ORIGINAL ARTICLE

Response of streamflow and sediment variability to cascade dam development and climate change in the Sai Gon Dong Nai River basin

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Abstract

Future changes in streamflow and sediment, influenced by anthropogenic activities and climate change, have a crucial role in watershed management. This study aimed to quantify the effects of anthropogenic and natural drivers on future streamflow and sediment changes in the tropical Sai Gon Dong Nai River basin using the Soil and Water Assessment Tool (SWAT) model. Specifically, the model incorporated thirty-six reservoirs and analyzed twenty future climate projected scenarios from four Coupled Model Intercomparison Project Phase 6 (CMIP6) General Circulation Models (GCMs) for 2023–2100. These models include BCC-CSM2-MR (China), CanESM5 (Canada), MIROC6 (Japan), and MRI-ESM2-0 (Japan). Our findings indicate that (1) dam operation and diversion lead to a 0.5% decrease in streamflow during the dry season and a 4.1% increase during the rainy season compared to those in scenarios without dams; (2) there is a 37.4% decrease in annual sediment across the entire basin under same climate conditions; and (3) rainfall is projected to decrease (24.6% – 6.2%), resulting in a decrease in streamflow (0.2 – 32.2%) and sediment (39.3 – 56.0%) compared to historical records. Streamflow is expected to decrease during the rainy season (16.7 – 23.1%) and increase during the dry season (14.5 – 25.4%). Further potential degradation of the environmental conditions and water mismanagement are caused by the synergies between too much and too little rainfall conditions. The anticipated reductions in future streamflow and sediment could adversely affect ecological streamflow, water security, and sediment dynamics in the Sai Gon Dong Nai River basin. Our approach effectively identifies future changes in streamflow and sediment due to the combined effects of climate change and reservoir operations, providing valuable insights for integrated water resource management in tropical regions.

Keywords Dam operation · Climate change · Streamflow · Sediment · CMIP6 · Sai Gon Dong Nai River basin

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1 Introduction

Natural river flow regimes generate spatial and temporal variations in environmental conditions (e.g., temperature, sediment, and nutrients, which are essential for sustaining natural biodiversity and maintaining the integrity of riverine ecosystems (Richter et al. 1998; Tran et al. 2022a, b). Flow regimes are primarily influenced by climate change (Nguyen et al. 2023a; Tran et al. 2023a, b, Le et al. 2023) and are occasionally affected by periodic shifts in the El Niño-Southern Oscillation (ENSO) in which these shifts impact both inter- and intra-annual streamflow fluctuations (Li et al. 2023; Lu and Chua 2021; Nguyen et al. 2022). In recent years, with the widespread construction and planning of dams and reservoirs on many rivers, the assessment of hydrological and sediment impacts from dams has emerged as a prominent topic, attracting international attention across

continents (Nguyen et al. 2023a; Nguyen et al., 2024; Tran et al. 2023a).

River sediments are important in protecting low-lying areas from natural and man-made subsidence processes. They help mitigate riverine and coastal flooding caused by climate change and sea-level rise, providing aggregates for construction and other human activities. However, the sediment load of global rivers has substantially decreased due to anthropogenic activities, especially river damming (Dethier et al. 2022). Globally, more than 47,000 large dams are operational (Van Binh et al. 2020a), which, while beneficial for renewable energy generation, have adverse effects on downstream environments. They alter flow regimes and trap significant sediment loads from upper basins, leading to sediment scarcity in downstream regions. This thus causes morphological degradation and can potentially increase salinity intrusion (Binh et al. 2021; Nguyen et al. 2023b).

Some studies worldwide have evaluated the effects of climate change and dams on flow alterations and sediment reduction (De Girolamo et al. 2022). However, research results mainly focus on past or future assessments, with very few assessments in both periods. The impacts of the Manwan dam, the first megaminator (total capacity > 1 km³) in the Mekong basin, on the lower Mekong River flow regime were assessed by Lu and Siew (2006), while Kummu and Varis (2007) were the first to evaluate the effect of dam closure on the downstream sediment load comprehensively. In China's Yangtze River, the effects of dams, notably the Three Gorges Dam, on sediment transport and river morphology have been thoroughly investigated (Yang et al. 2015, 2018; Zhao et al. 2015). The construction of the Sidi Mohamed Ben Abdellah dam on Morocco's Bouregray River in Africa in 1974 significantly lowered the downstream sedimentation rate from approximately 3.64 cm/year (1950–1978) to roughly 0.41 cm/year between 1990 and 2017 (El Aoula et al. 2021). A general finding is that dams reduce flood flows, increase dry flows, and decrease sediment loads; however, the results vary significantly depending on geography and climatic zone. Additionally, previous studies have focused more on large, especially transboundary river basins, while smaller, domestic river basins have been less studied. Therefore, new studies are needed to evaluate the influence of both climate change and dams on streamflow and sediment from the past to the future in smaller river basins to provide diverse results for planning integrated river basin management.

The Sai Gon Dong Nai (SGDN) River basin is a crucial contributor to Vietnam's economic growth, supplying vital freshwater resources to approximately 20 million people (Fig. 1). As the second-largest river system in southern Vietnam after the Mekong River, it hosts thirty-six large hydropower dams, including several cascades, with a combined storage capacity of approximately 8.6 billion m³. These dams contribute roughly 32.5% of the river system's total water discharge. Therefore, understanding the impacts of dams and climate change on the streamflow and sediment load in the SGDN system is important to enhancing sustainable water resource management and planning. Numerous studies have examined the current hydrological processes within the SGDN River basin. Giang et al. (2022) revealed long-term water level changes along the Dong Nai River, relating these changes to urbanization, dikes, and dam construction, while Luong et al. (2021) examined water level changes downstream, considering the effects of climate change and reductions in storage areas. In addition, Pham et al. (2019) assessed the impacts of climate and land-use changes on water balance alterations in the upper basin. Truong et al. (2018) examined the effect of land use/land cover (LULC) changes on flow regime alterations in the upper Dong Nai basin, while Khoi et al. (2021) assessed the effects of LULC changes on sediment load.

In summary, our review of existing literature on the SGDN River basin reveals several research gaps, underscoring the necessity of this study. Firstly, most related studies are limited to small areas, such as the SGDN estuary, resulting in a limited understanding of streamflow and sediment dynamics across the entire river system. Secondly, these studies mainly focused on the effects of either climate change or LULC changes, leaving the impacts of dams on downstream streamflow and sediment largely unexplored. Thirdly, despite its significance, sediment dynamics within the SGDN River basin have not been extensively studied, indicating a knowledge gap about the long-term effects of dams and climate change on sediment load. Therefore, this study aimed to assess the projected impacts of both dam operations (thirty-six) and climate change scenarios (from the Coupled Model Intercomparison Projects [CMIP] Version 6) on streamflow and sediment in the SGDN River basin using the semi-distributed Soil and Water Assessment Tool (SWAT). This work quantitatively analyses the effects of these factors in terms of seasonal, annual, and long-term streamflow and sediment dynamics in this river system. These findings are vital for developing effective solutions and ensuring sustainable basin development, significantly contributing to global and regional understanding of these complex issues.

2 Study area

The SGDN, with a total area of 29,667.5 km², is Vietnam's largest domestic river system and includes Ho Chi Minh City, the country's foremost economic center (Fig. 1). This city is home to approximately 20 million people, and provides a total annual discharge of approximately 32.5 billion m³ (Tran et al. 2022a, b). The SGDN basin experiences two seasons: the rainy season (July to December), which
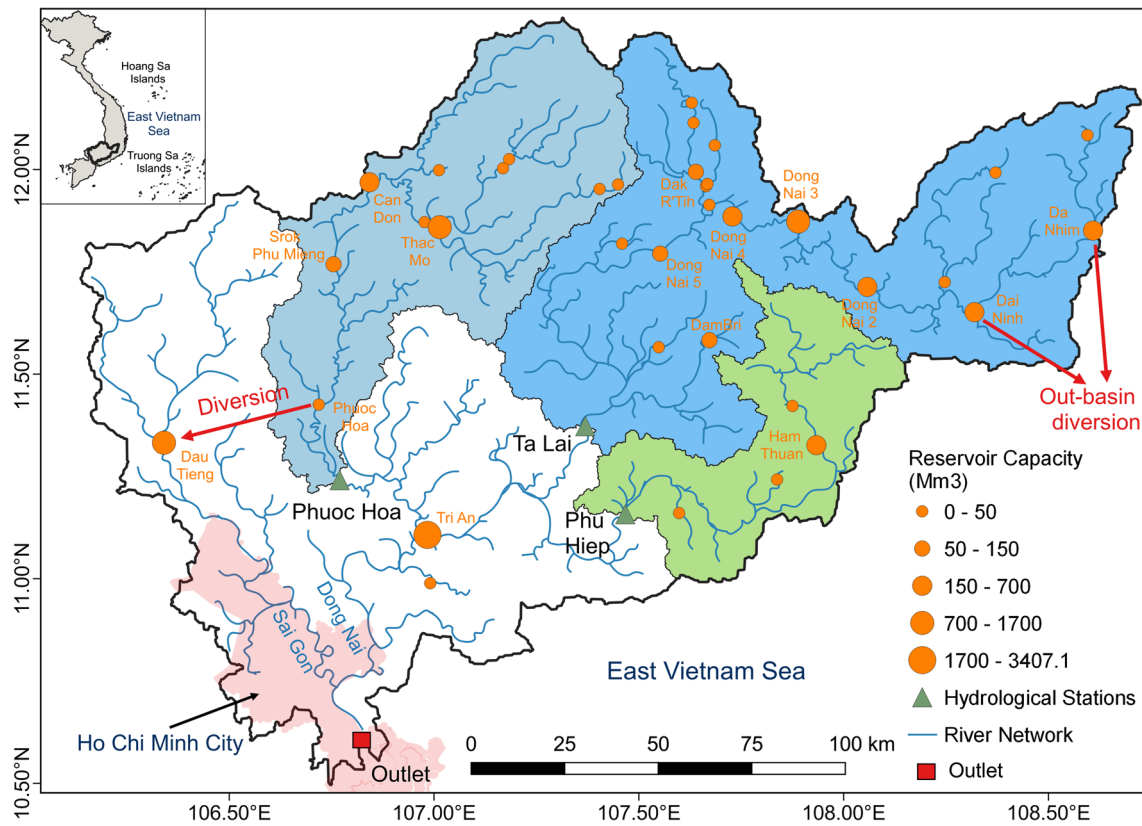
Fig. 1 Geospatial map of the SGDN River basin and locations of current dams and reservoirs. The size of the orange bubble represents the corresponding capacity of the reservoir

accounts for more than 80% of the total annual discharge, and the dry season from January to June. In this basin, particularly in Ho Chi Minh City near the outlet (Fig. 1), flooding is a major natural disaster, resulting in significant socioeconomic losses and infrastructure damage. The characteristics of the three large subbasins within the SGDN (derived from the corresponding hydrological stations) are presented in Table 1. They can be used to understand the basin's basic information, instrumental in effective water management planning and developing flood mitigation strategies.

