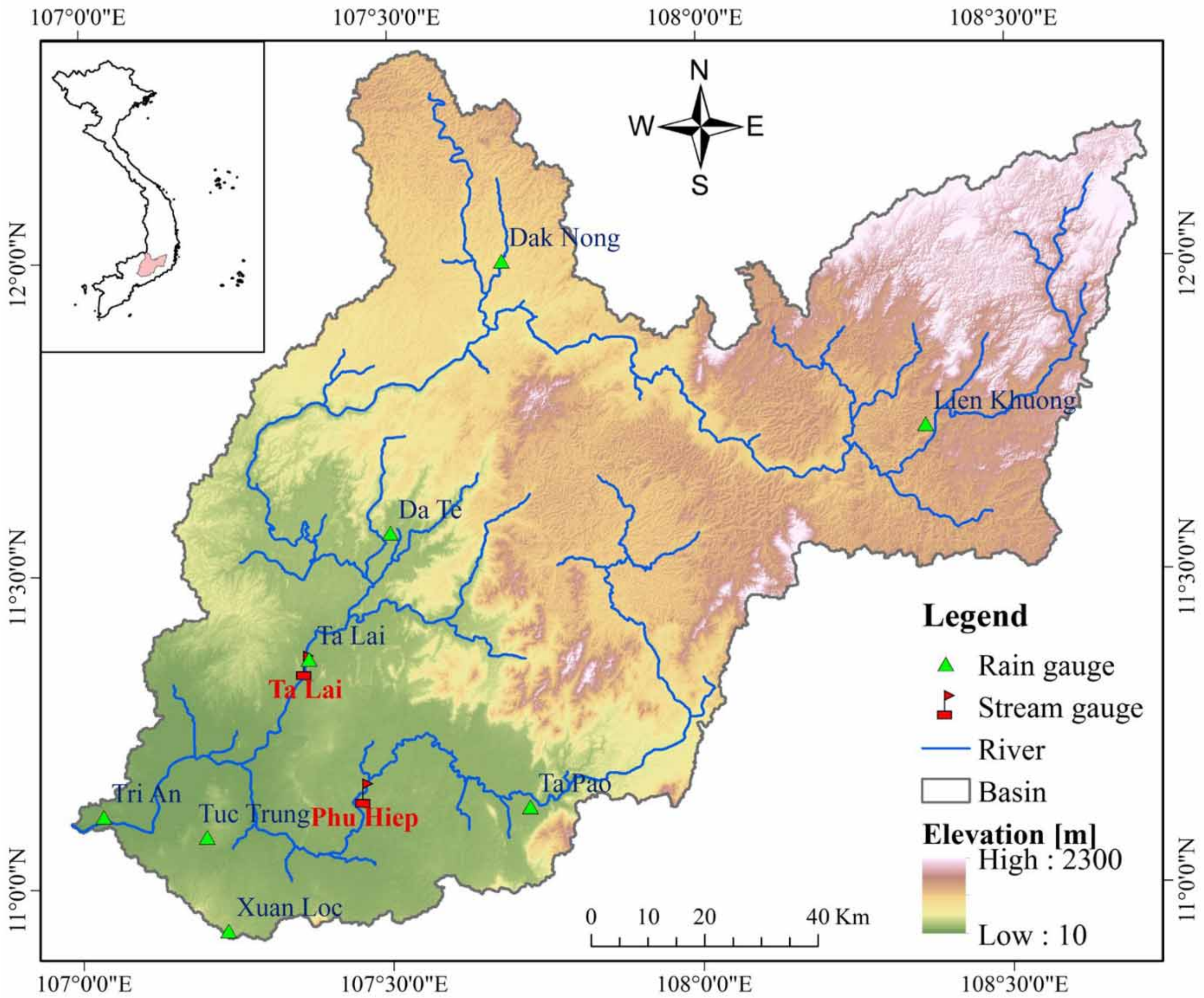

Figure 1 | Location map of the study region.

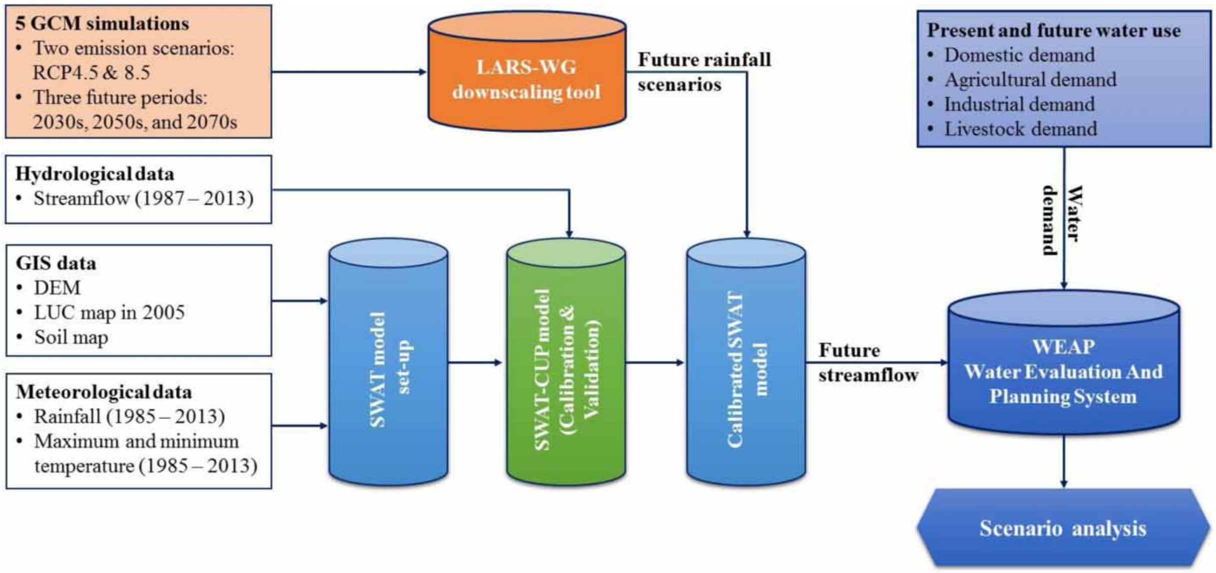

Figure 2 | Modeling framework of the study.

change scenarios for three future periods of the 2030s (2021–2040), 2050s (2041–2060), and 2070s (2061–2080) were produced by the statistical downscaling tool, the Long Ashton Research Station Weather Generator (LARS-WG), based on five general circulation model (GCM) simulations under RCP4.5 and RCP8.5 emission scenarios. After that, the WEAP model was used to estimate water availability based on balance between water supply and water demand.

3.1. SWAT hydrological model

The SWAT model is a semi-distributed hydrologic model, which was applied in this study to evaluate the climate change impact on river discharge of the upper DNRB. This model has been broadly applied in many basins in Vietnam and presented reasonable results (e.g., Truong *et al.* 2018; Khoi *et al.* 2019a, 2019b; Nhi *et al.* 2019). Regarding the SWAT model, it separates a basin into subbasins in reliance on topography and river networks and further divided these subbasins into hydrological response units (HRUs) based on slope, land-use, and soil features. In this model, the water balance equation is calculated at the HRU level, totalized at the subbasin level, and ultimately distributed to the outlet of the basin. More details on the hydrological description of the SWAT model can be referred to Neitsch *et al.* (2011).

