Van Binh, D., Nguyen, B.Q., Nguyen, T.-T.-H., Le, X.-H., Tuan, L.A., Le, M.-H., Kantoush, S.A., **Nguyen, V.T.**, Dinh, V.N., Luan, N.T., Ahmed, M.F., Sumi, T. (2025):
Quantifying the impacts of climate change and human interventions on flow alterations in a tropical river
Water Resour. Manag. **39** , 3537 – 3552

https://doi.org/10.1007/s11269-025-04121-w

Quantifying the Impacts of Climate Change and Human Interventions on Flow Alterations in a Tropical River

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Abstract

This study aims to quantify the effects of climate variability, dams, and land use/land cover (LULC) changes on the alterations in the monthly, seasonal, and annual discharge in the Sai Gon Dong Nai (SGDN) River basin, a tropical river system in Vietnam. We employed statistical methods (statistical tests, linear regression, and double mass curves) combined with the Soil and Water Assessment Tool (SWAT) model. We found that 1) climate variability is the primary driver of natural flow, but human activities are essential contributors to statistically significant flow alterations. 2) Dams and reservoirs in the SGDN River basin may have dampened the effects of LULC changes on reducing downstream flood discharge. 3) The Da Nhim and Dai Ninh diversion reservoirs may have had a limited impact on flow alterations in the Dong Nai River. 4) In contrast, the Phuoc Hoa diversion reservoir may have reduced flooding in the Be River but partially increased flooding in the Sai Gon River. 5) Quantitatively, human activities contributed −14.2% to +22.3% and −55.7% to +66.5% of the annual and monthly discharge changes in the SGDN River Basin. The findings of this study provide valuable insights for strategic water management in the SGDN River Basin and contribute to efforts to promote sustainable development in river basins within tropical monsoon regions.

Keywords: Human activities, climate change, LULC change, SWAT, tropical river, Sai Gon Dong Nai River basin.

1 Introduction

River flow regime variability is the backbone of riverine ecosystems and societal development (Chalise et al. 2021). Climate variability, accelerated by global warming, has significantly altered flow regimes, increasing the magnitude and frequency of extreme events (Tran and Lakshmi 2024). In addition, humans have increasingly exploited water and natural resources by constructing dams and reservoirs and changing LULC. These human activities have led to unfavorable changes in the flow regime; for instance, LULC changes may increase the severity and frequency of floods (Nguyen et al. 2023). In addition, dams can attenuate flooding through reservoir regulation (Binh et al. 2020). Thus, river damming is considered the most dominant driver of flow alterations worldwide (Vörösmarty et al. 2010).

Numerous studies have been conducted in different areas to assess the impacts of climate change/variability and human activities on flow alterations worldwide, such as in Europe (De Girolamo et al. 2022), Asia (Yang et al. 2018; Zhang et al. 2021), Africa (Ahmed et al. 2019; Banda et al. 2022), and America (Chalise et al. 2021; Reis et al. 2024). Most studies have highlighted human activities as the dominant driver, surpassing the impacts of climate change (e.g., Banda et al. 2022; Binh et al. 2020). Moreover, dams and climate interact synergistically (i.e., dams can exacerbate climate-driven flow alterations) or antagonistically (i.e., dams can dampen climate-driven flow alterations) by spatiotemporally changing flow (Chalise et al. 2021).

Effective water resource management under altered flow requires quantifying the contributions of climate change and human activities. Various approaches have been used, including statistical methods and numerical models (e.g., Li et al. 2024; Zhang et al. 2021), hydrological models (e.g., Nguyen et al. 2024), machine learning models (e.g., Cui et al. 2020), and analogy frameworks (e.g., Yang et al. 2018), and others have used only statistical methods (e.g., Banda et al. 2022; Gao et al. 2011; Reis et al. 2024). The dominant contributors to the changing flow varied geographically. Some basins that are predominantly influenced by climate change/variability include the Yellow River, China, at 82.2% (Gao et al. 2011); the upper Yangtze River Basin, China, at 70% (Zhang et al. 2021); and the Sha River, China, at 59.3–64.7% of the preflood monthly magnitude (Yang et al. 2018). Conversely, human activities drive 95% of the flow alterations in the upper Mekong Basin (2008–2014) (Han et al. 2019) and 75% in the Rietspruit subbasin, South Africa (Banda et al. 2022).