The Sai Gon River flows into the Dong Nai River to create the SGDN River system (Fig. 1). Three main hydrological stations, namely, Ta Lai, Phu Hiep, and Phuoc Hoa, monitor the daily discharge and sediment. Ta Lai represents the largest subbasin, followed by Phuoc Hoa and Phu Hiep. The annual sediment amounts recorded for these subbasins are $1,266 \times 10^3$ tons, $1,115 \times 10^3$ tons, and 290×10^3 tons, respectively (Table 1).

In the SGDN River basin, the construction of dams and reservoirs has been strategically implemented to optimize water resource utilization, facilitate flood and drought management, and generate electricity. Currently, the basin hosts seventy-five dams, primarily designed for irrigation, water supply, and hydropower, with a total storage capacity of approximately 10.6 billion m^3. This includes several cascade dams, which contribute approximately 32.6% of the total water discharge of the river system. Notably, thirty-six are classified as large dams, each exceeding 15 m. These developments are shown in Fig. 1 and detailed in Table 3,

Table 1 Description of the information at three hydrological stations in the SGDN River basin

Hydrological station	Area (km²)	Period year	Average annual rainfall (mm)	Average annual discharge (10^6 m³)	Average annual sediment (10^3 tons)
Ta Lai	8,592	1987–2021	2,212	10,466	1,266
Phuoc Hoa	5,546	1981–2021	2,417	6,980	1,115
Phu Hiep	1,083	1995–2021	2,236	3,813	290

providing a comprehensive overview of the infrastructural landscape within the SGDN River basin. This extensive dam network is pivotal in influencing the region's hydrological and ecological dynamics, and has significant implications for the environment and local communities.

3 Methodology and materials

3.1 SWAT model

The SWAT model was developed by the U.S. Department of Agriculture (USDA) and Agriculture Research Service (ARS) (Arnold et al. 1998). This advanced computer simulation tool was designed for comprehensive watershed-scale studies. It effectively integrates various components, such as climate, hydrology, land cover, and reservoir operation, including water transfer, and management practices (Arnold et al. 1998; Keitzer et al. 2016; Tran & Lakshmi. 2022). The SWAT model segments a watershed into smaller units called subbasins. These subbasins are divided into hydrological response units (HRUs) based on their distinct combinations of soil characteristics, land use patterns, and slope gradients. This division allows for a detailed understanding of the hydrological processes within a watershed. Previous studies have utilized this model, highlighting its versatility and effectiveness in analysing and predicting the impacts of various environmental factors on watershed dynamics (Nguyen et al., 2023b; Tran et al. 2022a, b, 2023a, b; Do et al. 2024; Ahmed et al., 2020; Aryal et al., 2022, 2023; Tapas et al. 2022, 2024). The combination of hydrological processes, including reservoir operation and water diversion, is an important advantage of SWAT. Additionally, the model can integrate multiple aspects of a watershed (cascade dams, water transfer), making it a valuable tool for environmental management and planning under the impact of climate change, particularly in complex and varied landscapes such as the SGDN River basin (Fig. 1).

3.2 Datasets

Daily streamflow and sediment data from 2001 to 2020 at three hydrological stations (Ta Lai, Phuoc Hoa, and Phu Hiep) (Fig. 1; Tables 1 and 2) were provided by the Vietnam National Hydrometeorological Data Centre. However, sediment data from Phu Hiep were available only from 2008 to 2020. The SGDN River basin covers a large area and has distinct climatic characteristics, but the distribution of rain gauges is sparse. Moreover, the data availability period is limited and inconsistent across the stations. Consequently, we utilized gridded precipitation products in this study. Le et al. (2023) evaluated six different products, such as the NASA Integrated MultisatellitE Retrievals for GPM (IMERG) V6.0 (2001–2020), Multi-Source Weighted-Ensemble Precipitation (MSWEP) V2.8 (1979–2020), and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) V2.0 (1981–2020), for streamflow simulation. While MSWEP V2.8 and CHIRPS V2.0 offer extended temporal coverage, they tend to overestimate streamflow and rainfall compared to observational data. In contrast, IMERGF-V6, despite its shorter temporal range (2001–2020), demonstrated superior accuracy. IMERG exhibited high detection accuracy over large (> 4,000 km^2) and medium-sized ($\leq$ 4,000 km^2 and > 1,000 km^2) basins (Tran et al. 2023a, b, Le et al. 2023). However, its performance is suboptimal in coastal areas prone to high hurricane risks (Tran et al. 2023a, b) and in regions with snowfall (Tang et al. 2020). Moreover, compared to commonly used products such as MSWEP, CHIRPS, and PERSIANN-CDR, this product demonstrated good performance in estimating

Table 2 Summary input data of the SWAT model

No	Name	Description	Reference
1	DEM	The 90-m DEM from the SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS)	HydroSHEDS; https://www.hydrosheds.org/products/hydrosheds
2	LULC	90-m LULC map was obtained from the SERVIR-Mekong Portal for the year 2018	SERVIR–Mekong; https://rlcms-servir.adpc.net/en/landcover
3	Soil	90-meter Harmonized World Soil Database (HWSD) version 1.2	Food and Agriculture Organization (FAO); http://www.fao.org
4	Rainfall	Integrated MultisatellitE Retrievals for GPM (IMERG) V6.0	NASA; https://pmm.nasa.gov/data–access/downloads/gpm
5	Temperature	Daily maximum and minimum air temperatures utilized the Global Land Data Assimilation System (GLDAS)	NASA's Goddard Space Flight Center (GSFC)
6	Streamflow, Sediment	Daily streamflow and sediment data from 2001 to 2020	Vietnam National Hydrometeorological Data Centre
7	Reservoirs	Thirty-six reservoirs have been chosen for this study	Official agencies in Vietnam and the Global Georeferenced Database of Dams (GOODD); http://thuyloivietnam.vn/home http://www.vncold.vn/

rainfall during event-based scenarios across different rain intensities (Lyu et al. 2024). Therefore, we used the IMERGF-V6 product for this study (Table 2).

IMERG is a Level-3 rainfall dataset that utilizes the Global Precipitation Measurement (GPM) estimation algorithm. Its primary goal is to integrate, intercalibrate, and interpolate various satellite microwave precipitation estimates, as indicated by Hou et al. (2014) and Yuan et al. (2018). This product was generated by combining microwave-calibrated infrared satellite estimates, precipitation gauge analyses, and other precipitation estimators, offering a spatial resolution of 0.1°. The IMERG dataset provides extensive global coverage and a finer temporal resolution (at half-hour intervals) than Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis (TMPA) products (Hou et al. 2014). In this study, we utilized the final run (version 6.0) of IMERG, referred to as IMERGF–V6. This half-hourly, 0.1° gridded product can be accessed from the NASA Goddard Space Flight Center website (https://pmm.nasa.gov/data-access/downloads/gpm). We adapted the gridded precipitation data to the centroids of subbasins in SWAT by defining the intersecting grids between the gridded precipitation products and the subbasin boundaries. The weight-area table consists of two components: the gridded value and the normalized fraction of the grid (weight). Normalization was conducted to ensure one total weight for each subbasin.

We utilized the Global Land Data Assimilation System (GLDAS) to extract the daily maximum and minimum air temperatures from 2001 to 2020 (Table 2). These data were developed by NASA's Goddard Space Flight Center (GSFC), aiming to integrate satellite- and ground-based observational data through advanced land surface modeling and data assimilation techniques. This process generated optimal fields of land surface states and fluxes (Rodell et al. 2004; Beaudoing at al., 2016). We derived daily maximum and minimum air temperatures using three-hourly GLDAS version 2.0 datasets (available at https://ldas.gsfc.nasa.gov/data). This was achieved by selecting the highest and lowest values from the eight available readings each day, as Mohammed et al. (2018) described.

The 90-meter void-filled Digital Elevation Model (DEM) was constructed from hydrological data and maps based on the SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS, accessible at https://www.hydrosheds.org/) (Fig. 2a; Table 2). Additionally, a land use map (2018) with a 90-meter spatial resolution was obtained from the Lower Mekong Basin Land Use portal-SERVIR-Mekong (available at https://rlcms-servir.adpc.net/en/landcover/) (Fig. 2b; Table 2). We also utilized the 90-meter Harmonized World Soil Database (HWSD) version 1.2, which is managed by the Food and Agriculture Organization (FAO; http://www.fao.org) (Fig. 2c; Table 2).

Dam and reservoir data were primarily collected from official agencies in Vietnam and subsequently cross-verified with information available at http://thuyloivietnam.vn/home and http://www.vncold.vn/ (accessed October 5, 2023). We further compared the data from Vietnamese agencies with those from the Global Georeferenced Database of Dams (GOODD), as Mulligan et al. (2020) reported (Table 2). In this study, we incorporated thirty-six reservoirs into the SWAT model. The locations and total capacities of all these reservoirs are depicted in Fig. 1, while Table 3 shows the profiles of 15 selected major large reservoirs.