The spatio-temporal input data required for SWAT setup comprise elevation, land use, soil, and meteorology. This study utilized the digital elevation model derived from the National Aeronautics and Space Administration (NASA)'s Shuttle Radar Topography Mission (STRM), which has a spatial resolution of 90 m (Figure 3(a)). The land-use data in 2005 were acquired from the Climate Change Initiative (CCI) of the European Space Agency (ESA), which have a spatial resolution of 300 m (Figure 3(b)). The soil data with a spatial resolution of 10 km were achieved from the Food and Agriculture Organization (FAO) (Figure 3(c)). These data were utilized to define subbasins and HRUs and provide topographical features, crop information, and physical–chemical properties of soils in the study regions. The upper DBRN was divided into 115 subbasins and 1,463 HRUs. Additionally, the meteorological data (i.e., rainfall and maximum and minimum temperatures) were obtained from the Hydro-Meteorological Data Center (HMDC) of Vietnam for the period of 1986–2013. Furthermore, the hydrological data (e.g., river discharge) are necessary for the SWAT model to calibrate and validate the model performance. The present study utilized daily river discharge at the Ta Lai and Phuoc Hiep stream gauges, which was acquired from the HMDC for the period of 1987–2013.

The SWAT model was calibrated and validated by utilizing the Sequential Uncertainty Fitting version 2 (SUFI-2) incorporated in the SWAT Calibration and Uncertainty Program (SWAT-CUP) (Abbaspour 2015). There are five calibration techniques built in the SWAT-CUP, such as GLUE (Generalized Likelihood Uncertainty Estimation), MCMC (Markov Chain Monte Carlo), ParaSol (Parameter Solution), PSO (Particle Swarm Optimization), and SUFI-2. Amidst these techniques, the SUFI-2 technique was selected because this technique could provide more satisfactory and accurate simulation in the tropical region as compared to other techniques (Khoi *et al.* 2017). The calibration and validation steps were conducted for the periods of 1987–1995 and 1996–2013, respectively. The reproducibility of the SWAT model in simulating the river discharge was judged after the model calibration and validation. Three model performance statistics, namely the efficiency index of Nash–Sutcliffe (NSE), coefficient of determination (R^2), and percent bias (P_{BIAS}), were applied to estimate the satisfaction between simulated and observed river discharge. As reported by Moriasi *et al.* (2007), a model performance with $NSE > 0.5$, $R^2 > 0.5$, and $P_{BIAS} = \pm 25\%$ is considered satisfactory for the streamflow simulation.

3.2. WEAP model

WEAP, developed by the Swedish Environmental Institute (SEI), was utilized for assessing the balance of water demand and water supply (water availability) in the upper DNRB. The WEAP model has been widely applied to solve water management issues in many basins throughout the world (Hussen *et al.* 2018; Allani *et al.* 2020; Touch *et al.* 2020). The basic theory of the WEAP model is the balanced equation of water supply and water demand, and the model spatially solves this equation at a monthly time step. In reliance on scenario analysis, WEAP will help policymakers estimate water resources allocation under different socioeconomic scenarios or management strategies. Further details on the WEAP model can be referred to Seiber & Purkey (2015).

The water system in the WEAP model for the upper DNRB is depicted in Figure 4. The study region was divided into five subbasins and water-use activities in each subbasin, which are presented in Table 1. In the present study, the water supply sources for each subbasin were provided by the simulation results obtained from the SWAT model. There are four identified water demands, including domestic, agriculture, industry, and livestock. The domestic demand within the basin is essentially focused on the urban and rural areas of the subbasin. The water consumption for domestic use was estimated relying on the population at the district level, which was collected from the Provincial Statistical Offices (PSOs) in the basin, and water-use

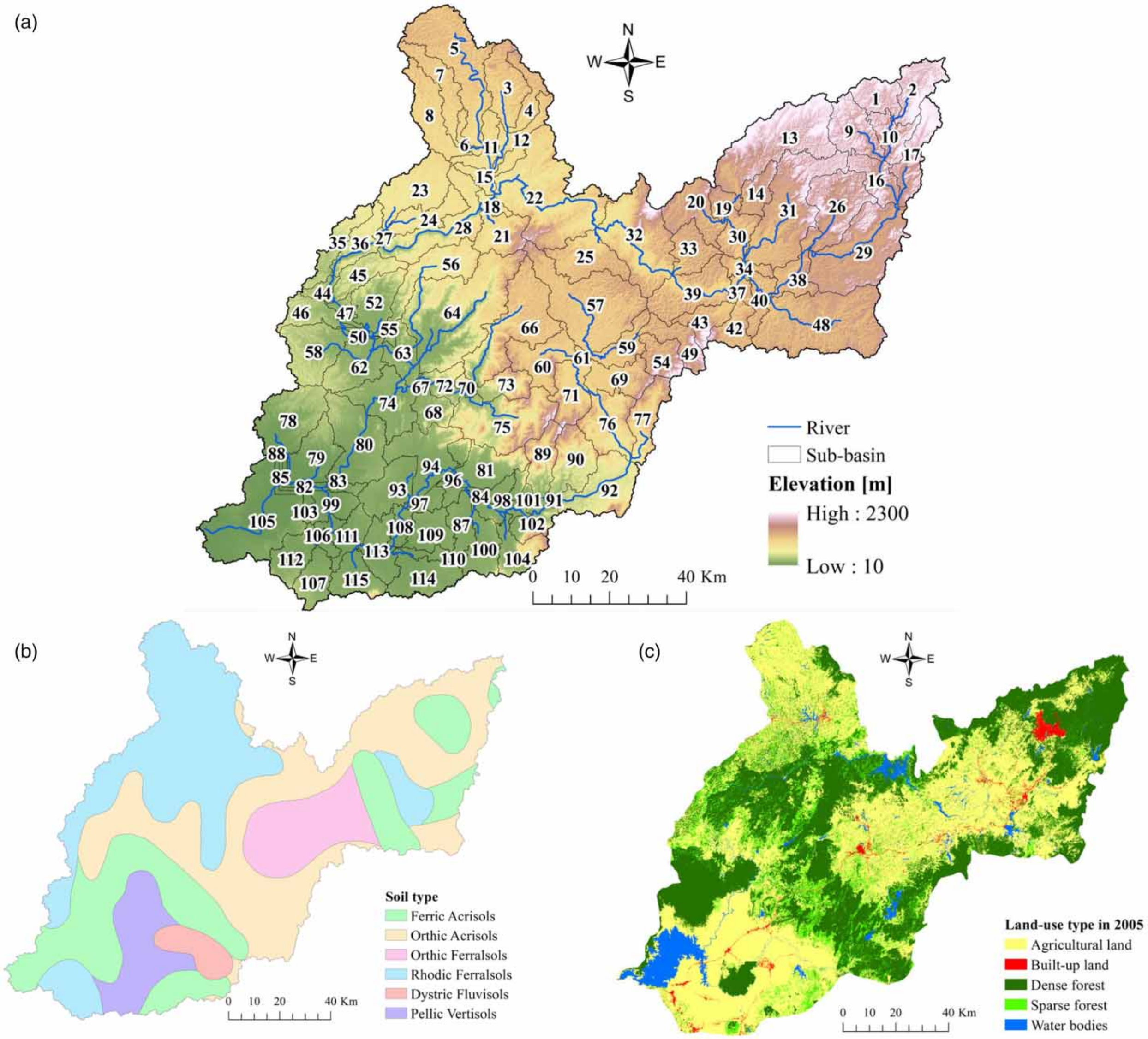

Figure 3 | Maps of (a) DEM, (b) land-use types, and (c) soil types of the study region.