The combined effects of climate change and human activities on flow alterations are complicated and case-specific. Despite being the second-largest tropical basin in southern Vietnam, the SGDN Basin has been the subject of limited research on these impacts. Pham et al. (2019) and Truong et al. (2018) assessed water balance and flow regime alterations due to climate and LULC changes. Recently, Nguyen et al. (2024) evaluated the effects of dams and climate change on future flow regimes and sediment loads. With these limited studies, some research gaps can be identified. *First*, how historical streamflow variations and their controlling drivers are not fully understood. *Second*, the contributions of climate variability and human activities to historical streamflow changes have not been adequately explored. Therefore, there is an urgent need to quantify the contributions of climate variability, dams, and LULC changes to long-term streamflow alternations. Understanding these past changes is essential for future preparedness and proactive management.

This study addresses research gaps by combining statistical analyses with hydrological modeling to understand how climatic variability and human interventions influence flow changes across spatiotemporal scales. The objectives of this research are threefold: (1) to delineate the relative influence of climate change and human activities on streamflow changes; (2) to provide a methodological framework for analyzing streamflow changes in tropical river systems; and (3) to inform sustainable water management practices that accommodate both natural and anthropogenic drivers of change. In addition to contributing to improving global and regional knowledge, the current research is the first effort to quantitatively identify the contributions of each driver to the seasonal and annual flow alterations within this vital river system, contributing valuable insights for strategic water management and promoting sustainable development in tropical monsoon river basins.

2 Study area and materials

2.1 Study area

The SGDN is Vietnam's largest domestic river system, covering Ho Chi Minh City, the largest economic city in Vietnam. It is the backbone of the livelihood of approximately 20 million people in the basin. The Sai Gon River flows into the Dong Nai mainstem, together with the Be and La Nga tributaries, to create the SGDN River system (Fig. 1a). This river system discharges 32.5 billion m^3 of water to the East Vietnam Sea (Anh et al. 2022), ranking second to the Mekong River in southern Vietnam. Seven hydrological stations (see Fig. 1a; Table S1) monitored the daily discharge from the 1980s to 2021.

Hydrologically, there are two seasons: the flood season from June−November (constituting more than 80% of the annual total discharge) and the dry season from December−May (Fig. 1b). The discharge increases from January to July (i.e., rising limb) and decreases from August to December (i.e., falling limb) (Fig. 1b), which is consistent with the seasonal variations in rainfall (Fig. 1c). Flooding is one of the most severe natural disasters in the SGDN Basin, especially in Ho Chi Minh City, and has caused enormous socioeconomic losses and infrastructure damage.

