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Impact of future climate change on river discharge and groundwater recharge: a case study of Ho Chi Minh City, Vietnam

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ABSTRACT

Climate change (CC) is likely to have a long-term influence on regional water resources, including surface water and groundwater. Therefore, quantifying the CC influence is indispensable for proper management of water resources. This study scrutinized the influence of CC on river discharge and groundwater recharge (GWR) in Ho Chi Minh City (HCMC), Vietnam, utilizing the Soil and Water Assessment Tool (SWAT). The calibrated SWAT was utilized to simulate the discharge and GWR under projected climate scenarios in reliance on an ensemble of seven General Circulation Models (GCMs) derived from Coupled Model Intercomparison Project Phase 6 (CMIP6) under three Shared Socioeconomic Pathways (SSPs), including SSP1-2.6, SSP2-4.5, and SSP5-8.5. Results pointed out that the climate of HCMC is warmer and wetter in the 21st century. Under the CC influence, the future discharge is envisaged to rise from 0.1 to 4.5% during the near-future period of 2030s (2021–2045), 8.1 to 11.6% during the mid-future period of 2055s (2046–2070), and 7.7 to 19.6% during the far-future period of 2080s (2071–2095) under the three SSP scenarios. In addition, the GWR is prognosticated to have rising trends of 0.9–4.9%, 5.3–7.9%, and 5.7–13.5% during the near-future, mid-future, and far-future periods, respectively. Furthermore, uncertainties in the discharge and GWR projections connected with SSP scenarios and CMIP6 GCMs are considerable.

Key words: climate change, CMIP6, groundwater recharge, hydrological model, river discharge, Vietnam

HIGHLIGHTS

- This study investigated the projected influence of climate change on discharge and groundwater recharge (GWR).
- Discharge and GWR will rise in the 21st century under three SSPs.
- Uncertainties related to SSPs and CMIP6 GCMs are considerable.

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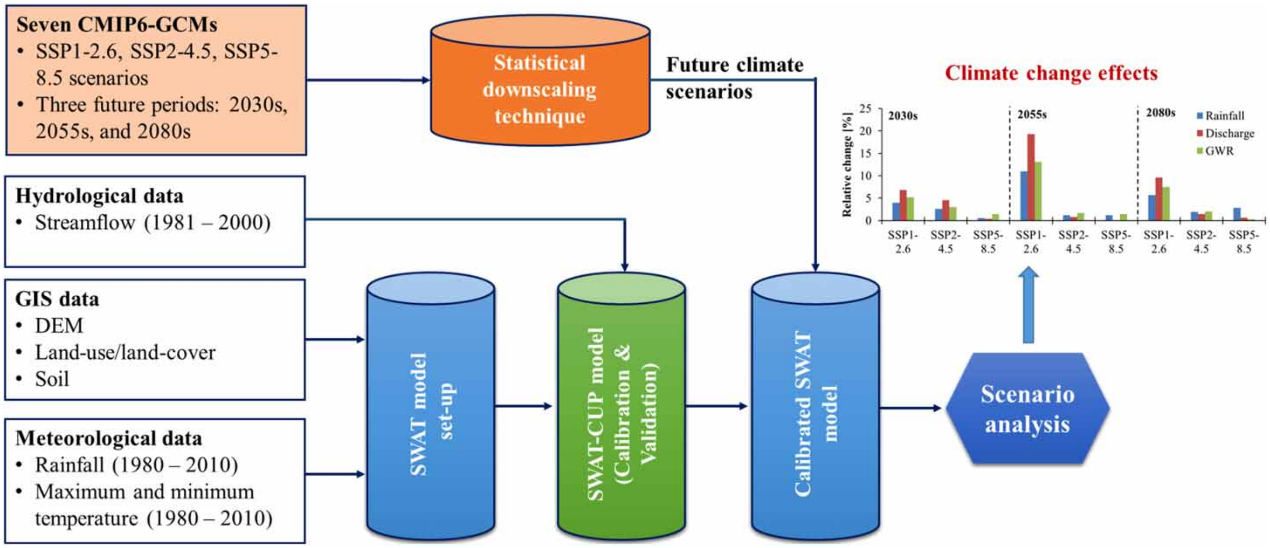
GRAPHICAL ABSTRACT



1. INTRODUCTION

According to the World Economic Forum's Global Risks Report, climate change (CC) is listed as one of the topmost environmental challenges at both global and regional scales (WEF 2021). The rising emission of greenhouse gas (GHG) into the atmosphere owing to anthropogenic activities is the main cause of CC (IPCC 2018). Changes in climatic conditions (i.e., temperature rise and rainfall alteration) will directly affect the water cycle by altering actual evapotranspiration, infiltration, lateral flow, groundwater recharge (GWR), and surface runoff. Consequently, these alterations will influence the availability of freshwater resources, including surface water and groundwater, across many regions of the world. CC directly affects both surface water and groundwater resources, but estimating the influence on groundwater resources shows a considerable challenge. Since groundwater is a vital source of freshwater for both human uses and ecosystems, the GWR is considered as one of the key hydrological factors for estimating the surface and subsurface water balance (Ghimire *et al.* 2021). According to Amanambu *et al.* (2020), groundwater accounts for approximately 96% of the unfrozen freshwater and 33% of global water withdrawals. Therefore, understanding changes in the GWR under the CC influence is of the essence for effective management and planning of groundwater.

In the last few years, many investigations have been carried out to estimate the projected influence of CC on freshwater availability in many areas of the globe (e.g., Bhatta *et al.* 2019; Nilawar & Waikar 2019; Singh & Saravanan 2020). For example, Gebrechorkos *et al.* (2020) inspected the CC effect on hydrology of the Awash basin using the Soil and Water Assessment Tool (SWAT) and downscaled climate data from CanESM2 under two Representative Concentration Pathways (RCPs), namely RCP4.5 and RCP8.5. They denoted that the annual precipitation, maximum temperature (Tmax), minimum temperature (Tmin), and streamflow may rise during the period of 2011–2100. Negewo & Sarma (2021) scrutinized the response of water yield of the Genale basin to changing climate and revealed that a reduction in precipitation and a rise in temperature are likely to decrease the future water yield. Recently, Li & Fang (2021) utilized a statistical downscaling technique (delta change (DC) method) to downscale climate data from 34 General Circulation Models (GCMs) under three RCP scenarios (RCP2.6, RCP4.5, and RCP8.5) in the Chi Mun basin. The downscaled climate data were applied as input for the SWAT hydrological model to calculate streamflow. Results denoted that the streamflow of the Chi Mun basin is prognosticated to have a rising trend in the future period of 2020–2093. In general, the influence of CC on water availability varies depending on the region; subsequently, it is indispensable to have the regional studies. Additionally, many investigations have addressed the potential influence of CC on the surface water, but few have investigated the response of groundwater to changing climate (i.e., Gemitzi *et al.* 2017; Petpongpan *et al.* 2020).