3.3 GCMs and climate change scenarios

CMIP and GCMs have been extensively utilized to reveal future climate impacts on flow regimes across various studies (Bhatta et al. 2019; Shafeeque et al. 2023). The sixth iteration of the CMIP (CMIP6) introduces the Scenario Model Intercomparison Project (ScenarioMIP), which is based on Shared Socioeconomic Pathways (SSPs) (O'Neill et al. 2016). This iteration represents a significant advancement in the global project by integrating and anticipating
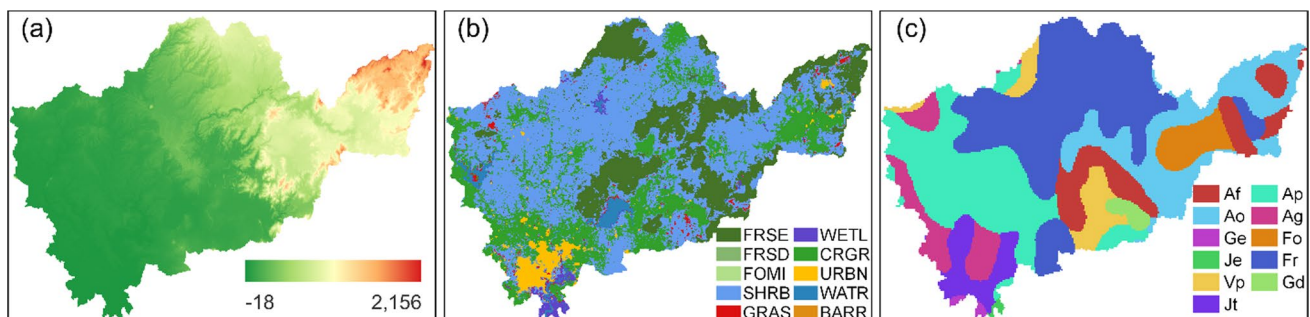

Fig. 2 **a** Digital elevation model (DEM) (m). **b** Land-use map, in which FRSE - evergreen, FRSD - deciduous forest, FOMI - mixed forest, SHRB - shrubland, GRAS - grassland, WETL - wetlands mixed, CRGR - cropland, URBN - urban areas, WATR - water bodies, BARR - barren land. **c** Soil-type map, in which Af, Ao - Sandy_Clay_Loam, Je - Clay_Loam, Ap, Ag - Loam, and Ge, Vp, Jt, Fo, Fr, Gd – Clay. The symbols have the same name but have different percentages

Table 3 Summary of fifteen major reservoirs in the SGDN River basin

Reservoir	Reservoir area (km²)	Total storage (10⁶ m³)	Capacity (MW)	Operation year
Da Nhim	18.87	165	160	1964
Dai Ninh	18.87	319.8	300	2008
Dong Nai 2	12.13	280.8	70	2015
Dong Nai 3	55.18	1,690	180	2011
Dong Nai 4	8.5	332.1	--	2013
Dong Nai 5	--	106.3	--	2015
Dak R'Tih	10.23	137.1	82	2007
Tri An	323.4	3,407.1	400	1998
DamBri	2.79	56.3	75	2014
Ham Thuan	25.2	695	300	2001
Thac Mo	109	1,360	150	1995
Can Don	19.02	165.5	77.6	2004
Srok Phu Mieng	28.57	99.3	51	2003
Phuoc Hoa	10.2	2.45	--	2011
Dau Tieng	270	1,580	--	1984

socioeconomic factors, a new aspect compared to CMIP5 highlighted in the IPCC AR6 report. The SSPs show potential future global societal trajectories, excluding climate change impacts and related mitigation or adaptation strategies. Each SSP provides a corresponding projection of greenhouse gas emissions and land-use changes based on the baseline SSP narrative. ScenarioMIP offers a database for water resource studies (O'Neill et al. 2016), allowing the incorporation of projected scenarios into hydrological models. This integration enhances our understanding of the physical interactions between climate, societal factors, and hydrological processes. For accurate climate scenario projections, we used the NASA Earth Exchange Global Daily Downscaled Projections from CMIP6 (NASA NEX-GDDP-CMIP6), with a resolution of 0.25 degrees, available at https://registry.opendata.aws/nex-gddp-cmip6/. NASA created these datasets by downscaling using the Bias-Corrected Spatial Disaggregation (BCSD) method. This statistical downscaling algorithm was developed to address common limitations of global GCM (Wood et al. 2002, 2004; Maurer et al., 2008). This product was proven reliable in previous studies (e.g., Thrasher et al. 2022). In this study, we decided

not to perform another downscaling stage before use for the simulations due to the large area of the SGDN River basin; the total number of cells covering the entire basin is nearly 50.

3.4 Simulation scenarios

Using the SWAT model, we evaluated the dam's impact on streamflow and sediment in the SGDN River basin over 20 years. The model was simulated for two scenarios from 2001 to 2020: without and with dams.

Four CMIP6 GCMs were selected for this study during the 2023–2100 period (Table 4): BCC-CSM2-MR from the Beijing Climate Center, China Meteorological Administration (China); CanESM5 from the Canadian Centre for Climate Modeling and Analysis (Canada); MIROC6 from the Japan Agency for Marine-Earth Science and Technology and the Atmosphere and Ocean Research Institute, The University of Tokyo (Japan); and MRI-ESM2-0 from the Meteorological Research Institute (Japan). This selection was based on the findings of Wang et al. (2021) and Xu et al. (2023), who evaluated the performance of current

Table 4 Details of the chosen CMIP6 GCMs used in this study

No	GCM	Country	Institution
1	BCC-CSM2-MR	China	Beijing Climate Center China Meteorological Administration
2	CanESM5	Canada	Canadian Centre for Climate Modeling and Analysis, Environment and Climate Change Canada, Canada
3	MIROC6	Japan	Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan & Atmosphere and Ocean Research Institute (AORI), The University of Tokyo, Japan & National Institute for Environmental Studies, Japan (NIES) & RIKEN Center for Computational Science, Japan (R-CCS)
4	MRI-ESM2-0	Japan	Meteorological Research Institute, Japan

GCMs for monitoring disasters at a global scale. In addition, previous work has indicated significant uncertainty associated with the individual use of GCMs, with typical factors such as model structure, historical data used, projected scenarios, and initial conditions (Chen et al. 2022; Dong et al. 2022; Peng et al. 2023). This underscores the importance of employing ensemble models (Tran et al. 2024). Therefore, our study used an ensemble model comprising these four selected GCMs for assessments. We utilized four scenarios—SSP-1.26, SSP-2.45, SSP-3.70, and SSP-5.85—representing low, intermediate, high, and very high greenhouse gas emission levels, respectively, from each GCM. The SSP-1.26, SSP-2.45, SSP-3.70, and SSP-5.85 scenarios are constructed assuming that the possible additional radiative forcings in 2100 are 2.6 W/m^2, 4.5 W/m^2, 7.0 W/m^2, and 8.5 W/m^2, respectively. In total, twenty scenarios were simulated for four CMIP6 GCMs (four SSP scenarios and four ensemble scenarios). This approach was designed to provide a comprehensive understanding of the impacts of future climate on streamflow and sediment.

3.5 Model setup

The basin was delineated into 424 subbasins (threshold 50) with 2,531 HRUs. This delineation was based on a combination of factors: slope class, land use, soil type class, and location of dams and hydrological stations. For this study, the entire 20-year simulation period was segmented into three phases: two years for model warm-up (2001–2002), twelve years for calibration (2003–2014), and six years for validation (2015–2020). The calibration and validation phases were specifically conducted at the Ta Lai, Phu Hiep, and Phuoc Hoa hydrological stations (Fig. 1) due to the availability of relevant data.

For the reservoir setup in the SWAT model, the reservoir's operating policies are based on monthly storage targets. This is a piecewise linear function for each reservoir in the river system. The model adjusts the outflow to meet the minimum and maximum flow discharge criteria (Arnold et al. 2012). The basic parameters are the operational start date of the reservoir (MORES for the month and IYRES for the year), the non-flood season (IFLOD1R and IFLOD2R for the start and end months, respectively), the initial volume of water in the reservoir (RES_VOL; 10^4 m^3), the surface area at the principal spillway (RES_PSA; ha), the volume to reach this capacity (RES_PVOL; 10^4 m^3), the reservoir's surface area at the emergency spillway (RES_ESA; ha), the corresponding volume (RES_EVOL; 10^4 m^3), the hydraulic conductivity of the reservoir bottom (RES_K; mm/hr), the number of days to reach target storage from current reservoir storage (NDTARGR; days), the average amount of water withdrawn (WURESN; 10^4 m^3), and the initial and normal sediment concentrations (RES_SED and RES_NSED,

respectively). Additionally, we considered the evaporation coefficient (EVRSV), the average daily principal spillway release rate (RES_RR; m^3/s), the monthly target reservoir storage (STARG), and the minimum and maximum daily outflows (OFLOWMN, OFLOWMX).

3.6 Calibration and validation

For this study, we employed the interactive web- and R-programming-based app R-SWAT (Nguyen et al. 2022), facilitating both parameter sensitivity and uncertainty analysis, thus providing deeper insights into the model's calibration and validation. Sensi_Cali (uniform_Latin_Hypercube_Sampling; LHS) was selected for the parameter sensitivity and calibration approach (Helton and Davis 2003; Helton et al. 2005). In this approach, R-SWAT generates parameter sets within given parameter ranges using uniform Latin Hypercube Sampling, and parameter sensitivity is assessed via a multivariable regression approach. To assess model performance, we chose five common statistical metrics based on key findings from Babalola et al. (2021), Kouchi et al. (2017), Gupta et al. (2009), and Moriasi et al. (2007), including the correlation coefficient (VG: $1 \geq R > 0.75$; G: $0.65 < R \leq 0.75$; S: $0.5 < R \leq 0.65$; US: $R \leq 0.5$), Kling-Gupta efficiency (VG: $0.8 < KGE \leq 1$; G: $0.7 < KGE \leq 0.8$; S: $0.5 < KGE \leq 0.7$; US: $KGE \leq 0.5$), root mean square error to the standard deviation of measured data (VG: $RSR \leq 0.5$; G: $0.5 < RSR \leq 0.6$; S: $0.6 < RSR \leq 0.7$; US: $RSR > 0.7$), root mean square error (lower is better), and percentage of bias (VG: $PBIAS \leq \pm 5$; G: $\pm 5 < PBIAS \leq \pm 10$; S: $\pm 10 < PBIAS \leq \pm 15$; US: $PBIAS > \pm 15$). In which VG: very good, G: good, S: satisfactory, US: unsatisfactory).