rates were assumed to be 100 liters/capita/day for urban people and 60 liters/capita/day for rural people according to the Vietnam standard for water supply (MOC 2006). The industrial zone located in this basin is mainly small scale with a low water-use rate. The water consumption for industrial use was calculated in reliance on the area of industrial zones and assumed a water-use rate of 40 m^3/hectare/day following the Vietnam standard for water supply (MOC 2006). Regarding livestock and agricultural water demands, livestock water-use rate was assumed to be 30–50 liters/head/day according to the Vietnam standard for rural design and planning (TCVN 4454: 2012), and irrigation water demand for each crop type was estimated by the Crop Water and Irrigation Requirements Program (CROPWAT) developed by the FAO. The main crops in this basin consisted of rice, coffee, pepper, corn, and vegetables. The water requirement for agricultural use was calculated by multiplying the irrigation water requirement by the total area covered by crop pattern. The data of industry, livestock, and agriculture were collected from PSOs. Furthermore, the environmental flow requirement for the Dong Nai River was above 120 m^3/s to maintain the aquatic ecosystem according to Decision No. 471/QD-TTg on 24 March 2016. According to the field survey on current water resources management in the Central Highlands (JICA 2018), approximately 56–80% of the total water consumption is supplied by surface water and the remaining 20–44% is supplied by groundwater in the study region. Thus, in the present study, it is assumed that around 60% of the total water demand depends on the river discharge.

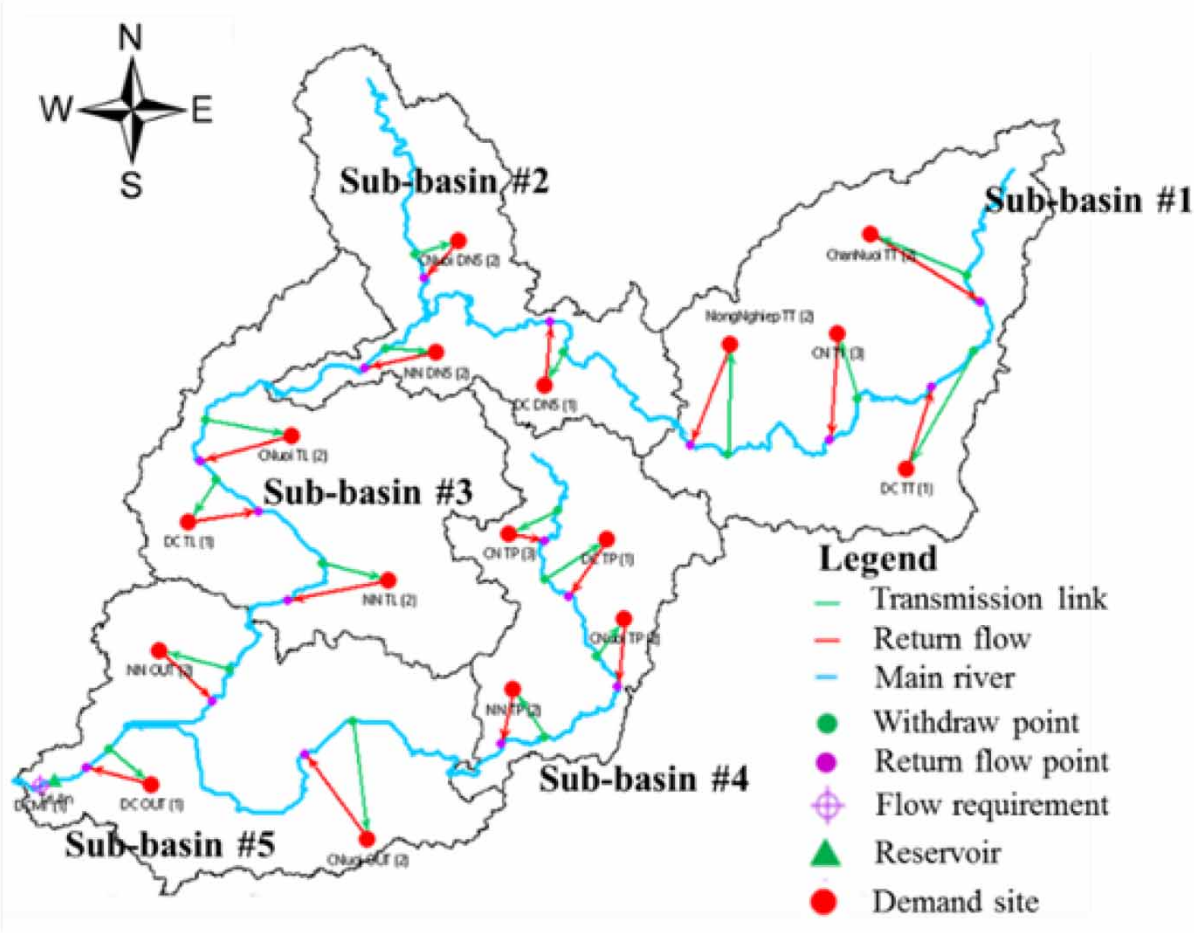

Figure 4 | Schematic diagram of the upper DNRB in the WEAP model.

Table 1 | Water-use distribution in the upper DNRB

			Water demand (million m^3)			
Subbasin	**Area (km^2)**	**Water-use activities**	**2010**	**2030**	**2050**	**2070**
Subbasin #1	3,669	Domestic, agriculture, industry, and livestock	178.1	181.8	189.5	197.3
Subbasin #2	2,522	Domestic, agriculture, and livestock	113.0	134.6	142.3	149.9
Subbasin #3	3,246	Domestic, agriculture, and livestock	114.6	127.8	130.8	133.8
Subbasin #4	2,020	Domestic, agriculture, industry, and livestock	160.2	197.3	241.6	286.0
Subbasin #5	3,243	Domestic, agriculture, and livestock	236.5	275.8	319.5	363.2
Total	14,700		802.3	917.3	1,023.8	1,130.3

In the present study, the water-use data in 2010 were considered as the baseline period. The total demand for water use was estimated to be approximately 802.3 million m^3 (Mm^3) in 2010 (Table 1). Additionally, the agricultural sector utilized a high water consumption in comparison to domestic, industrial, and livestock sectors in the upper DNRB. Three future scenarios of water use in the 2030s, 2050s, and 2070s were generated based on linear increases in population and agriculture from the period 2010–2018. The other water uses, including livestock and industry, will keep constant in the future. The total water demands of the study region for the future periods are presented in Table 1. Under the water-use scenarios, the total water demand is anticipated to increase by approximately 917.3 Mm^3 in 2030, 1,023.8 Mm^3 in 2050, and 1,130.3 Mm^3 in 2070.