The prevalent approach for quantifying the CC influence is the use of a hydrological model for simultaneous simulation of surface water and groundwater. In this approach, the hydrological model is coupled with downscaled climate projections in

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reliance on the GCM simulations under different emission scenarios. Among the hydrological models, SWAT, an open-source and semi-distributed model, has been extensively employed in hydrological studies in many basins all over the world (e.g., Khoi *et al.* 2020; Li & Fang 2021; Negewo & Sarma 2021). Additionally, this model has been utilized to estimate the response of GWR to environmental change conditions (i.e., CC and land-use/land-cover change) (e.g., Gyamfi *et al.* 2017; Adhikari *et al.* 2020). Recently, the Intergovernmental Panel on Climate Change (IPCC) has released the sixth phase of the Coupled Model Intercomparison Project Phase 6 (CMIP6) climate simulations for the sixth IPCC world climate report. The improvement of CMIP6 GCMs is expected to solve the limitation of CMIP5 CGMs, such as the presence of bias in annual and seasonal rainfall (Iqbal *et al.* 2021). CMIP6 characterizes new scenarios called Shared Socioeconomic Pathways (SSPs). As a consequence, the implementation of new CMIP6 climate simulations in hydrological studies is likely to become a hot issue in the very near future. In addition, uncertainty in future projections of river discharge and GWR originating from a range of CC scenarios derived from CMIP6 has not been fully investigated yet.

As stated in the United Nations Development Program (UNDP) report, Asia is identified as the most vulnerable region to water scarcity in the world, especially in the context of changing climate (UNDP 2007). In the midst of Asian nations, Vietnam, the developing country with the Gross Domestic Product (GDP) growth rate of approximately 5–7% per year in the period 2010–2019 is listed as one of the top vulnerable nations to changing climate (IPCC 2018). This country had experienced a temperature rise of approximately 0.62 °C and a rainfall change, including rainfall reduction of approximately 5.8–12.5% in the northern region and a rainfall increase of around 6.9–19.8% in the southern region in the historical period of 1958–2014 (MONRE 2016). CC is envisaged to influence the spatio-temporal distribution of water availability in the country. Ho Chi Minh City (HCMC) is an economic and financial center of Vietnam, contributing approximately 23% of Vietnam's GDP and 27% of the national budget revenue (HCMC-SO 2019). There are two main sources of water supply for the socio-economic development of HCMC, including surface water from the Sai Gon and Dong Rivers and groundwater. In 2010, the exploited water volume was approximately 1.5 million m^3/day from surface water and 0.7 million m^3/day from groundwater (van Leeuwen *et al.* 2016). There is a high reliance of water supply on surface water and groundwater; however, the river discharge and GWR have been influenced by CC. Accordingly, it is very important to inspect the CC influence on river discharge and GWR in HCMC, which is essential for a robust comprehension of projected changes in water availability.

The major objective of the present study was to scrutinize the projected influence of CC on river discharge and GWR in HCMC, Vietnam. Given that very few investigations have been conducted into the influence of CC on GWR and its uncertainty in GWR projections, especially using CMIP6 climate simulations, this work seeks to fill the research gap. The findings of the present study will provide a scientific basis for sustainable water resource management in the CC context.

2. STUDY REGION

The study region was HCMC (latitude 10°10′–10°40′ N and longitude 106°20′–106°50′ E) situated in South Vietnam (Figure 1). The HCMC's total area is 2,095 km^2, and the total population was approximately 8.8 million in 2018 with an average population density of 4,197 persons/km^2 (HCMC-SO 2019). The study region is located in the downstream part of the Dong Nai River Basin. The climate in HCMC is a tropical monsoon with a wet season from May to October (accounting for approximately 80–85% of the total annual rainfall) and a dry season from November to April. The annual rainfall varied from 2,000 to 2,700 mm, and the annual mean temperature fluctuated from 28.5 to 28.8 °C in the period of 2010–2018. HCMC is the largest and most crowded metropolis in Vietnam. Moreover, it is the biggest economic hub of the country with a 7.7% Gross Regional Domestic Product (GRDP) growth rate and contributing approximately 23% of Vietnam's GDP (HCMC-SO 2019). The lower Dong Nai River Basin plays a vital role in water supply for domestic, agricultural, industrial, and service purposes for the socio-economic development of HCMC.

3. MATERIAL AND METHODS

3.1. SWAT model description

This investigation applied the SWAT model to scrutinize the CC influence on hydrological processes in HCMC. The SWAT model, a physically based and semi-distributed hydrological model, is developed to project the effect of CC, land-use/land-cover change, and land management practices on hydrological components, sediment, and nutrient yields at a basin scale (Neitsch *et al.* 2011). In the SWAT model, hydrological processes of the basin are reproduced using the balance equation

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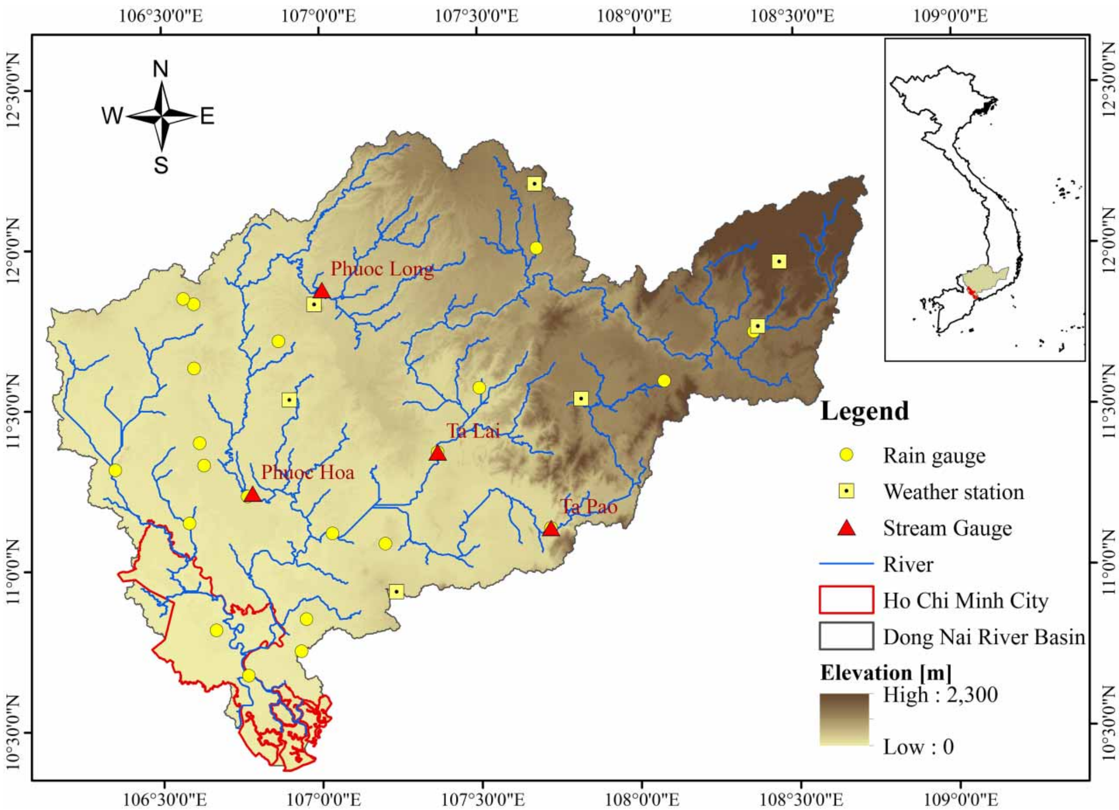