4 Results

4.1 Model calibration and validation

The SCS runoff curve number for moisture conditions (CN2) was found to be the most sensitive parameter, followed by Manning's "n" value for the main channel (CH_N2), the effective hydraulic conductivity in the main channel alluvium (CH_K2), the baseflow alpha factor for bank storage (ALPHA_BNK), Manning's "n" value for overland flow (OV_N), the deep aquifer percolation fraction (RCHRG_DP), the available water capacity of the soil layer (SOIL_AWC), and the saturated hydraulic conductivity (SOL_K). These results show that the SWAT model established for the SGDN River basin is significantly sensitive to surface runoff parameters. These results are consistent with the findings of Tran et al. (2023a). The authors investigated the Srepok River basin, which is close to the SGDN River basin. However, groundwater-related

parameters were not sensitive for the SGDN River basin. This insensitivity may be due to groundwater extraction, diversion, and dam operation.

Figures 3 and 4 present comparative analyses of the observed and simulated daily streamflow and monthly sediment data across two periods: the calibration period (2003–2014) and the validation period (2015–2020), at the three hydrological stations (shown in Fig. 1). The results show that the simulation's overall performance was satisfactory, exhibiting good agreement alignment with the observed data.

In general, the model performed well in terms of the indices used (Fig. 4). For streamflow in the calibration stage, R was between 0.80 and 0.82, KGE ranged from 0.72 to 0.74, and PBIAS varied from -8.72% to $+9.96\%$. During the validation period of streamflow, R was between 0.67 and 0.80, KGE ranged from 0.45 to 0.65, and PBIAS varied from -7.69% to $+34.02\%$.

For sediment, the model performance can be considered acceptable. Thus, the SWAT model's overall performance is considered satisfactory for evaluating hydrological processes under the impacts of climate change and dams. Table A1 details the parameter method, description, range, and fitted values used in the parameter sensitivity analysis using the SWAT model for the SGDN River basin.

4.2 Effects of cascading reservoirs on monthly, seasonal, and annual streamflow variations

Figures 5 and 6; Table 5 show the monthly, seasonal, and annual variations in streamflow for the major subbasins and the outlet of the SGDN River basin. These results include the mean streamflow for each month, calculated under scenarios both with and without dams. The data show that dams resulted in reduced streamflow during the dry months, particularly in the Ta Lai and Phuoc Hoa subbasins. Water is transferred to other basins in these areas, as shown in Fig. 1. The dry season reduction rates in the Ta Lai and Phuoc Hoa subbasins were 10.9% (equivalent to 20 m³/s) and 12.8% (16.4 m³/s), respectively, as shown in Figs. 5a and b and 6a, and Table 5.

The annual streamflow at Ta Lai has experienced a significant decline since 2007, coinciding with the operation of the Dai Ninh reservoir, which has a total storage capacity of 319.8 Mm³ (Fig. 1; Table 1). This reduction is attributed to streamflow diversion from this reservoir to areas outside the basin, which is aimed at improving electricity generation efficiency. Additionally, water diversion from the Dam Nhim reservoir, which has been operational since 1964 and has a storage capacity of 165 Mm³, has further contributed to the reduced streamflow in this subbasin. Consequently, the
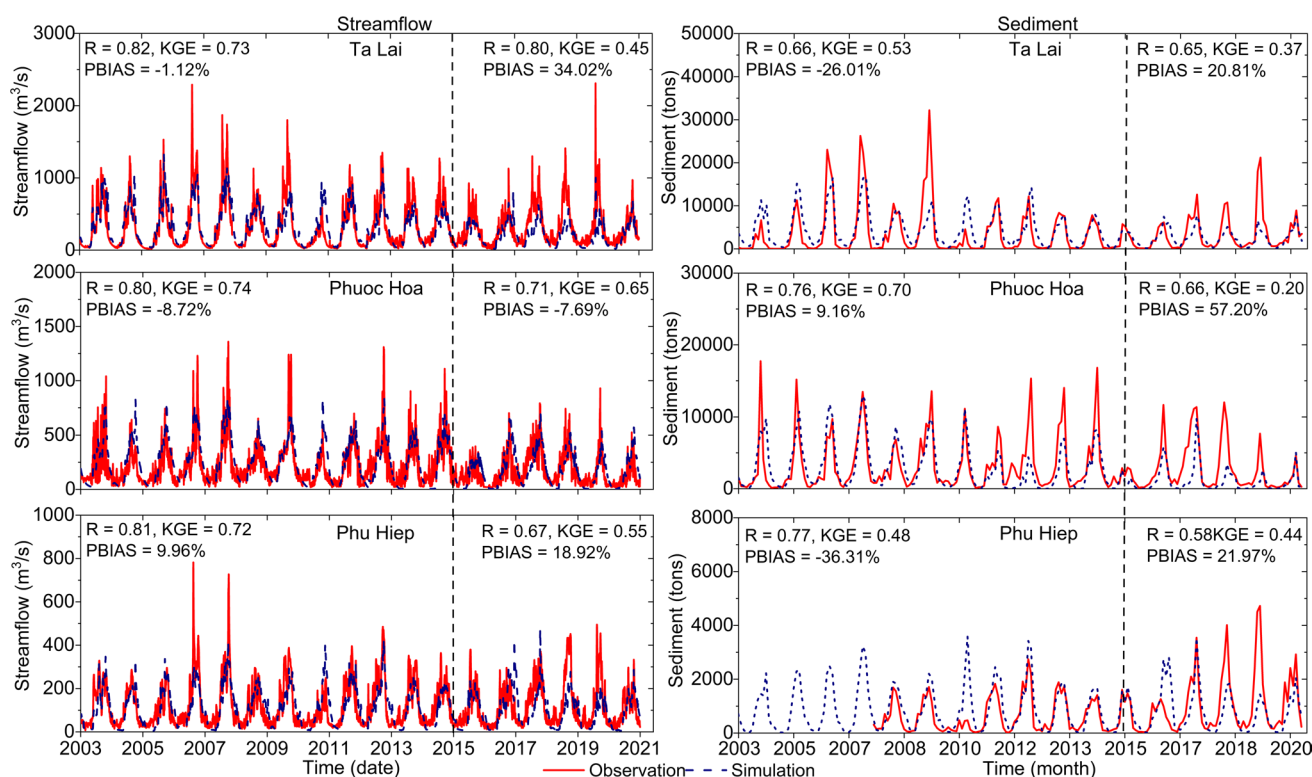
Fig. 3 The hydrographs of the daily streamflow and average monthly sediment at the Ta Lai, Phuoc Hoa, and Phu Hiep stations during the calibration (2003–2014) and validation (2015–2020) periods
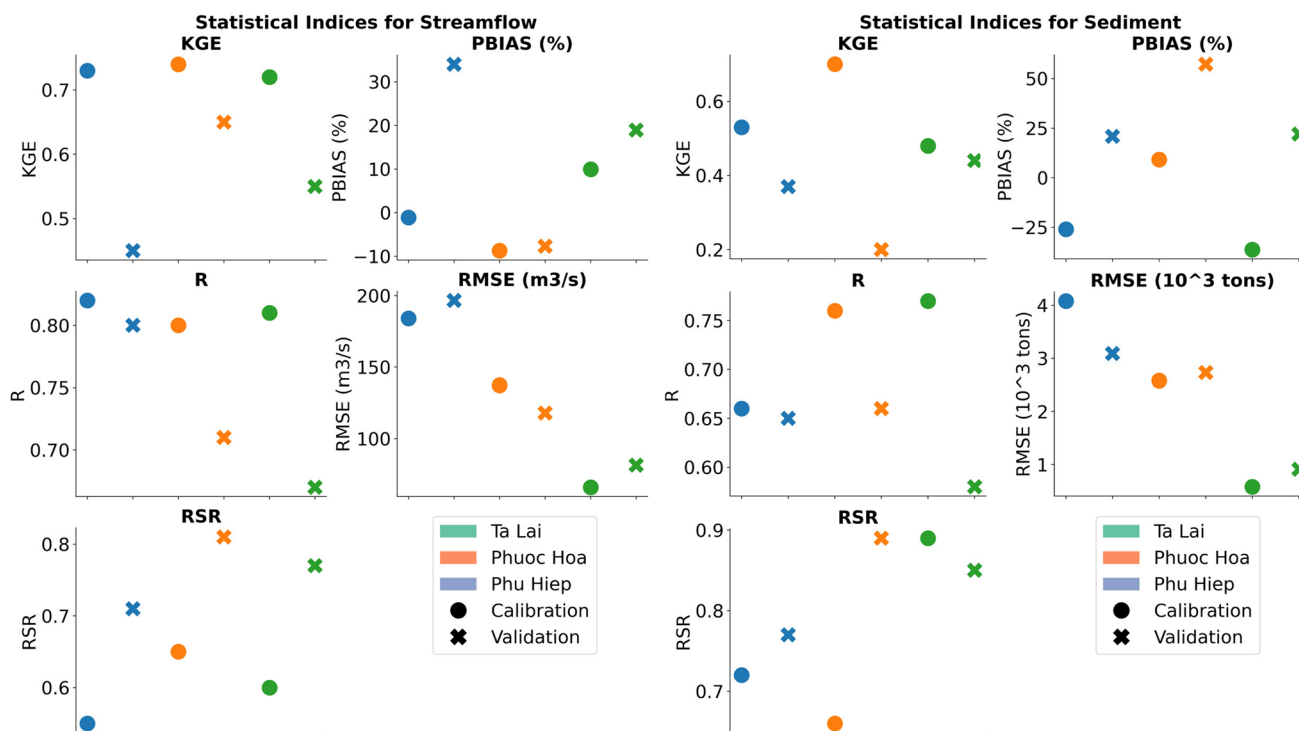
Fig. 4 Statistical indices of the streamflow and sediment at three hydrological stations

average annual streamflow in the Ta Lai subbasin decreased by 18.8 m³/s compared to that in the scenario without dams, as shown in Figs. 5a and e and 6c, and Table 5. Moreover, a minor decrease of 3.1% in streamflow during the rainy season was observed, which may not significantly impact the SGDN outlet.