3.3. LARS-WG statistical downscaling tool

As shown in Table 2, the finest spatial resolution of five GCMs is about 125 km (1.125° × 1.125°); therefore, downscaling methods from the GCM projections are usually utilized to obtain finer resolutions of river basin scales. In this study, the LARS-WG version 5.5 was applied to produce future climate scenarios of rainfall for the study region because this downscaling tool is broadly applied to evaluate the climate change impact in many regions over the world (e.g., Sha *et al.* 2019; Birara *et al.* 2020; Pushpalatha & Gangadharan 2021). The rainfall was considered for this study because it is the most important factor affecting the hydrological cycle, especially in the tropical area. The LARS-WG is a stochastic weather generator in reliance on the approach of semi-empirical distribution to estimating the weather variables (i.e., rainfall, maximum and minimum temperatures, and solar radiation) for a single site (Semenov & Barrow 1997; Semenov 2008). More details on the LARS-WG model can be referred to Semenov & Barrow (1997).

The LARS-WG setup required three steps, including calibration, validation, and weather generation of future scenarios. First, the LARS-WG was calibrated and validated using the rainfall at eight rain gauges during the period of 1986–2005 (Figure 1). The calibration and validation processes were conducted for the periods of 1987–1995 and 1996–2005, respectively. The LARS-WG performance was judged by measuring the differences between observed and simulated rainfall data using R^2 and root-mean-square error (RMSE). After successful calibration and validation against the historical data from 1986 to 2005, the LARS-WG tool was utilized to generate the future scenarios of rainfall based on five GCM outputs (Table 2) acquired from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Three future periods of 2030s (2021–2040), 2050s (2041–2060), and 2070s (2061–2080) under two emission scenarios of RCP4.5 and RCP8.5 were considered in the present study. RCP4.5 is an intermediate stabilization scenario with an equivalent concentration of CO_2 varying from 580 to 720 ppm in 2100, while RCP8.5 is a high emission scenario representing an equivalent concentration of CO_2 above 1,000 ppm in 2100 (IPCC 2013).

4. RESULTS AND DISCUSSION

4.1. Performance of calibration and validation of the SWAT model

The performance of the SWAT model in simulating the river discharge of the upper DNRB was examined against daily observed river discharge during the period of 1987–2013. Figures 5 and 6 illustrate the daily hydrographs of observed and simulated river discharge at two examined stream gauges, namely Ta Lai and Phu Hiep. The hydrographs display a good correlation between observed and simulated river discharge during the calibration period of 1987–1995 and the validation period of 1996–2013, excluding some events of extreme low and high flows. The mismatch between observed and simulated extreme flows can be attributed to the spatial unequal distribution of rain gauges, accounted existence of small dams or reservoirs, or some SWAT hydrological processes, which may not be suitable for the tropical regions, including Vietnam (Khoi & Suetsugi 2014).

Statistical indices of the SWAT performance also indicate that the daily river discharge was well reproduced by the model in reference to the ‘good’ criteria of Moriasi *et al.* (2015). Specifically, for the calibration period, the values of NSE, R^2, and P_{BIAS} were 0.83, 0.83, and −3.9% at the Ta Lai station, and 0.82, 0.82, and −0.3% at the Phu Hiep station, respectively. Regarding the

Table 2 | Five GCMs in the LARS-WG used for the present study

GCM	Institute, country	Grid resolution
GDFL-CM3	National Oceanic and Atmospheric Administration (NOAA)'s Geophysical Fluid Dynamics Laboratory, United States	2° × 2.5°
EC-EARTH	European EC-Earth consortium, Europe	1.125° × 1.125°
HadGEM2-ES	UK Meteorological Office, UK	1.25° × 1.88°
MIROC5	University of Tokyo, National Institute for Environmental Studies, Japan Agency for Marine-Earth Science and Technology, Japan	1.39° × 1.41°
MPI-ESM-MR	Max Planck Institute for Meteorology, Germany	1.85° × 1.88°

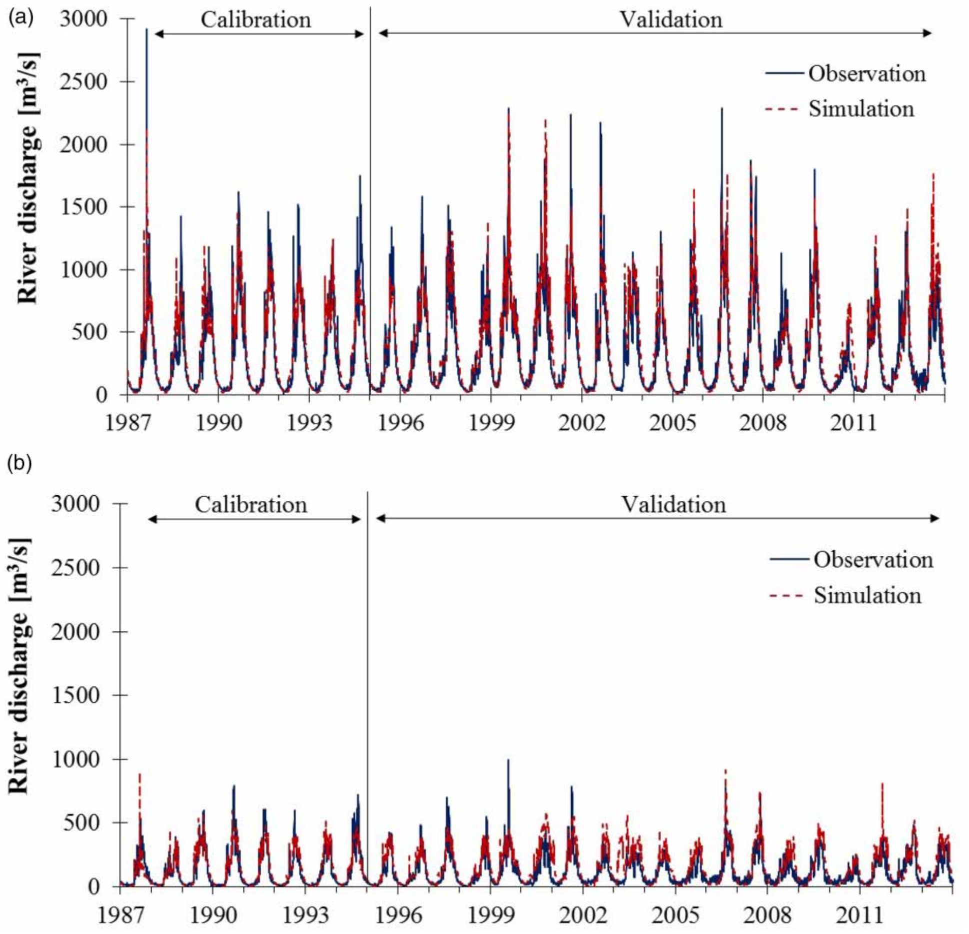

Figure 5 | Observed and simulated daily river discharge for the calibration period (1987–1995) and the validation period (1996–2013). (a) Tai Lai stream gauge. (b) Phu Hiep stream gauge.

validation period, the NSE, R^2, and P_{BIAS} values were 0.84, 0.85, and −9.2% at the Ta Lai station, and 0.60, 0.72, and −18.7% at the Phu Hiep station, respectively. Additionally, the negative values of P_{BIAS} showed that the SWAT model slightly underestimated the river discharge at both Ta Lai and Phu Hiep stations. It seems that the SWAT performance in the validation period (1996–2013) is better than that in the calibration period (1987–1995) in terms of the NSE and R^2 values at the Ta Lai stream gauge. This may be attributed to the use of land-use map in 2005. In general, it is rational to come to the conclusion that the SWAT model is reliable to be used as a simulation tool for the hydrological processes in the upper DNRB.