Figure 1 | Location map of the HCMC.

of soil water storage that comprises rainfall, surface runoff, evapotranspiration, water percolation, and groundwater or base flow. The hydrology processes related to surface runoff generation and channel routing are estimated using the soil conservation service – curve number (SCS-CN) and variable storage coefficient methods, respectively. More detailed information on the SWAT theory is given in Neitsch *et al.* (2011). Main outputs of the SWAT simulation, including river discharge (Q) and GWR, were scrutinized in this study.

3.2. SWAT setup, calibration, and validation

Data necessary to run the SWAT model comprise topography, land-use/land-cover, soil, and meteorology. Table 1 presents the input data collected for this study. This study utilized the Digital Elevation Model (DEM) data to delineate the basin and sub-basins, and estimate topographical features of these sub-basins. The land-use/land-cover and soil data were utilized to define hydrological response units (HRUs) and link the topography with the crop and soil databases. Because there was a

Table 1 | Datasets utilized in this study

Data required	Description	Spatial/temporal resolution	Data source
Topography	Digital Elevation Model	30 m	Shuttle Radar Topography Mission
Land-use/ land-cover	Land-use/land-cover classes in 2005	300 m	European Space Agency Climate Change Initiative
Soil	Physical and chemical features of soil types	10 km	Food and Agriculture Organization
Meteorology	Rainfall and temperature in the period of 1980–2010, 20 rain gauges, and 7 meteorological stations	Daily	Hydro-Meteorological Data Centre
Hydrology	River discharge in the period of 1981–2000 and 4 stream gauges	Daily	Hydro-Meteorological Data Centre

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difference in spatial resolutions of DEM, land-use/land-cover, and soil data, the SWAT automatically resampled land-use/land-cover and soil data to finer resolution. The spatial accuracy of the SWAT for this study was 30 m. A 10% threshold for land-use/land-cover, soil, and slope classes was utilized to define HRUs of the study region. Furthermore, the daily meteorological data from 20 rain gauges and 7 weather stations covering the study region were gathered for the period of 1980–2010. Missing values in the meteorological data were filled using a WGEN weather generator in the SWAT. The daily river discharge data were utilized to calibrate and validate the SWAT effectiveness. This study utilized the discharge data at four main stream gauges, namely Phuoc Long, Phuoc Hoa, Ta Lai, and Ta Pao, for the period of 1981–2000.

The Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm in SWAT Calibration and Uncertainty (SWAT-CUP) Program (Abbaspour 2015) was utilized for the SWAT calibration. The model calibration utilized 12 parameters related to surface, subsurface, and channel hydrological responses, which were chosen in reliance on a review of similar literature (e.g., Khoi *et al.* 2017; Thang *et al.* 2018; Adhikari *et al.* 2020). Based on the availability of the measured discharge data, the calibration step was carried out for the period of 1981–1990 and the validation step was conducted for the period of 1991–1993 at the Phuoc Long stream gauge and 1991–2000 at the Phuoc Hoa, Ta Lai, and Ta Pao stream gauges. The model effectiveness in the calibration and validation processes was evaluated by comparing the measured and simulated discharge using three efficiency statistics, comprising the coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), and percent bias (Pbias). Moriasi *et al.* (2007) recommended that a model simulation providing values of $R^2>0.5$, NSE>0.5, and PBIAS=$\pm$25% is considered as good enough.

3.3. Future climate projections using the change factor downscaling technique

The GCM simulations produce the climate information at a global scale, which are too coarse for regional studies on the hydrological influence of CC. Thus, the change factor (CF) or DC downscaling technique was used to convert the GCM outputs applied to climate variables (i.e., rainfall and temperature) at a regional or local scale. The CF method was used for the reason that it demands fewer computational resources and can effortlessly generate a broad range of climate scenarios from a variety of GCMs (Khoi & Suetsugi 2012). Furthermore, this method has been extensively used in studies on hydrological responses to changing climate (e.g., Ehteram *et al.* 2018; Feng *et al.* 2020; Farzin & Anaraki 2021). In the CF method, monthly CFs are estimated in reliance on differences between future and historical monthly climate variables simulated by a GCM. The monthly CFs are subsequently applied to modify the daily measured climate data in order to generate future climate projections. Specifically, the multiplicative CFs are utilized for modifying the measured daily rainfall, and the additive CFs are utilized for adjusting the measured daily maximum and minimum temperatures.

Future climate projections of the study region were created in reliance on seven CMIP6 GCM outputs under three SSPs, namely SSP1-2.6, SSP2-4.5, and SSP5-8.5 (Table 2). SSP1-2.6 represents the ‘sustainability with limit of 2 °C’ scenario with a nominal radiative forcing level of 2.6 W/m^2, SSP2-4.5 indicates the ‘middle of the road’ scenario with a nominal radiative forcing level of 4.5 W/m^2, and SSP5-8.5 indicates the ‘business as usual’ or ‘fossil-fueled development’ scenario with a nominal radiative forcing level of 8.5 W/m^2 by 2100 (Riahi *et al.* 2017). The use of an ensemble average of GCM simulations will

Table 2 | Brief description of seven CMIP6 GCM simulations selected for the present study

Model	Institution	Country	Resolution (lon × lat)
CanESM5-CanOE	Canadian Centre for Climate Modeling and Analysis	Canada	2.81° × 2.81°
CNRM-CM6.1	Centre National de Recherches Météorologiques	France	1.40° × 1.40°
CNRM-CM6.1-HR	Centre National de Recherches Météorologiques	France	0.5° × 0.5°
MIROC6	National Institute for Environmental Studies, The University of Tokyo	Japan	1.40° × 1.40°
MIROC-ES2 L	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (University of Tokyo), and National Institute for Environmental Studies	Japan	2.81° × 2.81°
MPI-ESM1-2-LR	Max Planck Institute for Meteorology	Germany	1.88° × 1.88°
MRI-ESM2	Meteorological Research Institute	Japan	1.12° × 1.12°

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minimize the potential bias of any specific GCM (Knutti *et al.* 2010) and help to reduce model uncertainty, i.e., the deviation range between observation and simulation, and to improve the reliability of the model outputs (Yang *et al.* 2018). In the present study, the future climate projections were produced for the near-future period of 2030s (2021–2045), mid-future period of 2055s (2046–2070), and far-future period of 2080s (2071–2095). The 25-year period of future climate projections was chosen for this study because it has been widely utilized in many CC investigations (i.e., Thang *et al.* 2018; Li & Fang 2021).