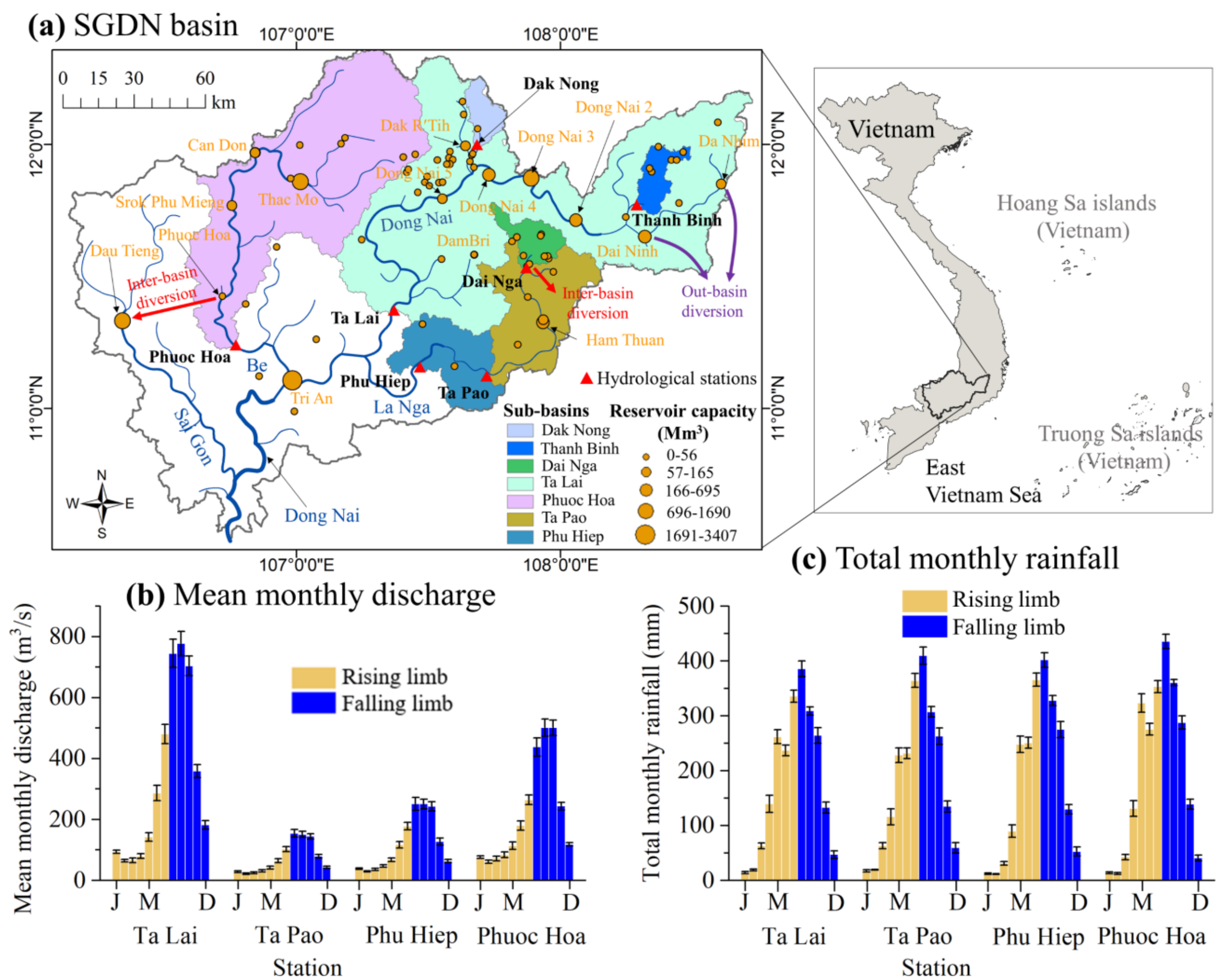

Fig. 1 Geospatial map of the seven studied subbasins in the SGDN Basin (a). In panels b and c, *J* is January, *M* is May, and *D* is December.

Dams and reservoirs in the SGDN Basin are being built to utilize water resources, regulate floods and droughts, and generate energy. Seventy-five irrigation, water supply, and hydropower dams were built with a combined storage capacity of 10.6 billion m^3, including multiple cascade dams, accounting for 32.6% of the river system's water discharge. Thirty-six are large dams (height > 15 m), and the dams were mostly developed after 2009. Urbanization is occurring rapidly because of booming economic development.

Table S2 lists 15 major large dams, including Tri An and Dau Tieng, the largest hydropower and irrigation dams with total storage capacities of approximately 3.4 km^3 and 1.6 km^3, respectively. The Da Nhim and Dai Ninh dams transport water from the Ta Lai subbasin to other basins, whereas the Phuoc Hoa dam diverts water from the Be River to the Sai Gon River (Fig. 1a). The Dai Nga subbasins have multiple irrigation reservoirs that hold water year-round to irrigate neighboring farms. The Dai Nga dam diverts water from the Dai Nga subbasin to the Ta Pao subbasin.

2.2. Data collection and processing

2.2.1 Discharge

Daily discharge data were obtained at seven hydrological stations from the 1980s to 2021 (Table S1) from the Vietnam Meteorological and Hydrological Administration. These datasets were quality-checked by Do et al. (2022). The mean annual discharge of the entire time series ranges from 299 million m^3/yr (at Thanh Binh) to 10,466 million m^3/yr (at Ta Lai) (Table S1). The monthly and yearly discharges and the 1-day, 3-day, 7-day, and 90-day maxima and minima were estimated via daily discharge data to analyze the seasonal and annual flow discharge fluctuations and quantify the driving forces.