4.2. Climate change scenarios

Table 3 exhibits the monthly calibration (1987–1995) and validation (1996–2005) of LARS-WG results against observation data at each rain gauge in regard to the performance indices. The R^2 and RMSE values at all rain gauges varied from 0.50 to 0.70 mm and 91.8 to 149.9 mm in the calibration period, and 0.50 to 0.61 mm and 99.7 to 183.9 mm in the validation period, respectively. Overall, the performance statistics suggested that the calibrated LARS-WG tool showed an acceptable performance in replicating the rainfall for the study region, and these statistics are compatible with the previous studies (Hassan *et al.* 2014; Khoi *et al.* 2019a, 2019b).

Based on the LARS-WG downscaling results from five GCM simulations (GDFL-CM3, EC-EARTH, HadGEM2-ES, MIROC5, and MPI-ESM-MR), the ensemble average changes in rainfall for the future periods of the 2030s (2021–2040), 2050s (2041–2060), and 2070s (2061–2080) under the RCP4.5 and RCP8.5 emission scenarios in comparison to the reference period of the 2000s (1986–2005) are shown in Table 4. The values in parentheses represent the minimum and maximum values amongst the five GCM simulations. In the context of climate change, rainfall under RCP4.5 may decline by 2.9% in the 2030s and rise by 1.6% in the 2050s and 9.5% in the 2070s. In regard to RCP8.5, rainfall is projected to rise by 1.8,

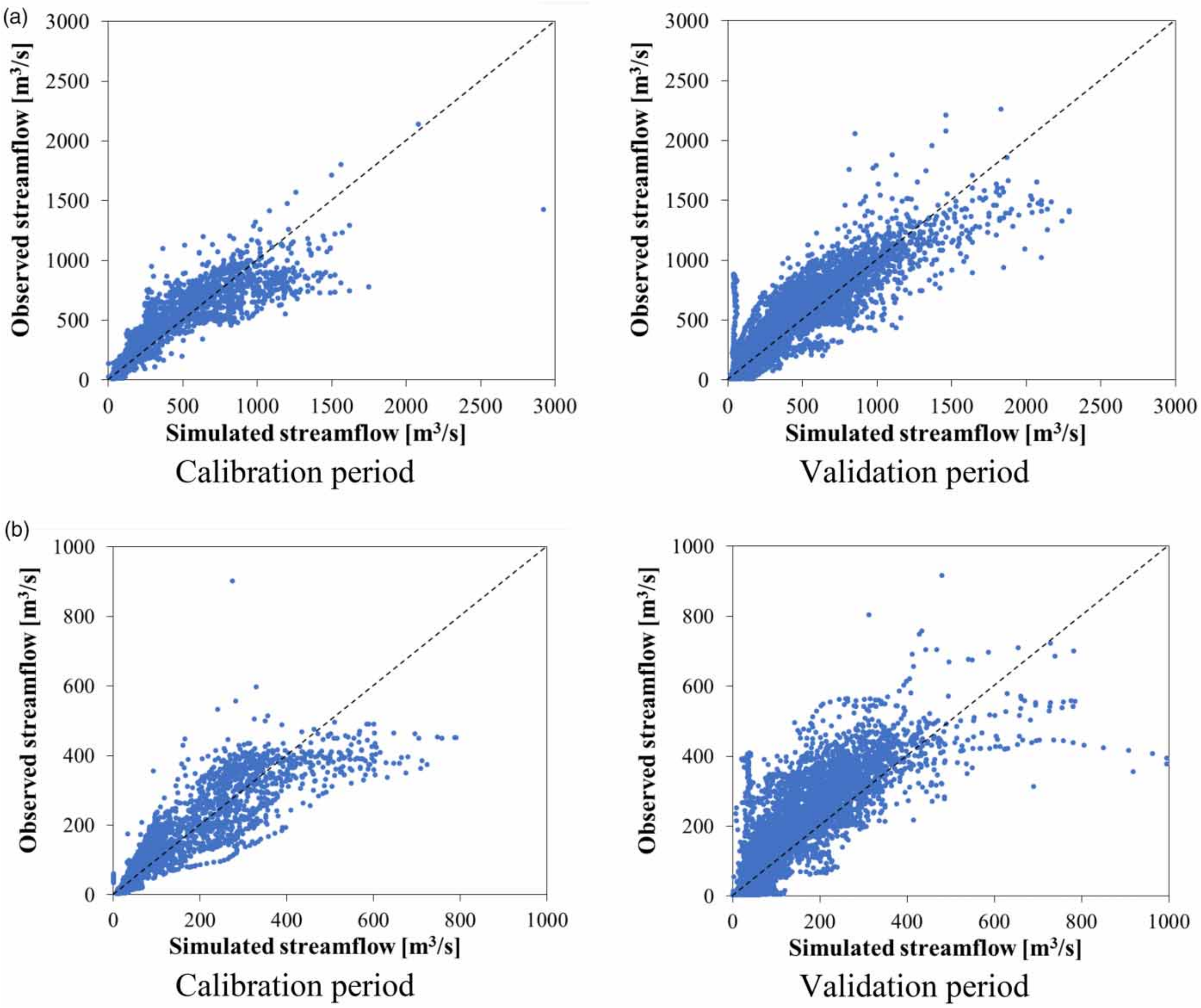

Figure 6 | Scatter plots of observed and simulated daily river discharge for the calibration period (1987–1995) and the validation period (1996–2013). (a) Ta Lai stream gauge. (b) Phu Hiep stream gauge.

Table 3 | Performance statistics of LARS-WG results against historical observed rainfall data during the calibration and validation periods

	Calibration period (1987–1995)		Validation period (1996–2005)	
Rain gauge	**RMSE**	**R^2**	**RMSE**	**R^2**
Dak Nong	141.0	0.53	151.8	0.50
Da Te	119.6	0.58	157.9	0.50
Lien Khuong	91.8	0.50	103.2	0.51
Ta Lai	125.8	0.64	153.4	0.52
Ta Pao	116.4	0.70	123.8	0.61
Tri An	106.8	0.57	112.0	0.51
Tuc Trung	118.3	0.60	99.7	0.58
Xuan Loc	112.0	0.56	116.5	0.55

4.2, and 3.5% during the 2030s, 2050s, and 2070s, respectively. In terms of seasonal rainfall, the wet-seasonal rainfall may vary from −7.6 to 9.6% for the RCP4.5 scenario, and −2.3 to 5.3% for the RCP8.5 scenario. The dry-seasonal rainfall under both RCP4.5 and RCP8.5 may substantially rise by 9.1–13.4% and 5.9–11.9%, respectively in the forthcoming time periods. In addition, there is a considerable amount of uncertainty in rainfall between the GCMs (Table 4), which may consequently affect future river discharge across the study region. Broadly speaking, the projected increase in future rainfall will lead to higher water availability at the peak of agricultural and domestic water demand in the basin.