4. RESULTS AND DISCUSSION

4.1. SWAT effectiveness evaluation

The effectiveness of the calibrated SWAT model for the study region was assessed against measured discharge data for the historical period of 1981–2000. Figure 2 displays the graphical comparison between measured and simulated daily discharge time series at the four stream gauges, namely Phuoc Long, Phuoc Hoa, Ta Lai, and Ta Pao, using the optimized values of 12 SWAT parameters as shown in Table 3. The figure points out that the simulated discharge was in good line with the measured discharge at the four stream gauges. However, the calibrated SWAT model could not always capture extreme events of low and high discharge, which might be assignable to the simplified assumption of several hydrological processes in the SWAT (Lee *et al.* 2018) and the asymmetrical distribution of meteorological stations within the study region.

The efficiency statistics of river discharge data for the calibration duration (1981–1990) and the validation duration (1991–2000) are presented in Table 4. It is noted that the SWAT effectiveness in the validation duration seems to be better than that in the calibration duration in the Phuoc Long and Ta Lai stream gauges. This can be attributed to using land-use/land-cover types in 2005 for both calibration and validation durations. In addition, the SWAT effectiveness in the validation duration is lower than that in the calibration duration in the Phuoc Long and Ta Pao stream gauges because of uncounted influence of hydropower dams and reservoirs in this study. According to the efficiency criteria provided by Moriasi *et al.* (2007), the NSE, R^2, and Pbias values were rated as very good at the Phuoc Long, Phuoc Hoa, and Ta Lai stream gauges, and satisfactory at the Ta Pao station in the calibration and validation durations. This suggests that the simulated daily discharge is in good conformity with the measured values. As a whole, the simulation results indicated that the calibrated SWAT model could replicate

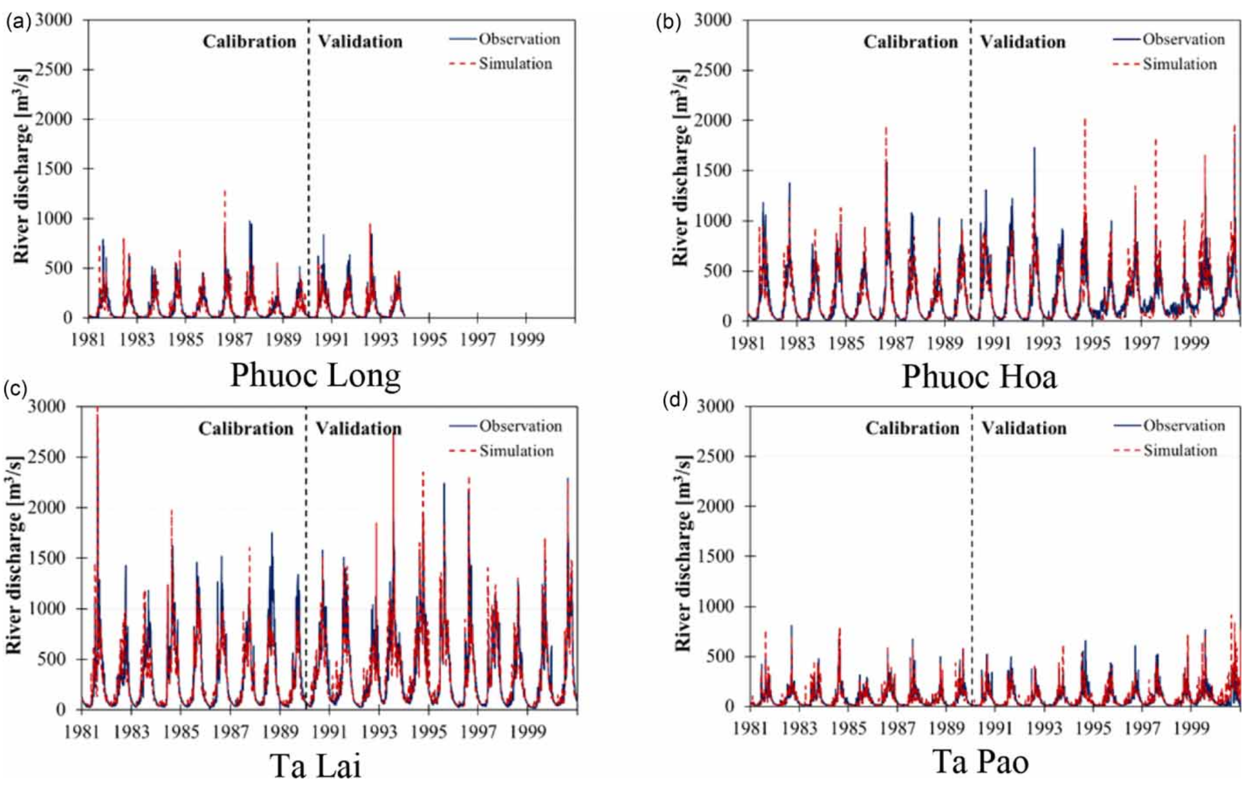

Figure 2 | The measured and simulated daily discharge during the calibration and validation durations at the four main stream gauges (a–d).