Similar to that in the Ta Lai subbasin, the streamflow in the Phuoc Hoa subbasin also experienced a significant decrease due to water transfer. This change became particularly noticeable from 2011 onwards, corresponding with operations at the Phuoc Hoa reservoir. This reservoir was primarily designed to transfer water to the Dau Tieng reservoir, as indicated in Fig. 1. The impact of this water transfer is most pronounced during the dry season, as shown in Figs. 5b and e, and 6, and Table 5. The reductions in streamflow amounted to 12.8% during the dry season and 1.5% annually. In contrast, during the rainy season, effective regulation by larger upstream reservoirs, such as Thac Mo, Can Don, and Srok Phu Mieng, resulted in a 1.9% increase in streamflow, equivalent to 8.1 m³/s, compared to scenarios without dams.

Unlike the Ta Lai and Phuoc Hoa subbasins, the Phu Hiep subbasins are unaffected by water transfer. The operating efficiency of the Ham Thuan reservoir (Fig. 1; Table 3), which has a storage capacity of 695 Mm³, has helped significantly increase streamflow during the dry season, especially in January. During the rainy season, the difference

is smaller (Fig. 5c and e). However, comparing the area of the Phu Hiep subbasin (1,083 km²) with that of the entire basin (29,667.5 km²), this difference has a small effect on the outlet streamflow.

Table 5 provides a detailed analysis of streamflow changes in four subbasins: Ta Lai, Phuoc Hoa, Phu Hiep, and the entire SGDN basin. During the dry season, notable decreases in streamflow were observed in the Ta Lai and Phuoc Hoa subbasins, with reductions of 20 m³/s and 16.4 m³/s, respectively. In contrast, the Phu Hiep subbasin experienced a minor increase of 0.9 m³/s due to the presence of dams. Overall, the entire basin decreased 3.2 m³/s in the dry season. However, the rainy season presented a contrasting trend, with increased streamflow observed in the Phuoc Hoa and Phu Hiep subbasins. Notably, the entire basin experienced a substantial increase of 84.7 m³/s during this period. On an annual scale, while the streamflow of Ta Lai and Phuoc Hoa decreased, that of Phu Hiep and the entire basin increased, with a minimum increase of at least 6.5 m³/s.

4.3 Effects of cascading reservoirs on monthly, seasonal, and annual sediment load variations

The monthly, seasonal, and annual streamflow in the SGDN basin exhibited heterogeneous changes at various locations. However, the sediment load significantly decreased in all the

Fig. 5 Comparison of monthly variations in streamflow at three locations and outlets of the SGDN River basin, with and without dams
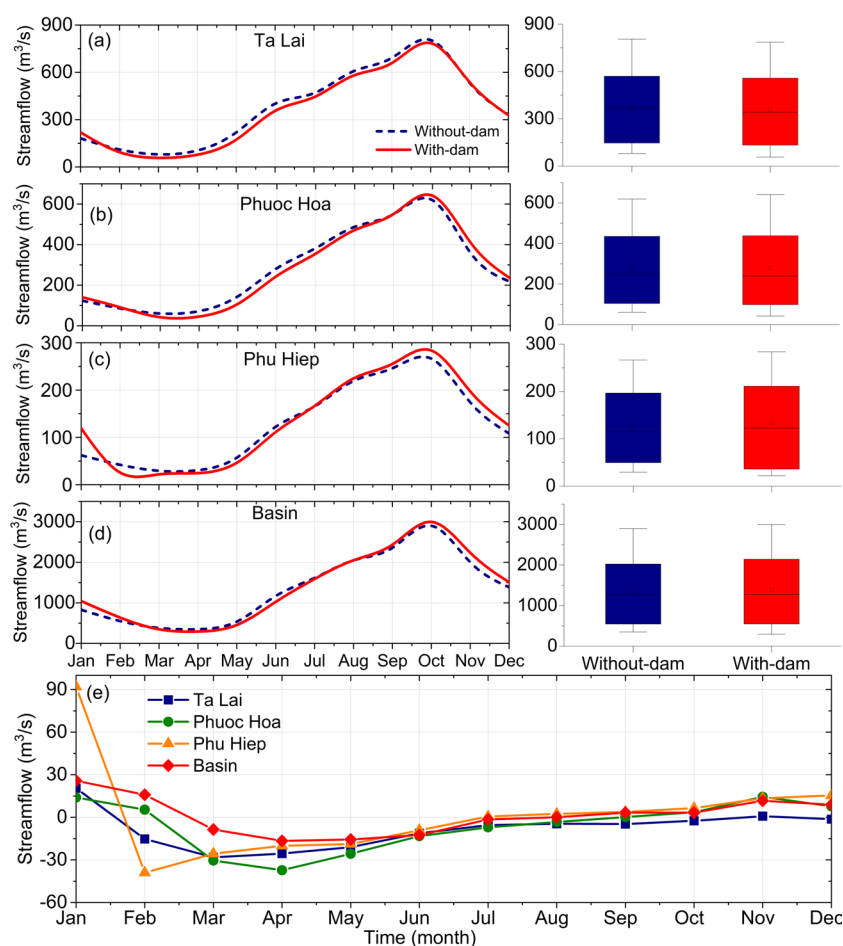
examined subbasins and across the entire basin, as shown in Fig. 7; Table 5. The sediment load decreases during both the flood and dry seasons, and the flood season has a more pronounced reduction.

The largest annual reduction observed at Phuoc Hoa was 40.9% (1.67×10^3 tons), a region with numerous large reservoirs. Similarly, the sediment loads at Ta Lai and Phu Hiep decreased by 29.8% and 21.9%, respectively, in the presence of dams. The sediment load at the basin outlet decreases by 37.4%, equivalent to 3.48×10^3 tons. This substantial reduction is attributed to the presence of two major downstream reservoirs, Dau Tieng (total storage capacity of 1,580 Mm³) and Tri An (total storage capacity of 3,407.1 Mm³) (Fig. 1). This means that these reservoirs trapped a substantial amount of sediment before it reached the SGDN outlet.

The sediment load changes showed a similar trend, with significant reductions found during the dry season across all the examined locations. This reduction was particularly pronounced in the Phuoc Hoa subbasin (57.5%) and across the basin with 57.7%. During the rainy season, there was also a decrease in sediment load, although the reduction was less severe compared to the dry season. Annually, all locations within the basin experienced reductions in sediment load,

with the most significant decreases occurring overall and in Phuoc Hoa. The percentage changes in sediment load reflect these trends, showing the greatest reductions during the dry season. In summary, these results indicate that the presence of dams and reservoirs in the SGDN River basin profoundly impacts streamflow and sediment transport, with the effects varying depending on the season and the specific location within the basin.

4.4 Projected climate change in the SGDN basin

Cascade dam development and climate change scenarios (CMIP6) were investigated to project future streamflow and sediment load changes across the entire basin, with a focus on the SGDN's outlet (Figs. 8 and 9; Table 7).

The projected annual rainfall in all the climate scenarios decreased by 24.6–6.2% compared with the historical data. Moreover, the maximum and minimum temperatures are projected to increase, ranging from 1.2 °C to 3.7 °C and from 1.2 °C to 4.3 °C, respectively (Table 6; Figs. 8 and 10).

Between 2023 and 2100, the rainfall is expected to decrease interdecadal. Notably, the rainfall amount under the
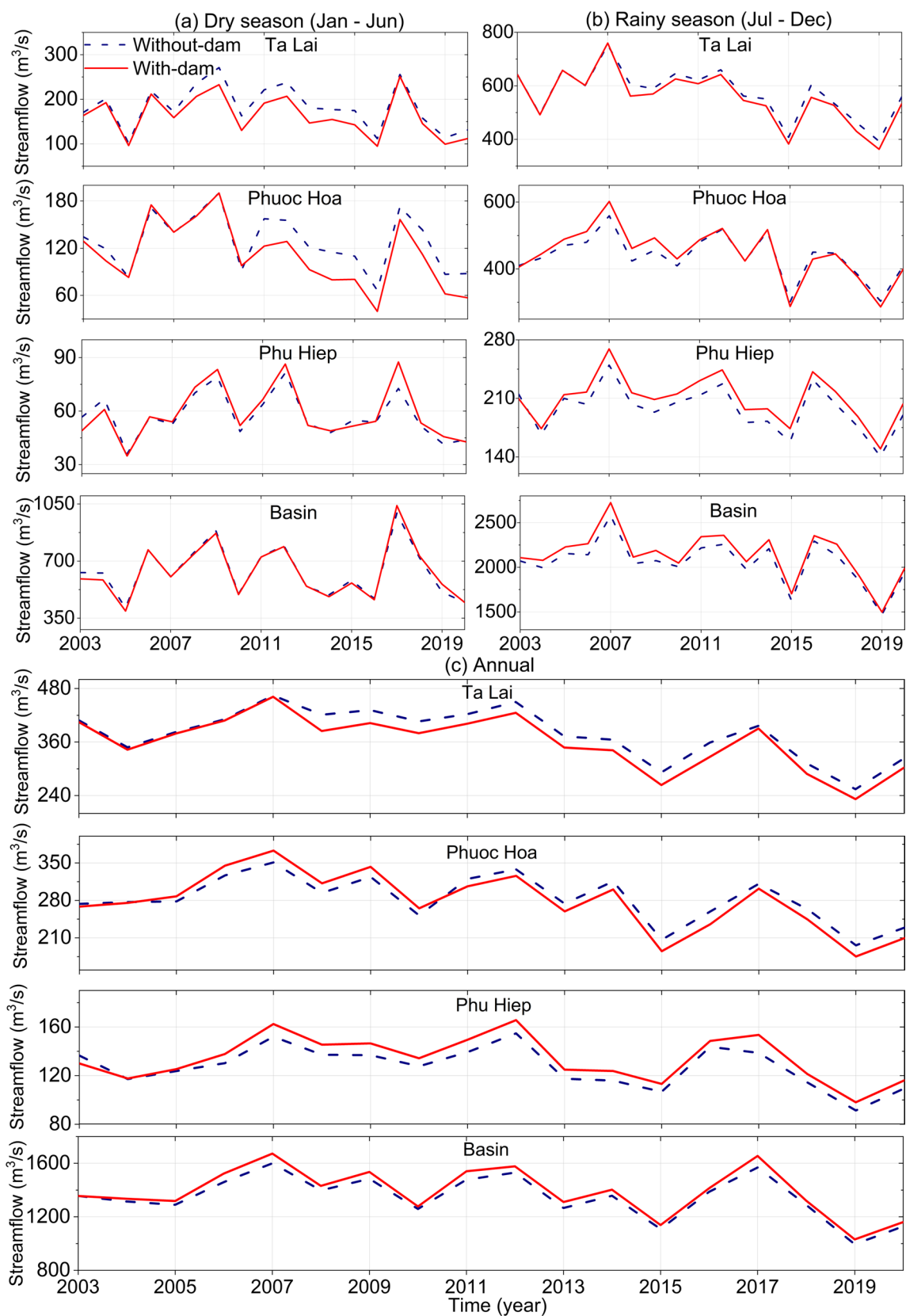
Fig. 6 The mean annual streamflow at Ta Lai, Phuoc Hoa, Phu Hiep, and the outlet of the SGDN basin in the (**a**) dry season, (**b**) rainy season, and (**c**) annual season