2.2.2 Rainfall and DEM

Daily Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) rainfall data (Funk et al. 2015) with 0.05-degree resolution (~ 5 km) for 1981–2021 were used to link discharge variations with rainfall variability. Derived from satellite and in situ measurements, CHIRPS has been validated globally (Shen et al. 2020) and is suitable for analyzing Vietnam's long-term precipitation trends (Le et al. 2020). Data were downloaded from the Climate Hazards

Center of the UC Santa Barbara portal (https://www.chc.ucsb.edu/data/chirps) and pixel-averaged for the seven subbasins.

These seven subbasin boundaries were delineated from a 30 m resolution SRTM (Shuttle Radar Topography Mission) digital elevation map (DEM) (https://dwtkns.com/srtm30m/) using *ArcGIS®10* software (Fig. 1a). Pixel-averaged daily rainfall was processed into total monthly and annual rainfall, along with 1-day, 3-day, 7-day, and 90-day maxima and minima. CHIRPS data reliability was validated against rain gauge data, yielding correlation coefficients of 0.74 and 0.79 for the Thanh Binh and Dak Nong subbasins, respectively.

2.2.3 LULC

Human activities, particularly LULC, are key drivers of flow alterations. The annual LULC data (1990–2020) from Phan et al. (2021) were derived using remotely sensed data and a random forest algorithm. These datasets, downloaded from https://www.eorc.jaxa.jp/ALOS/en/dataset/lulc_e.htm#download, were reclassified from ten original LULC classes (250×250 m resolution) into four categories: forest, agriculture, built-up areas, and water bodies. The percentages of these categories were pixel-averaged for each subbasin. Forests are generally dominant in the SGDN Basin, followed by agricultural land.

2.3.4 Dams and reservoirs

Dams and reservoirs were sourced primarily from Vietnamese official agencies and crosschecked with data from http://thuyloivietnam.vn/home, http://www.vncold.vn/, and the global georeferenced database of dams – GOODD (Mulligan et al. 2020). Many small dams in the SGDN Basin are not recorded in global databases or official reports, so we identified them using Google Earth. This method provides information on dam location, type, and diversion function but lacks details such as completion year and capacity.

3 Methodology

Figure 2 illustrates the research methodology. Historical data on daily discharge, rainfall, annual LULC, and dams were collected and checked for quality. The daily discharge and rainfall were aggregated into monthly and annual values, along with 1-day, 3-day, 7-day, and 90-day maxima and minima. Data analysis followed two steps: 1) statistical methods, including Mann–Kendall, Pettitt, and Sen's slope (Kendall 1938; Mann 1945; Pettitt 1979; Sen 1968), were applied to examine long-term changes in discharge, rainfall, and LULC, highlighting relationships between discharge and controlling factors (rainfall, LULC, and dams); 2) the contributions of rainfall and human activities (LULC and dams) to flow alterations were quantified using the double mass curve, linear regression (Banda et al. 2022; Sun et al. 2022), and SWAT model (Arnold et al. 2012) across various time scales. Finally, water management strategies to mitigate human impacts were discussed.