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Table 3 | The SWAT parameters and their optimized values for the river discharge simulation

No.	Parameter	Description	Range	Optimized value
1	ALPHA_BF	Base flow alpha factor	0–1	0.82
2	CN2	SCS runoff CN	−0.2–0.06	−0.18
3	CANMX	Maximum canopy storage	0–100	30.62
4	ESCO	Soil evaporation compensation factor	0–1	0.84
5	SOL_AWC	Soil available water storage capacity	−0.2–0.2	0.15
6	GW_DELAY	Groundwater delay time (days)	0–500	8.12
7	RCHRG_DP	Deep aquifer percolation fraction	0–1	0.31
8	GW_REVAP	Threshold depth of water in the shallow aquifer for 'revap' to occur	0.02–0.2	0.14
9	EPCO	Plant uptake compensation factor	0–1	0.39
10	SOL_K	Saturated hydraulic conductivity	−0.2–0.2	−0.16
11	CH_N2	Manning's *n* value for main channel	−0.01–0.3	0.15
12	SURLAG	Surface runoff lag	1–24	4.08

Table 4 | Efficiency statistics of the simulated river discharge compared with the measured river discharge during the calibration duration (1981–1990) and the validation duration (1991–2000)

	Calibration			Validation		
Stream gauge	*NSE*	R^2	*Pbias* (%)	*NSE*	R^2	*Pbias* (%)
Phuoc Long	0.75	0.76	11.1	0.93	0.79	13.4
Phuoc Hoa	0.85	0.86	−3.8	0.76	0.76	0.4
Ta Lai	0.83	0.83	7.6	0.91	0.89	−0.7
Ta Pao	0.79	0.81	−1.9	0.61	0.62	−15.3

the measured river discharge fairly well during the calibration duration and the validation duration at all four stream gauges, and it could be utilized for analyzing the CC influence on the discharge and GWR of the study region.

4.2. Projected changes in rainfall and temperature

Figure 3 displays the projected changes in monthly rainfall, maximum temperature (Tmax), and minimum temperature (Tmin) in HCMC using an ensemble average of seven CMIP6 GCMs as listed in Table 2 under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios. As compared with the historical baseline period (1986–2010), the annual Tmax under SSP1-2.6 is presumed to rise by 0.73, 1.10, and 1.16 °C, while the annual Tmin under SSP1-2.6 is foreseen to rise by 0.84, 1.20, and 1.27 °C during the near-future, mid-future, and far-future periods, respectively. Under SSP2-4.5, the Tmax is envisaged to rise by 0.85, 1.44, and 1.88 °C, and Tmin is presumed to increase by 0.93, 1.56, and 2.09 °C in the near-future, mid-future, and far-future periods, respectively. Finally, under SSP5-8.5, the Tmax is envisaged to have increasing trends of 0.91 °C in the 2030s, 1.86 °C in the 2055s, and 3.13 °C in the 2080s, while the Tmin is foreseen to have rising trends of 0.99 °C in the 2030s, 2.08 °C in the 2055s, and 3.54 °C in the 2080s. The highest rises in Tmax and Tmin are foreseen to occur under the SSP5-8.5 scenario, while the smallest rises in Tmax and Tmin are likely to happen under the SSP1-2.6 scenario. Overall, the projected rises of annual Tmin are greater than those of annual Tmax. In terms of seasonal variation, the projected rises of wet-seasonal Tmax and dry-seasonal Tmin are generally greater than those of dry-seasonal Tmax and wet-seasonal Tmin.

The annual rainfall under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios is foreseen to have increasing trends in all future periods (Figure 3). During the near-future period, the annual rainfall is envisaged to rise by 3.3% under SSP1-2.6, 5.9% under SSP2-4.5, and 4.9% under SSP5-8.5. Regarding the mid-future period, the annual rainfall is foreseen to have increasing trends of 2.4% under SSP1-2.6, 4.8% under SSP2-4.5, and 7.7% under SSP5-8.5. Lastly, in the far-future period, the annual rainfall is likely to rise by 0.6, 7.4, and 12.6% under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. Moreover, the rainfall in the wet and

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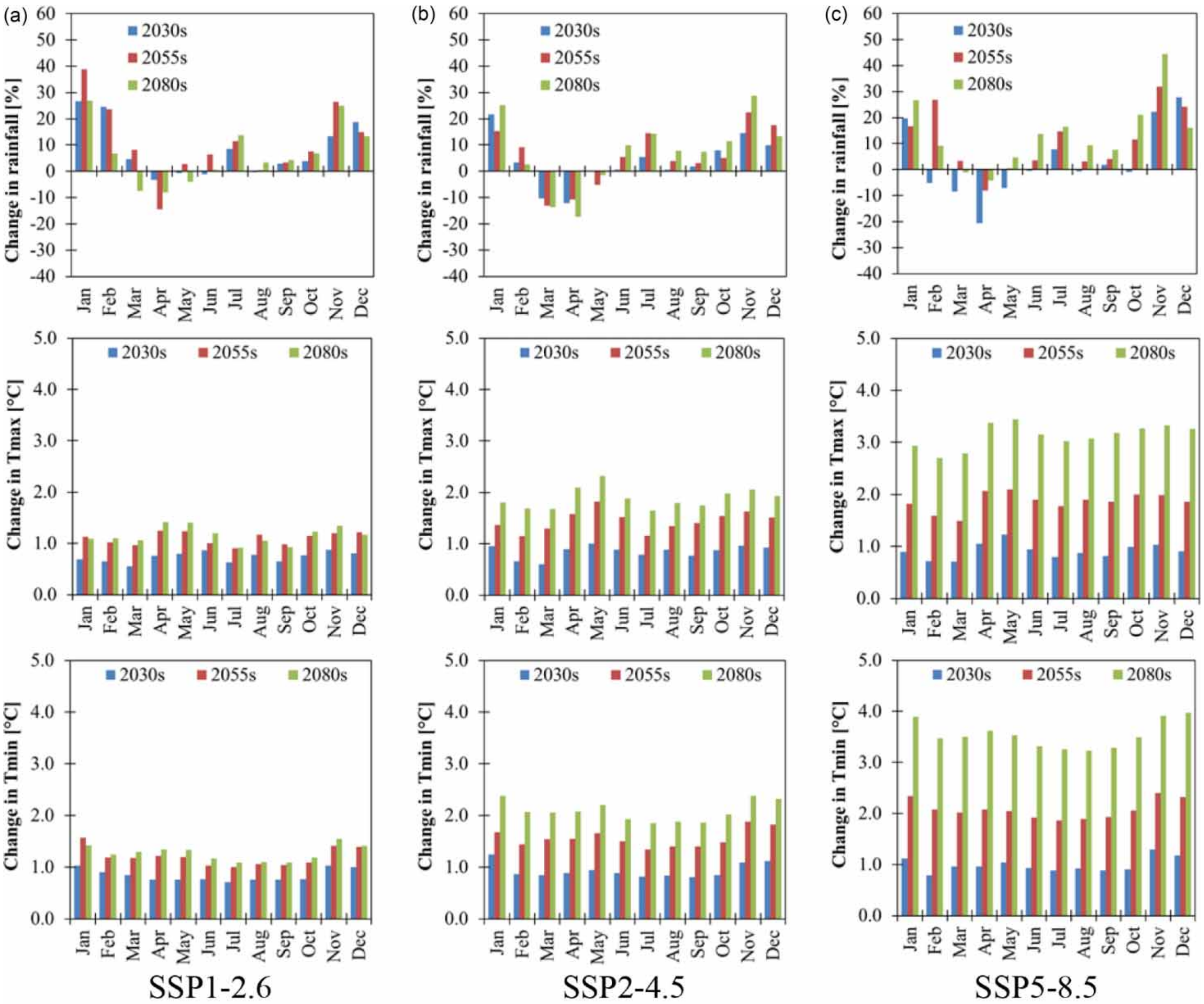