4.3. Climate change impacts on river discharge

Under the future climate scenario RCP4.5, the mean annual discharge may reduce by 9.0% in the 2030s, and increase by 2.4% in the 2050s and 13.1% in the 2070s in comparison to the reference period of the 2000s (Table 5). In regard to the RCP8.5 scenarios, the annual discharge at the outlet of the study region (at subbasin no. 105 as shown in Figure 3(a)) is expected to be increased by 0.9, 4.5, and 4.5% in the 2030s, 2050s, and 2070s, respectively. It should be noted that there is a sharp increase in annual rainfall ranging from 1.6 to 9.5% between the 2050s and 2070s in RCP4.5. This may be associated with the changes in radiative forcing under RCP4.5. Regarding the seasonal river discharge, the wet-seasonal discharge may vary from −13.6 to 12.2% under RCP 4.5, and −3.5 to 6.6% under RCP8.5; while the dry-seasonal discharge may increase by 17.5 to 33.4% under RCP4.5, and 11.9 to 15.4% under RCP8.5. Generally, the changes in annual and seasonal discharge are conforming to the changes in annual and seasonal rainfall over the study region.

The findings show general increases in annual and wet-seasonal river discharge throughout the upper DNRB in the future, except for the near-future period of the 2030s. The finding is partly consistent with previous studies for the DNRB (Thang *et al.* 2018; Khoi *et al.* 2019a, 2019b), which presented projected increases in annual and wet-seasonal streamflow in the future. Additionally, the increase in dry-seasonal river discharge is expected to occur in the future, which is potentially beneficial to minimize water shortage events. Khoi *et al.* (2019a, 2019b) also pointed out an upward trend of future river discharge in the dry season in the La Buong River, an adjacent basin of the upper DNRB. There are a bit of differences in the magnitude of increase due to differences in GCMs and statistical downscaling techniques used between the aforementioned studies.

4.4. Analysis of unmet water demand under scenarios of climate change and water use

In the present study, the baseline scenario was determined by a combination of climate conditions of the 2000s (1986–2005) and current water use in 2010. The average annual unmet demand for water use was estimated to be approximately $32.9 \times 10^3\ m^3$ in the baseline scenario, whereby the unmet demand for agricultural use accounted for around 98%. The water

Table 4 | Projected changes in annual and seasonal rainfall under the climate change impact

		Annual	**Wet season**	**Dry season**
RCP4.5	2030s	−2.9% (−10.8–6.9%)	−7.6% (−10.1–4.9%)	10.5% (−10.0–27.6%)
	2050s	1.6% (−9.0–11.4%)	3.5% (−16.6–21.4%)	9.1% (−8.2–20.6%)
	2070s	9.5% (−7.5–22.9%)	9.6% (−8.3–22.4%)	13.4% (−8.4–43.4%)
RCP8.5	2030s	1.8% (−14.9–5.7%)	−2.3% (−28.1–6.9%)	5.9% (−2.8–10.8%)
	2050s	4.2% (−10.3–5.3%)	4.1% (−19.6–7.2%)	11.9% (−5.1–22.8%)
	2070s	3.9% (−15.9–25.5%)	5.3% (−18.7–27.4%)	9.4% (−15.1–32.4%)

Table 5 | Projected changes in annual and seasonal river discharge under the climate change impact

		Annual	**Wet season**	**Dry season**
RCP4.5	2030s	−9.0% (−21.1–8.4%)	−13.6% (−24.0–4.6%)	17.5% (−10.0–45.1%)
	2050s	2.4% (−18.1–16.8%)	−4.9% (−21.1–15.0%)	20.0% (−11.4–30.4%)
	2070s	13.1% (−14.9–35.0%)	12.2% (−15.7–13.5%)	33.4% (−13.4–63.1%)
RCP8.5	2030s	0.9% (−26.4–8.2%)	−1.0% (−30.4–8.7%)	12.7% (−11.3–40.0%
	2050s	4.5% (−20.0–6.4%)	−3.5% (−21.9–5.7%)	11.9% (−15.2–26.0%)
	2070s	4.5% (−32.0–37.6%)	6.6% (−35.8–29.3%)	15.4% (−14.2–90.6%)

shortage mainly occurred in three dry-seasonal months (January–March) with the peak of unmet demand in February, and it was mostly taking place in the upstream of the upper DNRB at the Subbasin #1.

The unmet water demand under the climate change scenarios is represented in Figure 7. Under the impact of climate change, the unmet demand is projected to slightly reduce in the future. Specifically, the unmet demand is anticipated to decline ranging from 7.0 to 30.1% under RCP4.5 and 7.8 to 11.7% under RCP8.5, when compared to the baseline scenario. These reductions in water scarcity are due to projected increases in dry-seasonal river discharge. Similar to the baseline scenario, the water shortage under RCP4.5 and RCP8.5 may still occur in the three dry-seasonal months of January–March.

The unmet demand for water use under the combined scenarios of climate change and water use is shown in Figure 8. As mentioned in Table 1, the water demand in the study region is expected to significantly increase in the future as a result of population growth and agricultural expansion. Concerning the aggregated impacts of future climate change and water use, the unmet demand is anticipated to reduce by 12.2 in the 2030s, rise by 5.2% in the 2050s, and reduce by 18.6% in the 2080s under the RCP4.5 scenario in comparison to the baseline period. Under the RCP8.5 scenario, the unmet demand may slightly reduce by 3.3% during the near-future period of the 2030s, but slightly increase by 1.8 and 6.0% during the two following periods of the 2050 and 2070s, respectively. Generally speaking, the water shortage in the upper DNRB may be slightly reduced in the dry season by the climate change impact, but it still occurs in the future due to significantly increasing demand in agricultural and domestic uses. The previous study conducted by Dau *et al.* (2021) also indicated that climate change may reduce the water shortage and increasing demand for domestic use may accelerate the water scarcity in the Huong River Basin (Vietnam).