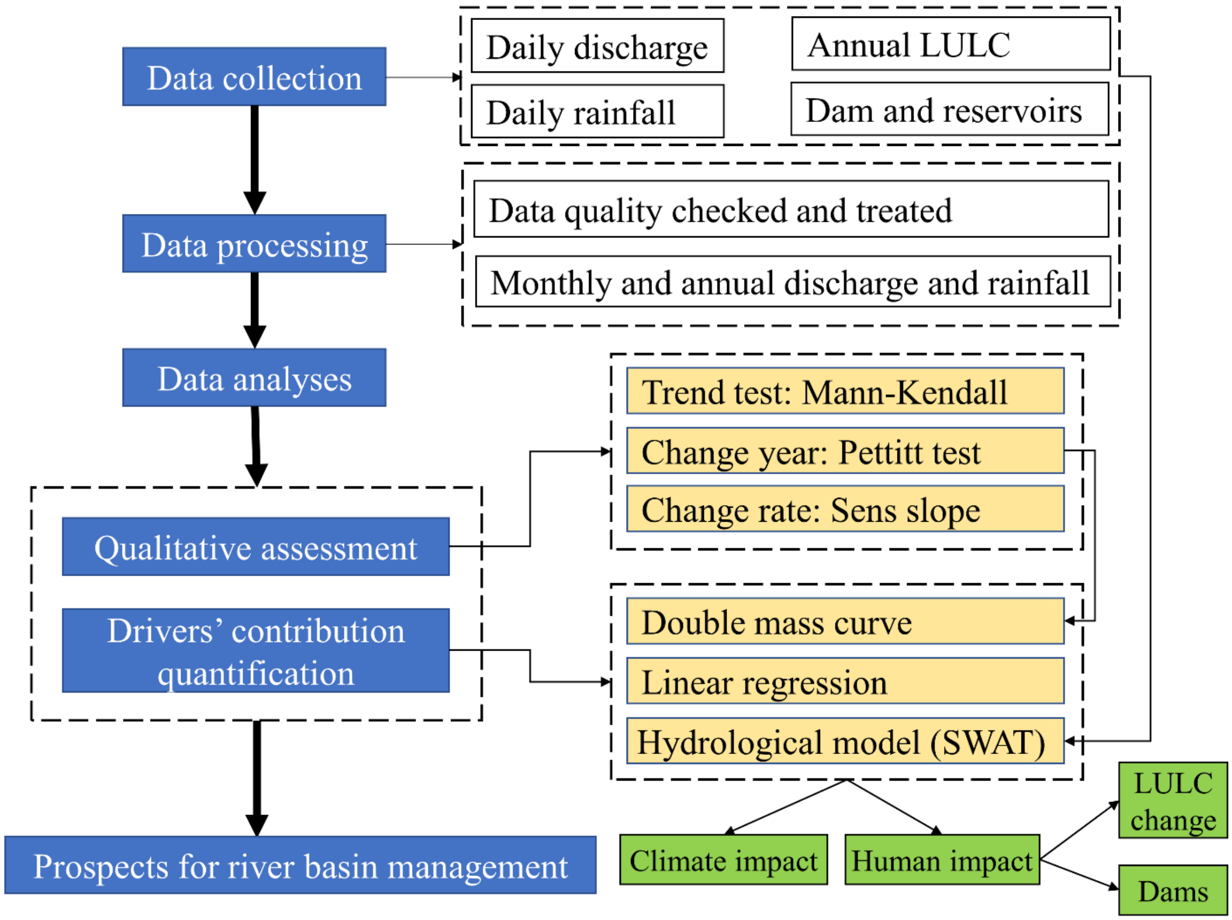

Fig. 2 Schematic methodology framework of the research.

3.1 Statistical trend tests

The Mann–Kendall test (Kendall 1938; Mann 1945) was applied to identify the trends in the monthly and annual discharge (1981–2021), rainfall (1981–2021), and LULC (1990–2020) data. The Pettitt method (Pettitt 1979) was then used to determine the change year, from which the whole time series was divided into pre- and postchange periods. Next, the Sen′s slope method (Sen 1968) was applied to estimate the rate of change (i.e., slope). These methods were performed with the *R* environment (https://www.r-project.org/) under the *Kendall* package. Statistical tests were considered statistically significant at the 10% significance level. Further details are provided in the Supplementary Information.

3.2 Double mass curve and simple linear regression

The double mass curve method was used to analyze the relationship between cumulative rainfall and discharge, identifying consistency and changes in long-term trends. Combined with linear regression, this approach quantifies the impacts of rainfall and human activities on flow and sediment regimes (Banda et al. 2022; Sun et al. 2022). Further details are provided in the Supplementary Information.