Figure 3 | Projected changes in monthly rainfall, maximum temperature (Tmax), and minimum temperature (Tmin) in HCMC during the near-future, mid-future, and far-future periods under (a) SSP1-2.6, (b) SSP2-4.5, and (c) SSP5-8.5.

dry seasons is prognosticated to have increasing trends in the 21st century under all SSP scenarios. Specifically, the future rainfall is prognosticated to rise by 2.3–4.5% under SSP1-2.6, 2.8–8.5% under SSP2-4.5, and 0.4–12.0% under SSP5-8.5 in the wet season, while the rainfall is prognosticated to rise by 6.7–9.4% under SSP1-2.6, 0.9–4.3% under SSP2-4.5, and 2.1–15.5% under SSP5-8.5 in the dry season.

4.3. CC influence on river discharge and GWR

The annual river discharge in HCMC is generally foreseen to have rising trends under all SSP scenarios (Figure 4), which corresponds to the projected rises in rainfall in the 21st century. The annual discharge is foreseen to rise by 4.5–9.8% under SSP1-2.6, 1.8–13.0% under SSP2-4.5, and 0.1–19.6% under SSP5-8.5. Concerning the seasonal variation, the discharge is envisaged to change by 3.4–9.3%, 1.9–8.4%, and −0.2–19.3% under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively, in the wet season. As regards the dry season, the discharge is prognosticated to have increasing trends of 6.1–12.6%, 1.6–6.7%, and 1.5–16.5% under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively.

Similar to projected rises in annual rainfall and discharge, the annual GWR is prognosticated to rise by 4.8–5.9%, 2.8–8.8%, and 0.9–13.5% under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. In respect of the seasonal variability, the wet-seasonal GWR is envisaged to rise by 4.4–6.0% under SSP1-2.6, 3.1–10.0% under SSP2-4.5, and 1.1–13.4% under SSP5-8.5, while the dry-seasonal GWR is foreseen to change by 2.4–8.6% under SSP1-2.6, −2.4–0.5% under SSP2-4.5, and −1.7–15.1% under SSP5-8.5.

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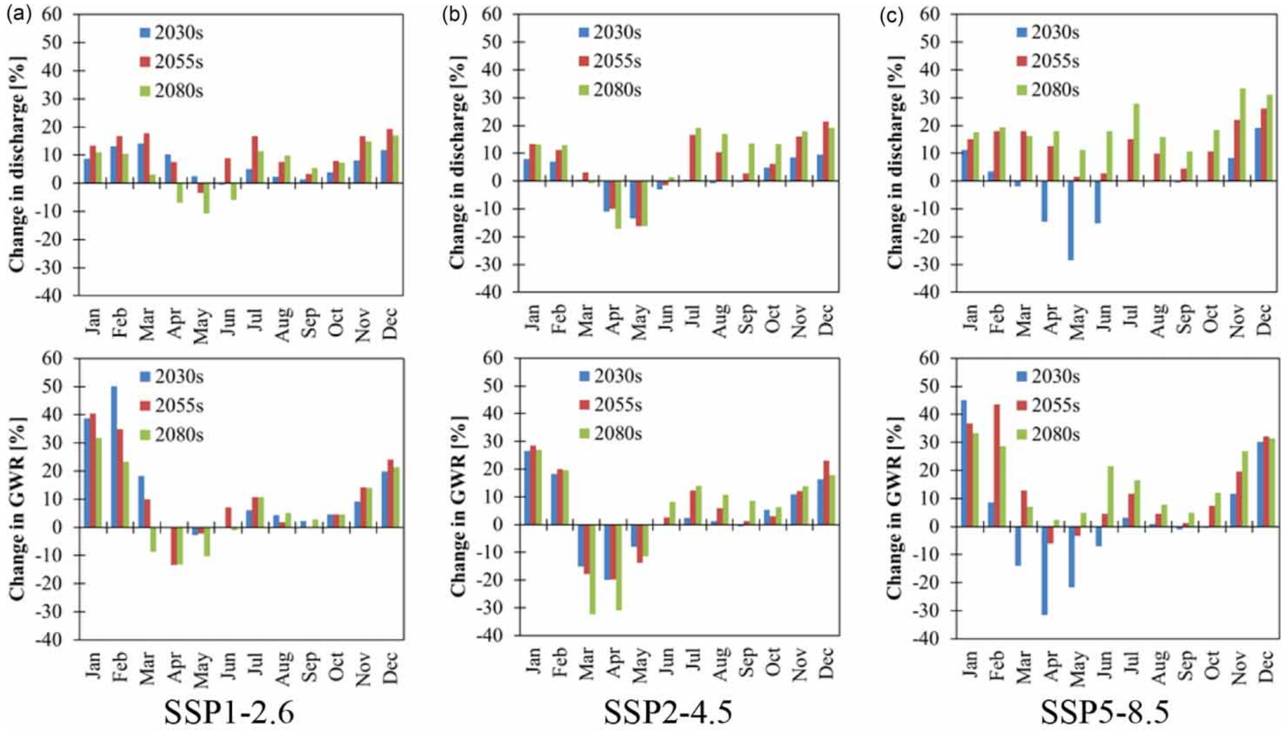

Figure 4 | Projected changes in monthly discharge and GWR in HCMC during the near-future, mid-future, and far-future periods under (a) SSP1-2.6, (b) SSP2-4.5, and (c) SSP5-8.5.

4.4. Uncertainty analysis of discharge and GWR projections

The discrepancies in future projections of discharge and GWR related to the use of CMIP6 GCMs and SSP scenarios were examined in the present study. Figure 5 displays the future changes in annual rainfall, Tmax, Tmin, discharge, and GWR using CNRM-CM6.1 GCM under three SSP scenarios, namely SSP1-2.6, SSP2-4.5, and SSP5-8.5. The projected rises in Tmax and Tmin vary from approximately 0.91–1.01 and 0.96–1.06 °C during the near-future period, 1.21–2.41 and 1.39–1.73 °C during the mid-future period, and 1.36–4.26 and 1.52 to 4.43 °C during the far-future period, respectively. Both Tmax and Tmin show the large uncertainties related to the three SSP scenarios in the mid-future and far-future periods, except for the near-future period. In addition, the projected rises in annual rainfall, discharge, and GWR are foreseen under the three SSP scenarios. The magnitudes of rises in annual rainfall, discharge, and GWR vary from 0.5 to 4.0%, 0.4 to 6.8%, and 1.4 to 5.2% in the near-future period, 1.2 to 11.0%, 0.1 to 19.3%, and 1.4 to 13.1% in the mid-future period, and 1.9 to 5.7%, 0.6 to 9.6%, and 0.3 to 7.5% in the far-future period, respectively. In general, the level of uncertainty from the different SSP scenarios is considerable.