The findings of the present study recommend that upgrading reservoirs and building more new reservoirs may be an appropriate solution to control water for irrigation activities and to ensure enough water for domestic water supply during the dry season, particularly on the upstream of the upper DNRB. Additionally, reasonable management of water demand, such as

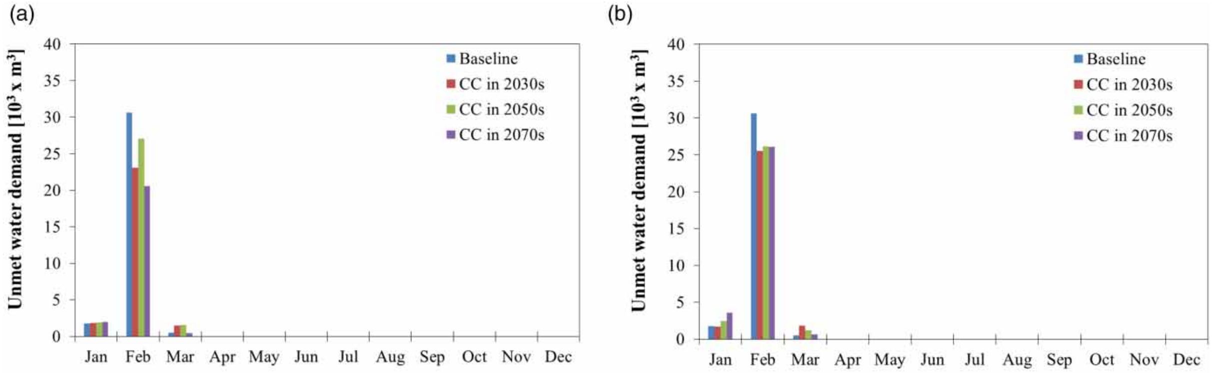

Figure 7 | Unmet water demand under the climate change (CC) scenarios: (a) RCP4.5 scenario and (b) RCP8.5 scenario.

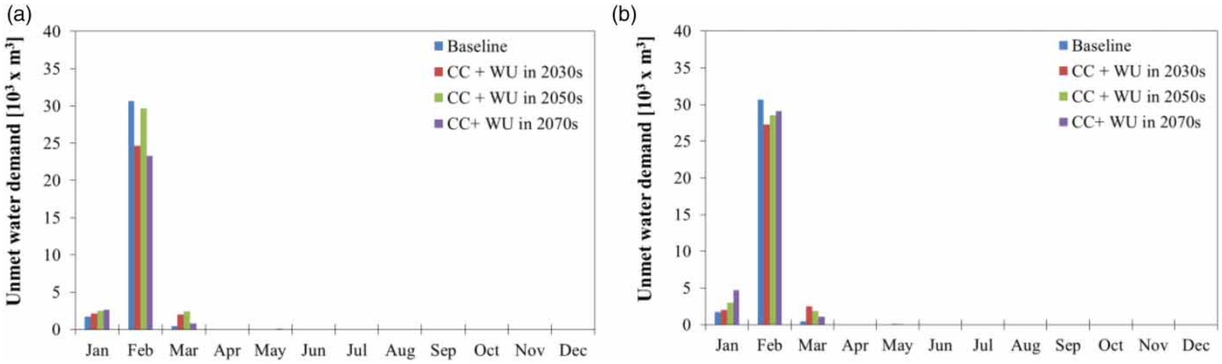

Figure 8 | Unmet water demand under the combined scenarios of climate change (CC) and water use (WU): (a) RCP4.5 scenario and (b) RCP8.5 scenario.

rearranging the crop pattern and structure in accordance with the ability of water allocations or changing the crops to crops requiring less water, will be a possible solution, especially in the context of increasing water demand in the future. The recommendations here are in line with these of the studies conducted by Sapkota *et al.* (2013) and Touch *et al.* (2020). Moreover, the optimization of water allocation is a feasible option for effective management of water supply, as for example of giving high priorities for supplying domestic water and irrigating high-value crops.

5. CONCLUSIONS

This study inquired into the impacts of climate change on water availability of the upper DNRB, an important river basin in southern Vietnam, using the SWAT and WEAP models. The results indicated that annual rainfall of the study region under RCP4.5 and RCP8.5 is anticipated to be increased by 1.6–9.5% in the future, excluding the 2.9% to be decreased in the 2030s under RCP4.5. Furthermore, the future rainfall is predicted to have an upward trend in the dry under both RCP4.5 and RCP8.5 scenarios. Similar to changes in future rainfall, the annual discharge is projected to increase from 0.9 to 13.1%, and the dry-seasonal discharge is anticipated to be increased from 11.9 to 33.4% in the future. Regarding water availability, water shortage happened in three dry-seasonal months of January–March in the baseline scenario. Climate change may result in a 7.0–30.1% reduction of water shortage in the future in comparison to the baseline scenario. In case of that the increasing demands for water use due to population growth and agricultural expansion are incorporated, water shortage will vary from −18.6 to 6.0% in the future. The results provide valuable insights to implement appropriate water management strategies to minimize water shortage in the future. Generally speaking, the findings highlight the need to propose suitable adaptation measures to meet future water requirements for domestic and agricultural uses in the context of climate change.

ACKNOWLEDGEMENTS

The study was supported by the Department of Science and Technology of Ho Chi Minh City and managed by the Institute for Computational Science and Technology under the contract number 05/2019/HĐ-KHCNTT.

AUTHOR CONTRIBUTIONS

D.N.K. was involved in the conceptualization, methodology, formal analysis, draft writing, review, and editing; V.T.N. was involved in the conceptualization, methodology, funding acquisition, supervision, review, and editing and finalized the manuscript; T.T.S. was involved in the software, formal analysis, visualization, and preparing original draft; N.T.H.M. was involved in the software, formal analysis, visualization, and preparing the original draft; N.D.V. was involved in the data collection and formal analysis; and H.V.C. was involved in the data collection and formal analysis.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

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

Alcamo, J., Florke, M. & Marker, M. 2007 Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrological Sciences Journal* **52** (2), 247–275. http://doi.org/10.1623/hysj.52.2.247.

Allani, M., Mezzi, R., Zouabi, A., Béji, R., Joumade-Mansouri, F., Hamza, M. E. & Sahli, A. 2020 Impact of future climate change on water supply and irrigation demand in a small Mediterranean catchment. Case study: Nebhana dam system, Tunisia. *Journal of Water and Climate Change* **11** (4), 1724–1747.

Asghar, A., Iqbal, J., Amin, A. & Ribbe, L. 2019 Integrated hydrological modeling for assessment of water demand and supply under socio-economic and IPCC climate change scenarios using WEAP in Central Indus Basin. *Journal of Water Supply: Research and Technology – AQUA* **68** (2), 136–148.

Beck, L. & Bernauer, T. 2011 How will combined changes in water demand and climate affect water availability in the Zambezi river basin? *Global Environmental Change* **21** (3), 1061–1072.

Birara, H., Pandey, R. P. & Mishra, S. K. 2020 Projections of future rainfall and temperature using statistical downscaling techniques in Tana Basin, Ethiopia. *Sustainable Water Resources Management* **6** (5), 77. http://doi.org/10.1007/s40899-020-00436-1.

Boretti, A. & Rosa, L. 2019 Reassessing the projections of the World Water Development Report. *NPJ Clean Water* **2** (1), 15.

Dahal, P., Shrestha, M. L., Panthi, J. & Pradhananga, D. 2020 Modeling the future impacts of climate change on water availability in the Karnali River Basin of Nepal Himalaya. *Environmental Research* **185**, 109430.