Table 5 Changes in the average streamflow and sediment during 2003–2020 at four locations under the with-dam and without-dam scenarios. The presented information is color-coded to emphasize percentage changes: red indicates the largest decreases, while blue represents the largest increases

Changes			Subbasins			
			Ta Lai	Phuoc Hoa	Phu Hiep	Basin
Streamflow	Changes in the magnitude (m^3/s)	Dry season	-20	-16.4	0.9	-3.2
		Rainy season	-17.6	8.1	12.2	84.7
		Annual	-18.8	-4.1	6.5	40.8
	Percent of change (%)	Dry season	-10.9	-12.8	1.5	-0.5
		Rainy season	-3.1	1.9	6.2	4.1
		Annual	-5.0	-1.5	5.1	3.0
Sediment load	Changes in magnitude (10^3 tons)	Dry season	-0.86	-0.82	-0.2	-2.6
		Rainy season	-2.46	-2.51	-0.47	-4.36
		Annual	-1.66	-1.67	-0.34	-3.48
	Percent of change (%)	Dry season	-36.5	-57.5	-38.1	-57.7
		Rainy season	-28	-37.4	-18.7	-30.9
		Annual	-29.8	-40.9	-21.9	-37.4

SSP-3.70 scenario is greater than that under the SSP-1.26, SSP-2.45, and SSP-5.85 scenarios (Table 6; Figs. 8 and 10).

4.5 Effect of cascade dams on the attenuating effect of climate change on streamflow and sediment

The total predicted streamflow under all the scenarios exhibited a predominantly decreasing trend in the future, which could adversely affect the ecological streamflow and water security in the SGDN River basin. Under the four chosen scenarios (SSP-1.26, SSP-2.45, SSP-3.70, and SSP-5.85), the annual streamflow changes are projected to range from − 19.4 to 2.8%, -22.0% to -0.2%, -32.2% to -6.2%, and − 21.5% to -1.0%, respectively (Fig. 8; Table 7). However, the ensembles of these four scenarios indicate consistent decreases of 7.4%, 8.1%, 14.7%, and 9.2%, respectively.

On a decadal basis, the streamflow demonstrated a decreasing trend under the SSP-1.26, SSP-2.45, SSP-3.70, and SSP-5.85 ensembles, with rates of 12.8 m³/s/decade (0.9%), 14.0 m³/s/decade (1.0%), 25.5 m³/s/decade (1.8%), and 16.0 m³/s/decade (1.2%), respectively.

The variations in the monthly streamflow under each climate scenario are shown in Fig. 9a. The operation of large-capacity reservoirs has proven effective at mitigating the impacts of climate change scenarios. In the future, monthly streamflows are expected to increase during the dry season (from January to April) and decrease during the rainy season (from July to October). There is a notable change in seasonal streamflow due to dam operation in the ensemble scenarios compared to the historical data. These changes ranged from an increase of 14.5–25.4% in the dry season to a decrease of 16.7–23.1% in the rainy season.

Upstream reservoirs are expected to continue trapping incoming sediments in the future. Thus, a consistent decrease in the predicted sediment load is observed across all the scenarios (Fig. 9; Table 7). This trend was particularly noticeable during the rainy season (Fig. 9b) and may significantly impact sediment dynamics, downstream river morphology, and estuarine stability. Under SSP-1.26, SSP-2.45, SSP-3.70, SSP-5.85, and the ensemble scenario, the total sediment load is predicted to decrease by 44.0 − 55.0%, 40.4 − 54.3%, 39.3 − 56.0%, and 41.6 − 53.3%, respectively (Figs. 8 and 9b, and Table 7). On a decadal scale, the sediment load is significantly reduced under these scenarios at rates of 0.4×10^3 tons/decade (6.9%),
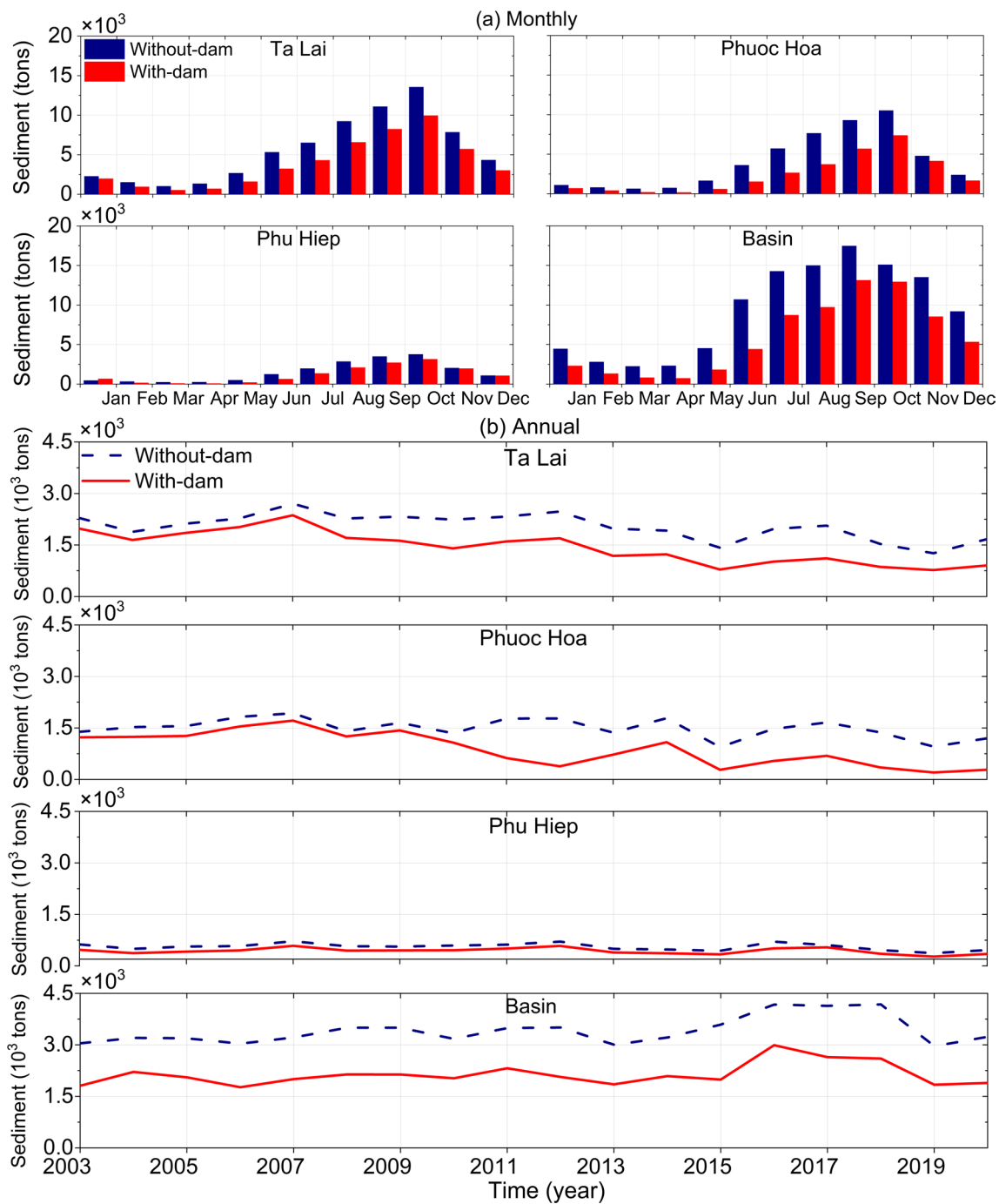
Fig. 7 a The average (2003–2020) monthly sediment load at Ta Lai, Phuoc Hoa, Phu Hiep, and the outlet of the basin and (**b**) the total annual sediment

0.4×10^3 tons/decade (6.8%), 0.41×10^3 tons/decade (7.0%), and 0.39×10^3 tons/decade (6.7%).