Figure 6 illustrates the annually projected changes in Tmax, Tmin, rainfall, discharge, and GWR using different CMIP6 GCMs under the SSP2-4.5 scenario. The figure shows the large variations of the Tmax, Tmin, rainfall, discharge, and GW projections over the seven CMIP6 GCMs. The increasing trends of Tmax and Tmin vary from 0.44 to 1.11 and 0.55 to 1.36 °C in the near-future period, 0.61 to 1.96 and 1.01 to 2.11 °C in the mid-future period, and 0.81 to 2.69 and 1.28 to 2.97 °C in the far-future period. The projected changes in rainfall, discharge, and GWR are envisaged to range from −9.5 to 11.8%, −21.9 to 19.4%, and −15.2 to 15.2% during the 2030s, −6.2 to 16.5%, −15.7 to 30.3%, and −11.1 to 20.5% during the 2055s, and −1.2 to 24.1%, 5.1 to 46.0%, and −2.9 to 29.2% during the 2080s, respectively. Generally, the level of uncertainty related to the different CMIP6 GCMs is large. Also, the uncertainty owing to the CMIP6 GCMs is larger than that owing to the SSP scenarios.

4.5. Discussion

In the present study, the SWAT was employed to scrutinize the CC influence on discharge and GWR in HCM. According to the guidelines provided by Moriasi *et al.* (2007), the effectiveness of SWAT hydrological simulation for the study region

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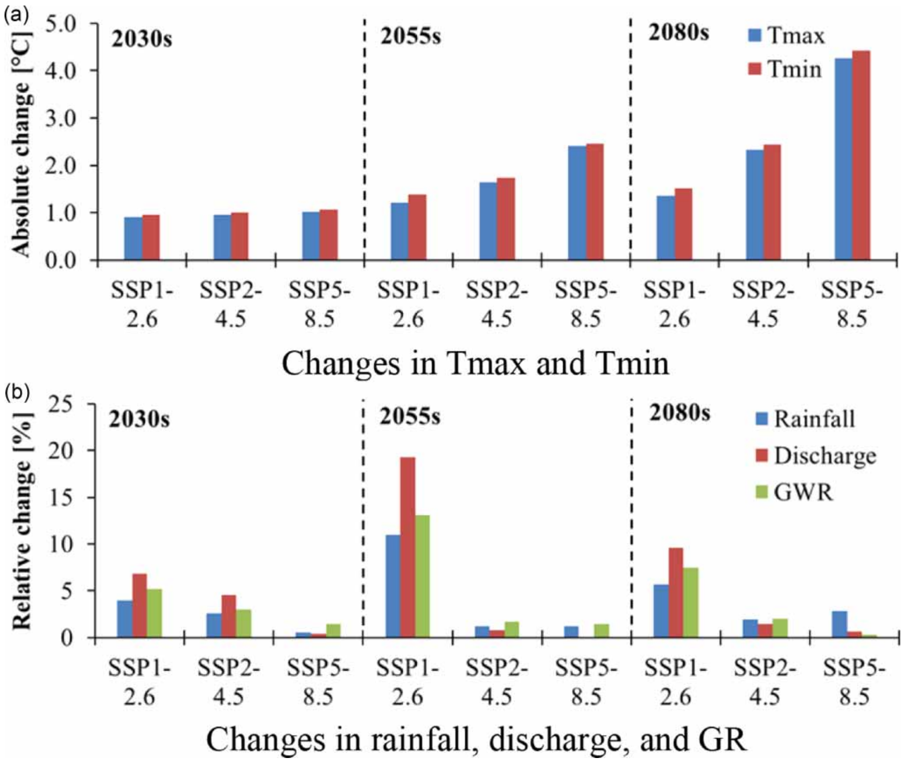

Figure 5 | Projected changes in annual (a) Tmax, Tmin, and (b) rainfall, discharge, and GWR using CNRM-CM6.1 under different SSPs.

exhibited the good agreement between observed and measured discharge in the calibration and validation durations. The SWAT effectiveness in this study is consistent with that of previous studies covering the parts of the Dong Nai River Basin (Khoi *et al.* 2017; Thang *et al.* 2018; Adhikari *et al.* 2020).

The projections of future climate in HCMC utilizing the CMIP6 GCMs indicate the rises in Tmax, Tmin, and rainfall under all SSPs in the near-future period, mid-future period, and far-future period compared with the historical baseline period (1986–2010). The projected rises in Tmax, Tmin, and rainfall are in conformity with the measured increases in temperature and rainfall of the study region (MONRE 2016; Quan *et al.* 2021). The temperature rise under SSP5-8.5 is significantly larger than that under SSP2-4.5 and SSP1-2.6 due to the higher radiative forcing level of SSP5-8.5 (Ba *et al.* 2018). In addition, the rising rate of annual Tmin is envisaged to be higher than that of annual Tmax, which is similar to the finding of Ghimire *et al.* (2021) in Bangkok. This may be attributed to the fact that the sensitivity of Tmin to a rise in GHG concentration is higher than that of Tmax (Salawitch 1998). Furthermore, the annual and seasonal rainfall of HCMC is prognosticated to have the increasing trends under all RSP scenarios in the 21st century, and this conforms with the findings of Khoi *et al.* (2021) in HCMC and Thang *et al.* (2018) in the upper Dong Nai River Basin. Corresponding to the projected rise in rainfall, the future river discharge and GWR of HCMC are envisaged to have rising trends. In correspondence to our results, Thang *et al.* (2018) demonstrated rises in the future discharge under RCP4.5 and RCP8.5 in the upper Dong Nai River Basin. Similarly, Ghimire *et al.* (2021) found the projected rises in future GWR under both RCP4.5 and RCP8.5 in the Bangkok region. Generally, the projected increases in future discharge and GWR will lead to higher freshwater availability in the study region, which may reduce the water shortage in the future. The previous investigation carried out by van Leeuwen *et al.* (2016) indicated that HCMC is predicted to face water scarcity due to increasing demands for domestic and industrial purposes in the future.