3.3 Hydrological model

The SWAT model was used to simulate streamflow and assess the impacts of climate variability and human activities at daily to annual scales. This tool integrates climate, hydrology, LULC change, reservoir operation, and management practices (Arnold et al. 2012; Tran et al. 2023). The model was established for the SGDN River Basin from 2001–2020 and was divided into a one-year warm-up (2001), 13 years of calibration (2002–2014), and six years of validation (2015–2020). Calibration and validation were performed at seven hydrological stations (Fig. 1). Model performance was assessed via four metrics: the correlation coefficient (*R*), Kling–Gupta efficiency (*KGE*), root mean square error (*RMSE*), and percentage of bias (*PBIAS*) Gupta et al. (2009) and Moriasi et al. (2007).

Figure S1 compares the observed and simulated daily streamflows during calibration (2002–2014) and validation (2015–2020) at the three representative hydrological stations. The results indicate satisfactory model performance, with the simulated data aligning well with the observations. During the validation period, *R* ranged from 0.67 to 0.80, *KGE* ranged from 0.45 to 0.65, and *PBIAS* ranged from -7.69% to +34.02%, confirming the reliability of the SWAT model for studying SGDN hydrology.

The validated model was then used to simulate four scenarios to examine the effects of dams, and LULC changes on streamflow: 1) without dams, 2) with dams, 3) the 1990 land use map, and 4) the 2020 land use map. The model parameters remained consistent across the scenarios. For the without-dam and with-dam scenarios, the 2020 land use map was used. In scenarios that assess LULC changes in streamflow, dams were deactivated because the inclusion of dams may interfere (either signify or dampen) with the signal of LULC change effects.

4 Results

4.1 Spatiotemporal variations in discharge

Generally, seasonal (flood and dry) and annual discharge patterns varied across hydrological stations from 1981–2021. There was a notable increase in the seasonal and annual discharge in the headwaters (i.e., Thanh Binh and Dak Nong subbasins) of the Dong Nai River, with statistically significant *p values* ranging from 3.2×10^{-4} to 0.092 for Thanh Binh (excluding June, October, November, and the 7-day maximum) and 5.93×10^{-10} to 0.074 for Dak Nong (Fig. 3a). Discharge pattern shifts occurred from 1995–1998 for the dry season and from 1998–2008 for the flood season. The greatest increases were in the 1-day maximum discharge, by +0.44 m^3/s/yr at Thanh Binh ($p = 0.017$) and by +0.87 m^3/s/yr at Dak Nong ($p = 0.064$).

At Ta Lai (the downstream station), the dry-season discharge significantly increased ($p = 3.85\times10^{-4}$–0.083) from February to May and across the 3-day–90-day minima. This contrasted with a decrease in the flood-season discharge, notably in September ($p = 0.027$), the 3-day maximum ($p = 0.086$), and the 90-day maximum ($p = 0.065$) (Fig. 3a). The change years were 2007–2009 in the flood season and 2011–2016 in the dry season. The increase rates ranged from +0.53 m^3/s/yr in February ($p = 0.003$) to +2.83 m^3/s/yr in May ($p = 0.006$), and the decrease rate was –8.97 m^3/s/yr in September ($p = 0.027$).

Discharge variations at Dai Nga (upstream station) in the La Nga River demonstrated a general decline across the annual, dry-season, and flood-season discharges (Fig. 3a). Significant decreasing trends were found for most periods (p = 0.0007–0.071), except for July in the flood season and March–May in the dry season ($p > 0.1$). The flood-season discharge decreases ranged from –0.30 $m^3/s/yr$ in November (p = 0.004) to –0.85 $m^3/s/yr$ in the 1-day maximum (p = 0.031). At Ta Pao and Phu Hiep (downstream stations), the discharge increased during the dry season and decreased during the flood season (Fig. 3a), with trends most significant at Ta Pao (p = 2.18×10^{-5}–0.099) and in the dry season at Phu Hiep (p = 5.24×10^{-5}–0.024).