Table 7 shows the analysis of streamflow and sediment yield changes under the different SSP scenarios using the various models. Generally, the projected streamflow and sediment loads are predicted to change significantly compared to the historical values. In streamflow, all the models,

except for MIROC6, which exhibited a slight increase (2.8% under SSP-1.26), exhibited decreases compared to the historical values under all the other scenarios. The most significant streamflow decreases are observed in MRI-ESM2-0, with reductions ranging from 19.4 to 32.2%, highlighting a notable sensitivity to climate change scenarios. The ensemble model also showed a consistent decrease in streamflow
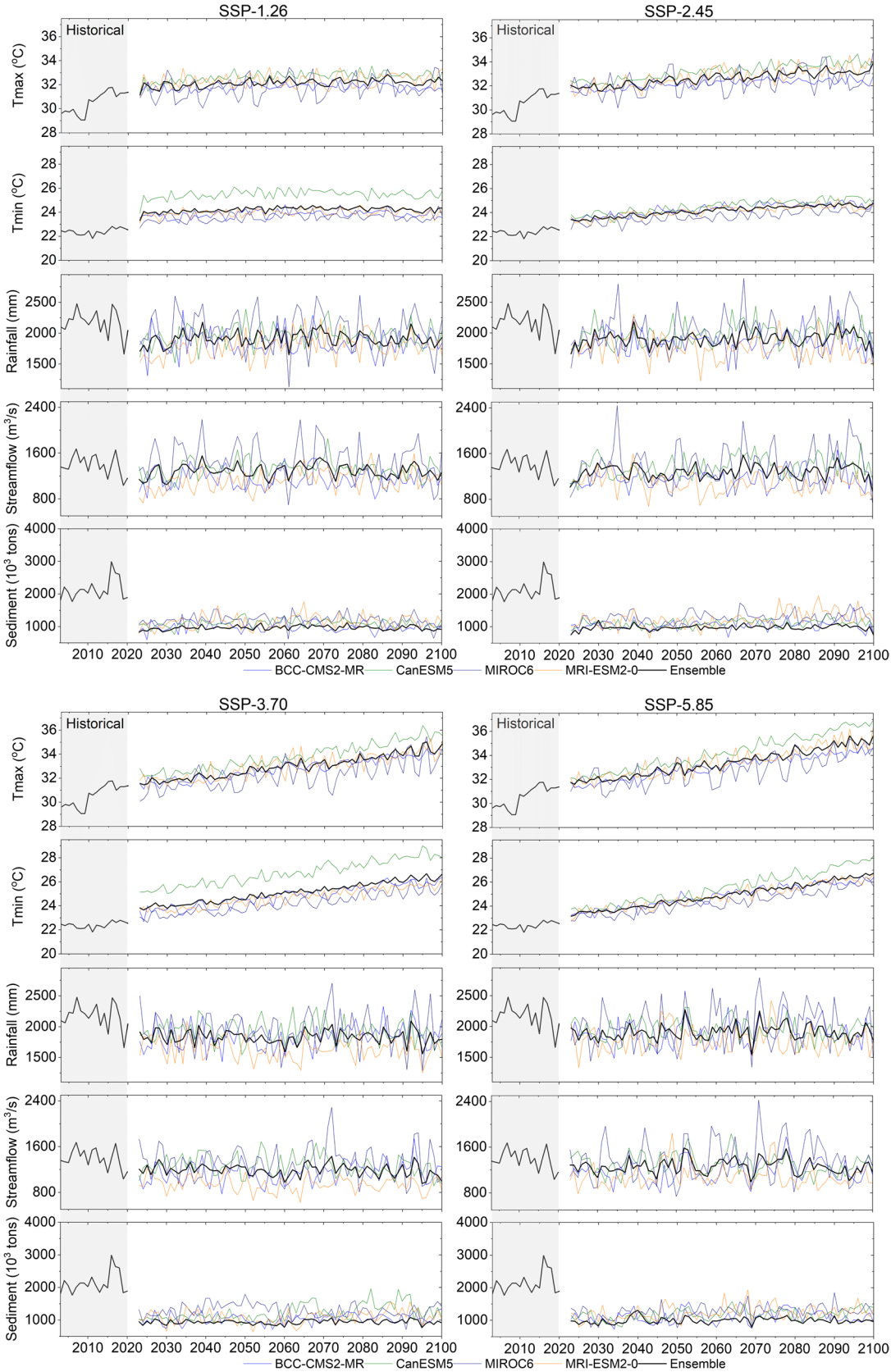
◀ **Fig. 8** The average maximum temperature, minimum temperature, annual rainfall, annual streamflow, and total sediment load at the basin outlet from the GCMs and the ensemble model (2023–2100) under the SSP-1.26, SSP-2.45, SSP-3.70, and SSP-5.85 scenarios. The black line represents the ensemble model, whereas the other colors represent individual GCMs

across all the scenarios, with reductions ranging from 7.4 to 14.7%. There is a decrease across all models and scenarios for sediment, signifying a consistent trend of reduced sediment transport under future climate conditions. The reductions are particularly significant, often exceeding 40%. The ensemble model revealed a decrease in sediment content, ranging from 53.3 to 56.0%, underscoring the notable anticipated impact of climate change on sediment dynamics. In summary, the results suggest a general trend of reduced streamflow and sediment discharge under future climate scenarios, with the degree of change varying across different models and SSPs. This highlights the potential impact of climate change on hydrological processes in this region.

5 Discussion

Although there are many studies, new Research is still needed to clarify the impact of climate change and dams on streamflow and sediment from the past to the future. In this study, previous works have not comprehensively studied our findings on the SGDN River basin, which is a watershed within the Ho Chi Minh economic zone. Although crucial, there are no hydrological stations monitoring streamflow and sediment downstream of major dams, such as Dau Tieng, Tri An, and Dong Nai (Fig. 1). Consequently, assessing the impacts of these dams on streamflow and sediment changes under climate change conditions is unfeasible using solely historical data analysis. Our results analysis revealed that upstream dams (with a total storage capacity of approximately 8.6 billion m³) are crucial drivers of streamflow and sediment alterations in the SGDN basin (Figs. 5, 6, 7, 8, 10 and 9; Tables 5 and 7). The significant influence of human activities, such as dam construction on streamflow changes has also been widely reported for rivers worldwide, including the Mekong River (Van Binh et al. 2020a; 2020b), the Vu Gia Thu Bon River basin (Nguyen et al. 2023b, 2023c), the Yellow River (Gao et al. 2011), and rivers in the U.S. (Chalise et al. 2021).

The diversion reservoirs of Dai Nga, Da Nhim, and Phuoc Hoa (Fig. 1) are identified as key factors influencing water availability. Consequently, the streamflow in the Tai Lai and Phuoc Hoa subbasins adversely decreased during the dry season (January – June) (Figs. 5a, b and e and 6, and Table 5). This could create significant water stress on local communities and government agencies. In contrast,

dams are recognized as the primary contributors to the increase in the dry season streamflow in the Phu Hiep subbasin (Figs. 5, 6 and 7; Table 5). This is because the dams in the Phu Hiep subbasin are hydropower and do not divert water to other basins. However, comparing the area of the Phu Hiep subbasin with the entire basin, this difference has a small effect on the outlet streamflow.

We found that future rainfall is projected to decrease compared to historical levels, as shown in Figs. 8 and 10; Table 6. The decreasing rainfall contributes to a reduction in annual streamflow and sediment load compared to historical data (Figs. 8 and 9, and Table 7). This change is also linked to reservoir operations, including water transfers. However, we found that changes in streamflow are primarily driven by dam and reservoir regulations, exceeding the effects of climate change. This finding is similar to the Mekong River basin (Van Binh et al. 2020a; 2020b). When considering monthly and seasonal variations, the operation of cascade dams led to a slight increase in streamflow during the dry season compared to historical levels (Figs. 8 and 9, and Table 7). These results could help mitigate the effects of out-basin diversion and alleviate drought conditions. This is a great concern in the current state of the SGDN River basin and could reduce pressure on water resources shortage for new urban areas and economic centers downstream. Moreover, during the rainy season, the large effective capacities of reservoirs help significantly reduce flood peaks from October to November (Figs. 8, 10 and 9; Table 7).

Understanding flow regime changes is important for humans' well-being and freshwater-dependent biot. We found a shift in the projected monthly future streamflow (Fig. 9). These shifts can disturb the ecology by affecting the functions of organisms, changing the population, and altering the ecosystem structure (Gitay et al. 2002; Assessment 2005; Döll et al., 2010; Döll et al., 2012; Tesfaye et al. 2020). Although there will likely be a future shortage of water resources compared to historical levels, the annual distribution is expected to be more uniform. This could reduce downstream flood risks and improve regulatory efficiency during dry months.

Reduced sediment in the historical and future periods was caused mainly by reservoirs (Figs. 7 and 8, and 9b; Tables 5 and 7). In the future, reservoir lifespans will be significantly shortened due to increased sedimentation. Additionally, sedimentation will lead to a loss of storage capacity, and higher temperatures will result in substantial evaporation. This may lead to several challenges, including increased flood risks and reductions in domestic and irrigation water supply. It also impedes the functionality of intake structures and accelerates the abrasion of hydraulic machinery. This may result in lower efficiency and higher maintenance costs, as Mekonnen et al. (2022) discussed.
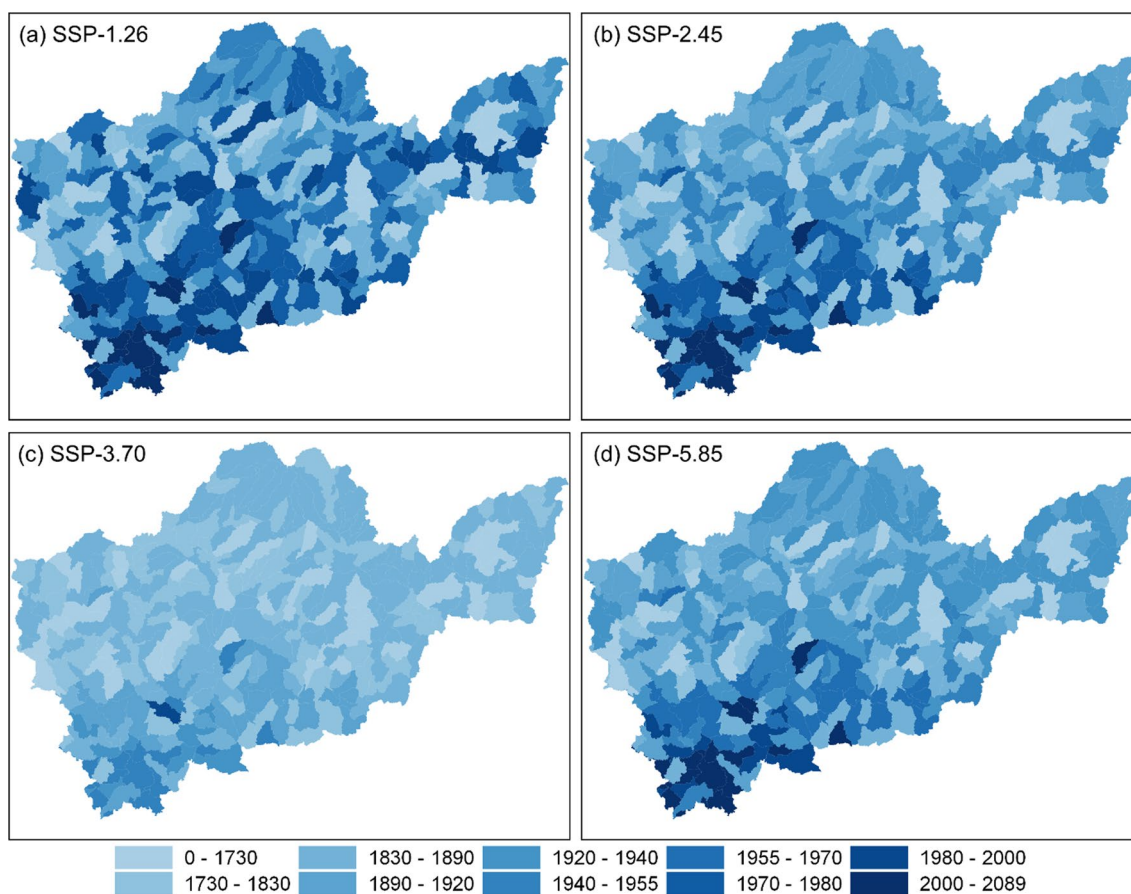
Fig. 9 The average annual rainfall of the ensemble model (2023–2100) under the SSP-1.26, SSP-2.45, SSP-3.70, and SSP-5.85 scenarios across the SGDN basin