The discrepancies in future projections of the CC influence on the discharge and GWR may be connected with various factors that are the GHG scenarios utilized, GCMs utilized, downscaling techniques utilized, and hydrological models utilized (Hoan *et al.* 2020). In the present study, the uncertainties connected with SSP scenarios and CMIP6 GCMs were examined. As for the GCM and SSP uncertainties, the projections of Tmax, Tmin, rainfall, river discharge, and GWR may vary widely depending on the GCM simulation or the SSP scenario. The results indicated that none of the two uncertainties

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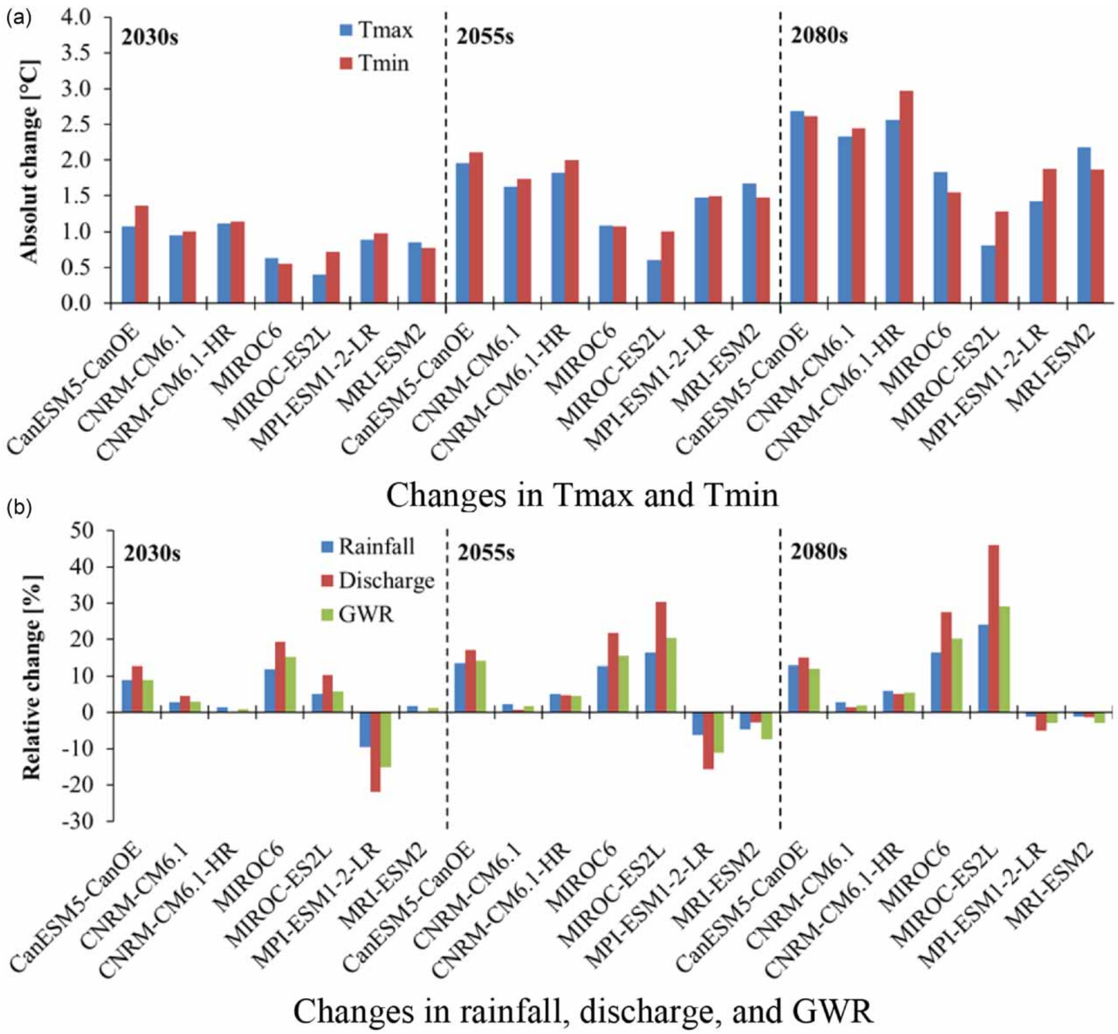

Figure 6 | Projected changes in annual (a) T_{max}, T_{min}, and (b) rainfall, discharge, and GWR using the seven CMIP6 GCMs under SSP2-4.5.

are negligible and the uncertainty connected with CMIP6 GCMs is largest. In addition to using multiple CMIP6 GCMs in the investigations on the CC influence on river discharge and GWR, the importance of using multiple SSP scenarios is emphasized. Many previous studies revealed the largest uncertainty related to CMIP5 GCMs (Hoan *et al.* 2020) or CMIP3 GCM (Bae *et al.* 2011).

Anthropogenic activities, including land-use/land-cover change, hydropower dams, and irrigation reservoirs, have a significant effect on hydrological components (Li & Fang 2021). Adhikari *et al.* (2020) indicated that urban expansions in HCMC have a considerable influence on GWR. In this study, we isolated the CC influence by assuming no changes in land-use/land-cover or other anthropogenic activities. Thus, our findings can provide a reference for future CC influence on the river discharge and GWR.

5. CONCLUSIONS

The present study revealed how the projected changes in climate may modify the future river discharge and GWR in HCMC, Vietnam. The findings indicated that HCMC's climate is warmer and wetter in the 21st century. Specifically, the annual Tmax and Tmin are prognosticated to increase from 0.73 to 3.13 °C and 0.84 to 3.54 °C, and the annual rainfall is envisaged to rise from 0.6 to 12.6%. Under the influence of CC, the future discharge and GWQ are foreseen to rise from 0.1 to 4.5% and 0.9 to 4.9% during the near-future period, 8.1 to 11.6% and 5.3 to 7.9% during the mid-future period, and 7.7 to 19.6% and 5.7 to 13.5% during the far-future period, respectively. The increases in future discharge and GWR will raise the water availability,

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which is beneficial for human uses in the study region. Finally, the uncertainty in the streamflow and GWR projections related to the SSP scenarios is significant, but smaller than that associated with the CMIP6 GCM outputs. This finding highlights the importance of using multiple emission scenarios and GCMs in the investigations on the CC influence on river discharge and GWR. On the whole, the findings derived from this investigation are likely to have significant implications for future water resource management.

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AUTHORS CONTRIBUTIONS

Dao Nguyen Khoi: conceptualization; methodology; formal analysis; funding acquisition; writing – review and editing. Truong Thao Sam: software; formal analysis; visualization. Nguyen Truong Thao Chi: software; formal analysis; visualization. Do Quang Linh: software; formal analysis; visualization. Pham Thi Thao Nhi: software; formal analysis; writing – review and editing.

COMPETING INTERESTS

The authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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