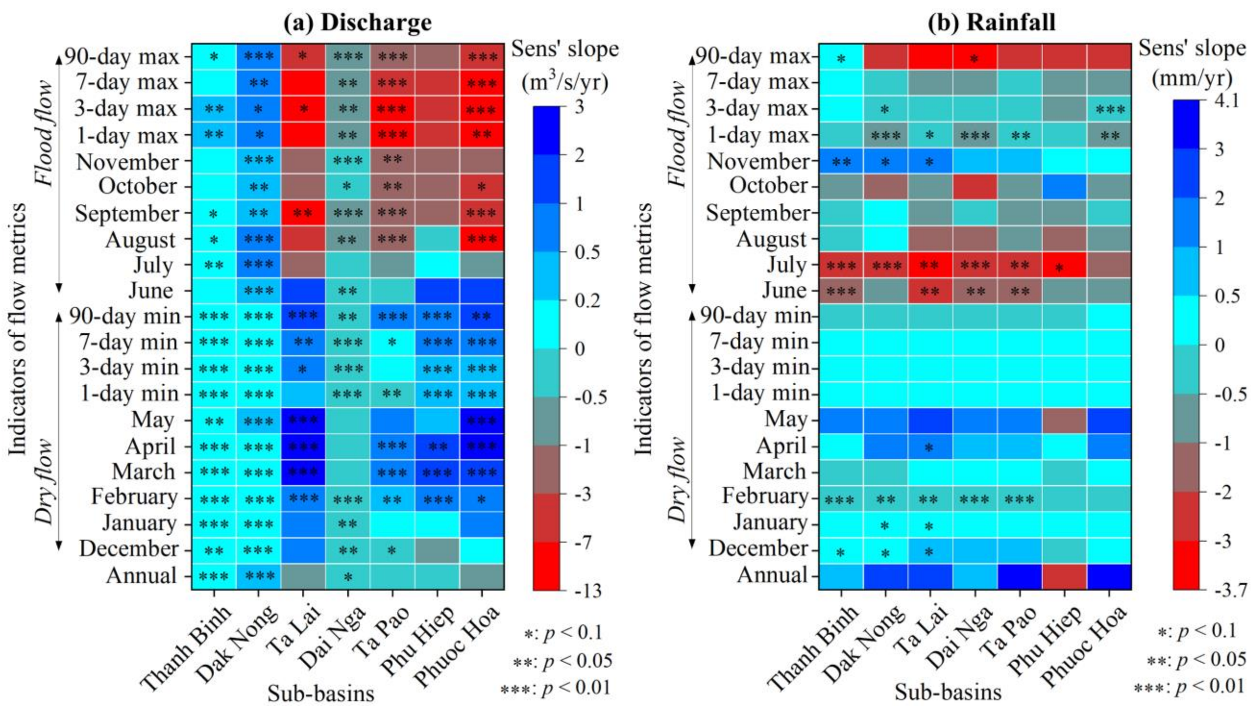

Fig. 3 Heatmap showing the Sen′s slope with three levels of significant p values in the annual, dry season, and flood season.

At Phuoc Hoa (in the midstream region) in the Be River, the discharge significantly increased in February–May and on the 1-day–90-day minima of the dry season (p = 0.0008–0.092), whereas it decreased in August–October and on the 1-day–90-day maxima during the flood season (p = 0.001–0.061). The change year was marked in 1994, with variations extending into 1995 and 1996. The most significant dry-season discharge increase was +2.50 m^3/s/yr in May (p = 0.002), whereas the greatest decrease in the flood-season discharge was −12.6 m^3/s/yr in the 3-day maximum (p = 0.007).

4.2 Spatiotemporal variations in rainfall

Rainfall variability showed no consistent trend across the seven studied subbasins (Fig. 3b). During the flood season, the rainfall significantly decreased in June and July ($p < 0.05$) in the Thanh Binh, Dak Nong, Ta Lai, Dai Nga, and Ta Pao subbasins, whereas it increased in November in the Thanh Binh (p = 0.032), Dak Nong (p = 0.055), and Ta Lai (p = 0.099) subbasins. The Phu Hiep subbasin exhibited no significant trend ($p > 0.1$) across all months except for a decrease of −3.7 mm/yr in July (p = 0.073). Similarly, no significant long-term trend ($p > 0.1$) was observed in the monthly or annual rainfall in the Phuoc Hoa subbasin.