Table 6 Future projected changes in precipitation and temperature (2023–2100) compared to historical data (2003–2020)

No	Model	Precipitation (%)			
		SSP-1.26	SSP-2.45	SSP-3.70	SSP-5.85
1	BCC-CSM2-MR	-15.0	-14.7	-15.3	-13.4
2	CanESM5	-9.6	-8.5	-11.3	-10.2
3	MIROC6	-6.2	-7.1	-10.5	-7.3
4	MRI-ESM2-0	-17.6	-19.2	-24.6	-18.1
5	Ensemble	-12.1	-12.4	-15.4	-12.3

No	Model	Temperature (°C)							
		Minimum				Maximum			
		SSP-1.26	SSP-2.45	SSP-3.70	SSP-5.85	SSP-1.26	SSP-2.45	SSP-3.70	SSP-5.85
1	BCC-CSM2-MR	+1.4	+1.9	+2.4	+2.4	+1.3	+1.7	+2.3	+2.5
2	CanESM5	+3.1	+2.1	+4.3	+3.1	+2.2	+2.7	+3.3	+3.7
3	MIROC6	+1.2	+1.3	+1.8	+1.9	+1.2	+1.8	+1.8	+2.3
4	MRI-ESM2-0	+1.6	+1.7	+2.3	+2.4	+1.8	+2.3	+2.5	+3.0
5	Ensemble	+1.8	+1.7	+2.7	+2.5	+1.6	+2.1	+2.5	+2.9

Additionally, the loss of storage capacity directly impacts reservoirs' water availability and operational schedules. Taken together, these findings indicate that the amount of water stored in reservoirs is projected to decrease in the future, which may reduce the capacity of reservoirs to support environmental flow maintenance and salinity control
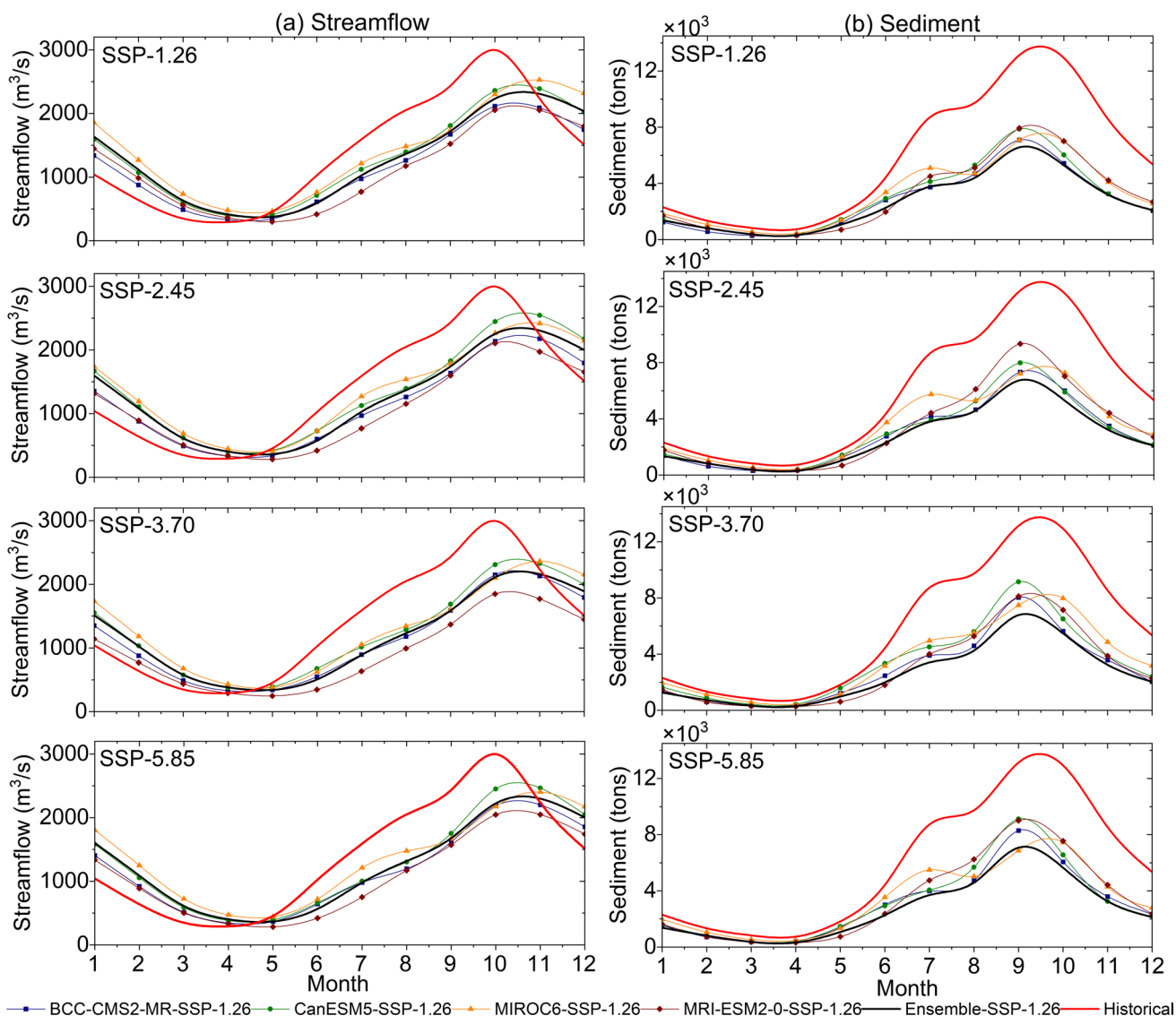
Fig. 10 The average monthly (**a**) streamflow and (**b**) sediment loads of the GCMs and the ensemble model (2023–2100) under the SSP-1.26, SSP-2.45, SSP-3.70, and SSP-5.85 scenarios at the SGDN outlet

in estuaries. Consequently, this study's predicted decrease in sediment results provides crucial information for various purposes. These include managing reservoir sedimentation, understanding river morphology evolution, addressing environmental-related concerns, and evaluating the effectiveness of different land use management strategies in the SGDN basin.

The interactions between climate change and human activities and their combined effects on flow regime alterations show a complex scenario (Ngo et al. 2018; Saedi et al. 2022). For example, while climate change is expected to exacerbate flooding in the Mekong basin (Try et al. 2020), the construction of dams typically mitigates floodwaters through reservoir trapping (Van Binh et al. 2020b). In Ho Chi Minh City, severe floods are predicted to increase

due to the impacts of climate change and rising sea levels (Schwarzer et al. 2016; Camenen et al. 2021). However, the findings from this study suggest that cascade dams might play a beneficial role in flood control in Ho Chi Minh City (Fig. 9a). Given the rapidly changing climate, which may lead to more frequent extreme weather events (Try et al. 2020), the effects on flow regimes may exceed the existing capacities of dams, potentially intensifying flood risks (Dang et al., 2017). Thus, water resource strategists and managers are increasingly focused on the compounded impacts of human interventions and climate change on water resources. These complex factors introduce significant challenges and uncertainties, underscoring the need for integrated and proactive management strategies to ensure sustainable and effective water resource utilization (Saedi et al. 2022).

(1) Dam operations and water diversions are responsible for a 0.5% decrease in streamflow during the dry season and a 4.1% increase during the rainy season compared to scenarios without dams. Additionally, there was a 37.4% decrease in the annual sediment load across the basin outlet. The Dai Nga and Da Nhim diversion reservoirs significantly reduced the streamflow in the Ta Lai subbasin, while the Phuoc Hoa diversion reservoir reduced the streamflow in the Phuoc Hoa subbasin.

(2) In the context of global warming, rainfall is expected to decrease (24.6% – 6.2%), reducing streamflow (0.2 – 32.2%) and sediment (39.3 – 56.0%) compared to historical levels. Specifically, the streamflow is projected to decrease in the rainy season (16.7 – 23.1%) and increase in the dry season (14.5 – 25.4%). We found that changes in streamflow are primarily driven by dam and reservoir regulations, exceeding the effects of climate change. The anticipated reductions in future streamflow and sediment load may have adverse implications for ecological flow, water security, sediment dynamics, and downstream river morphology in the SGDN River basin.

Our findings offer a valuable approach to understanding the comprehensive effects of cascading reservoirs and inter- and outer-basin water diversion. These data can serve as a reference for other basins globally. Our study provides a holistic method for quantifying the cascading impact of man-made infrastructures, distinguishing their effects from those of climate change. This study can aid regional decision-makers and stakeholders in planning for future water resource management and contributes to the literature that has employed combined hydrological models, water diversion, and reservoir operation to investigate the effects of reservoirs on hydrological simulations worldwide.

Declarations

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