Dau, Q. V., Kuntiyawichai, K. & Adeloye, A. J. 2021 Future changes in water availability due to climate change projections for Huong Basin, Vietnam. *Environmental Processes* **8** (1), 77–98. http://doi.org/10.1007/s40710-020-00475-y.

Ficklin, D. L., Abatzoglou, J. T., Robeson, S. M., Null, S. E. & Knouft, J. H. 2018 Natural and managed watersheds show similar responses to recent climate change. *Proceedings of the National Academy of Sciences* **115** (34), 8553–8557. http://doi.org/10.1073/pnas.1801026115.

GSO 2015 *Statistical Yearbook of Vietnam*. General Statistics Office of Vietnam, Hanoi, Vietnam. https://www.gso.gov.vn/en/data-and-statistics/2019/10/statistical-yearbook-of-vietnam-2015-2/

Hassan, Z., Shamsudin, S. & Harun, S. 2014 Application of SDSM and LARS-WG for simulating and downscaling of rainfall and temperature. *Theoretical and Applied Climatology* **116** (1–2), 243–257. http://doi.org/10.1007/s00704-013-0951-8.

Hussen, B., Mekonnen, A. & Pingale, S. M. 2018 Integrated water resources management under climate change scenarios in the sub-basin of Abaya-Chamo, Ethiopia. *Modeling Earth Systems and Environment* **4** (1), 221–240. http://doi.org/10.1007/s40808-018-0438-9.

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

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

IPCC 2018 *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*. In press.

JICA 2018 *Data Collection Survey on Water Resources Management in Central Highlands: Final Report*. Tokyo, Japan.

Khoi, D. N. & Suetsugi, T. 2014 The responses of hydrological processes and sediment yield to land-use and climate change in the Be River Catchment, Vietnam. *Hydrological Processes* **28** (3), 640–652. http://doi.org/10.1002/hyp.9620.

Khoi, D. N., Thom, V. T., Quang, C. N. X. & Phi, H. L. 2017 Parameter uncertainty analysis for simulating streamflow in the upper Dong Nai river basin. *Houille Blanche* (1), 14–23. http://doi.org/10.1051/lhb/2017003.

Khoi, D. N., Nguyen, V., Sam, T. T. & Nhi, P. 2019a Evaluation on effects of climate and land-use changes on streamflow and water quality in the la buong river basin, southern Vietnam. *Sustainability* **11** (24), 7221.

Khoi, D. N., Sam, T. T., Nhi, P. T. T., Quan, N. T., Hung, B. V., Phung, N. K. & Van Thinh, N. 2019b Uncertainty assessment for climate change impact on streamflow and water quality in the Dong Nai River Basin, Vietnam. In: *World Environmental and Water Resources Congress 2019*. American Society of Civil Engineers, Reston, VA, pp. 366–373. http://doi.org/10.1061/9780784482346.037.

Kifle Arsiso, B., Mengistu Tsidu, G., Stoffberg, G. H. & Tadesse, T. 2017 Climate change and population growth impacts on surface water supply and demand of Addis Ababa, Ethiopia. *Climate Risk Management* **18**, 21–33.

MOC 2006 *TCXD 22:2006 Water Supply – Distribution System and Facility Design Standard*. Ministry of Construction, Hanoi, Vietnam. https://www.scribd.com/document/413833119/TCXDVN-33-2006-Design-Standard-Water-Supply-External-Networks-and-Facilities

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., H, R. D. & Veith, T. L. 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **50**, 885–900.

Moriasi, D. N., Gitau, M. W., Pai, N. & Daggupati, P. 2015 Hydrologic and water quality models: performance measures and evaluation criteria. *Transactions of the ASABE* **58** (6), 1763–1785.

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

Nhi, P. T. T., Khoi, D. N. & Hoan, N. X. 2019 Evaluation of five gridded rainfall datasets in simulating streamflow in the upper Dong Nai River Basin, Vietnam. *International Journal of Digital Earth* **12** (3), 311–327. http://doi.org/10.1080/17538947.2018.1426647.

Pushpalatha, R. & Gangadharan, B. 2021 Assessing the influence of climate model biases in predicting yield and irrigation requirement of cassava. *Modeling Earth Systems and Environment* **7** (1), 307–315. http://doi.org/10.1007/s40808-020-01038-8.

Sapkota, P., Bharati, L., Gurung, P., Kaushal, N. & Smakhtin, V. 2013 Environmentally sustainable management of water demands under changing climate conditions in the Upper Ganges Basin, India. *Hydrological Processes* **27** (15), 2197–2208. http://doi.org/10.1002/hyp.9852.

Seiber, J. & Purkey, D. 2015 *Water Evaluation and Planning System: User Guide for WEEAP21*. Stockholm Environment Institute Tellus Institute, Boston, MA.

Semenov, M. A. 2008 Simulation of extreme weather events by a stochastic weather generator. *Climate Research* **35** (3), 203–212.

Semenov, M. A. & Barrow, E. M. 1997 Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change* **35**, 397–414.

Sha, J., Li, X. & Wang, Z.-L. 2019 Estimation of future climate change in cold weather areas with the LARS-WG model under CMIP5 scenarios. *Theoretical and Applied Climatology* **137** (3–4), 3027–3039. http://doi.org/10.1007/s00704-019-02781-4.

Thang, L. V., Khoi, D. N. & Phi, H. L. 2018 Impact of climate change on streamflow and water quality in the upper Dong Nai river basin, Vietnam. *La Houille Blanche* **2018** (1), 70–79. http://doi.org/10.1051/lhb/2018010.

Touch, T., Oeurng, C., Jiang, Y. & Mokhtar, A. 2020 Integrated modeling of water supply and demand under climate change impacts and management options in tributary basin of Tonle Sap Lake, Cambodia. *Water* **12** (9), 2462.

Touseef, M., Chen, L. & Yang, W. 2021 Assessment of surface water availability under climate change using coupled SWAT-WEAP in Hongshui River Basin, China. *ISPRS International Journal of Geo-Information* **10** (5), 298.

Tram, V. N. Q., Liem, N. D. & Loi, N. K. 2019 Simulating surface flow and baseflow in Poko catchment, Kon Tum province, Vietnam. *Journal of Water and Climate Change* **10** (3), 494–503. https://doi.org/10.2166/wcc.2018.185.

Truong, N., Nguyen, H. & Kondoh, A. 2018 Land use and land cover changes and their effect on the flow regime in the upstream Dong Nai River Basin, Vietnam. *Water* **10** (9), 1206.

UNESCO and UN-Water 2020 *The United Nations World Water Development Report 2020: Water and Climate Change*. UNESCO, Paris.

WEF (World Economic Forum) 2021 *The Global Risks Report 2021*. Geneva, Switzerland.

World Bank 2019 *Vietnam: Toward a Safe, Clean, and Resilient Water System*. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/31770

Yan, D., Yao, M., Ludwig, F., Kabat, P., Huang, H. Q., Hutjes, R. W. A. & Werners, S. E. 2018 Exploring future water shortage for large river basins under different water allocation strategies. *Water Resources Management* **32** (9), 3071–3086. https://doi.org/10.1007/s11269-018-1975-8.

First received 1 July 2021; accepted in revised form 30 August 2021. Available online 13 September 2021