In the dry season, the rainfall increased significantly in January in the Dak Nong (p =0.078) and Ta Lai (p =0.088) subbasins (Fig. 3b). Conversely, February showed significant decreases across several subbasins: Thanh Binh (–0.3 mm/yr, p = 0.005), Dak Nong (–0.2 mm/yr, p = 0.05), Ta Lai (–0.2 mm/yr, p = 0.025), Dai Nga (–0.2 mm/yr, p = 0.007), and Ta Pao (–0.2 mm/yr, p = 0.007). Notably, no discernible trends were identified in the dry season for the Phu Hiep and Phuoc Hoa subbasins, further illustrating the heterogeneous rainfall distribution within the study area.

4.3 Spatiotemporal variations in LULC

The forest areas in the seven studied subbasins decreased from 1990–2020 (except for the Phu Hiep subbasin) (Fig. S2). Significant declines were observed in the Dak Nong (–550 ha/yr, p =

2.22×10^{-8}), Ta Lai (–5,309 ha/yr, $p = 3.78\times10^{-6}$), and Dai Nga (–370 ha/yr, $p = 4.82\times10^{-6}$) subbasins. However, the forest area recovered in the Thanh Binh, Dak Nong, Ta Lai (in 2007), and Phuoc Hoa (in 1999) subbasins, but the ultimate long-term trend decreased (Fig. S2a–c, g). The lost forests were primarily converted to agricultural areas, built-up areas, and water bodies (Figs. S2, S3).

Additionally, the agricultural area significantly increased in the Dak Nong (+540 ha/yr, $p = 2.72\times10^{-8}$), Ta Lai (+5,114 ha/yr, $p = 7.22\times10^{-6}$), and Dai Nga (+362 ha/yr, $p = 6.65\times10^{-6}$) subbasins. Figure S3 indicates that most forest losses were converted into agricultural land, especially after 2015. The built-up area and water body significantly increased in all subbasins ($p < 0.001$), except for the water bodies in the Thanh Binh ($p = 0.02$) and Phu Hiep ($p > 0.1$) subbasins.

4.4 Contributions of controlling drivers to discharge alterations

The long-term annual discharge significantly changed at Thanh Binh ($p = 0.005$), Dak Nong ($p = 1.15\times10^{-6}$), and Dai Nga ($p = 0.061$); thus, the double mass curves were established for these three subbasins only. Figure S4 shows that human activities contributed most to annual discharge changes at Dak Nong and least at Thanh Binh from 1981–2021. Quantitatively, human activities increased the annual discharge by +6.2% at Thanh Binh and +22.3% at Dak Nong but reduced it by –14.2% at Dai Nga by 2021.

The results from the SWAT model were also consistent with the statistical estimates (Figs. 4, S5), showing that LULC changes increased the flow discharge by +1.1% at Thanh Binh and +2.2% at Dak Nong (LULC 2020 scenario) (Figs. 4a–b, S5a–b). Conversely, dams reduced the flow discharge by –5.9% at Dai Nga (with-dam scenario) (Figs. 4e, S5c). The period of significant change began in 2014 when a new reservoir, including diversion, began operating in the Dai Nga subbasin (Fig. 1a).

Human activities, including water transfer (Fig. 1a), have altered the flow discharge at downstream stations. Typically, at Ta Lai and Phuoc Hoa, dams sharply decreased the discharge by −11.8% and −8.9%, whereas the LULC change slightly increased it by +1.6% and +0.3%, respectively (Figs. 4c–d). On the other hand, dam development and LULC changes increased the discharge at Ta Pao and Phu Hiep on the La Nga River (Figs. 4f–g).

Figure 5 shows the contribution of human activities to the monthly discharge changes by 2021 in the seven subbasins, with a focus on months with significant trends. In the Dong Nai River, human activities increased both the flood and dry-season discharges at the two upstream stations: Thanh Binh (up to +25.2% in February) and Dak Nong (up to +50.9% in May) (Figs. 5a–b). In contrast, they reduced the flood-season discharge at Ta Lai (the downstream station) by −10.5% in September but increased the dry-season discharge by up to +34.3% in March (Fig. 5c). These changes are consistent with the results of the SWAT model (Figs. 4, S5).

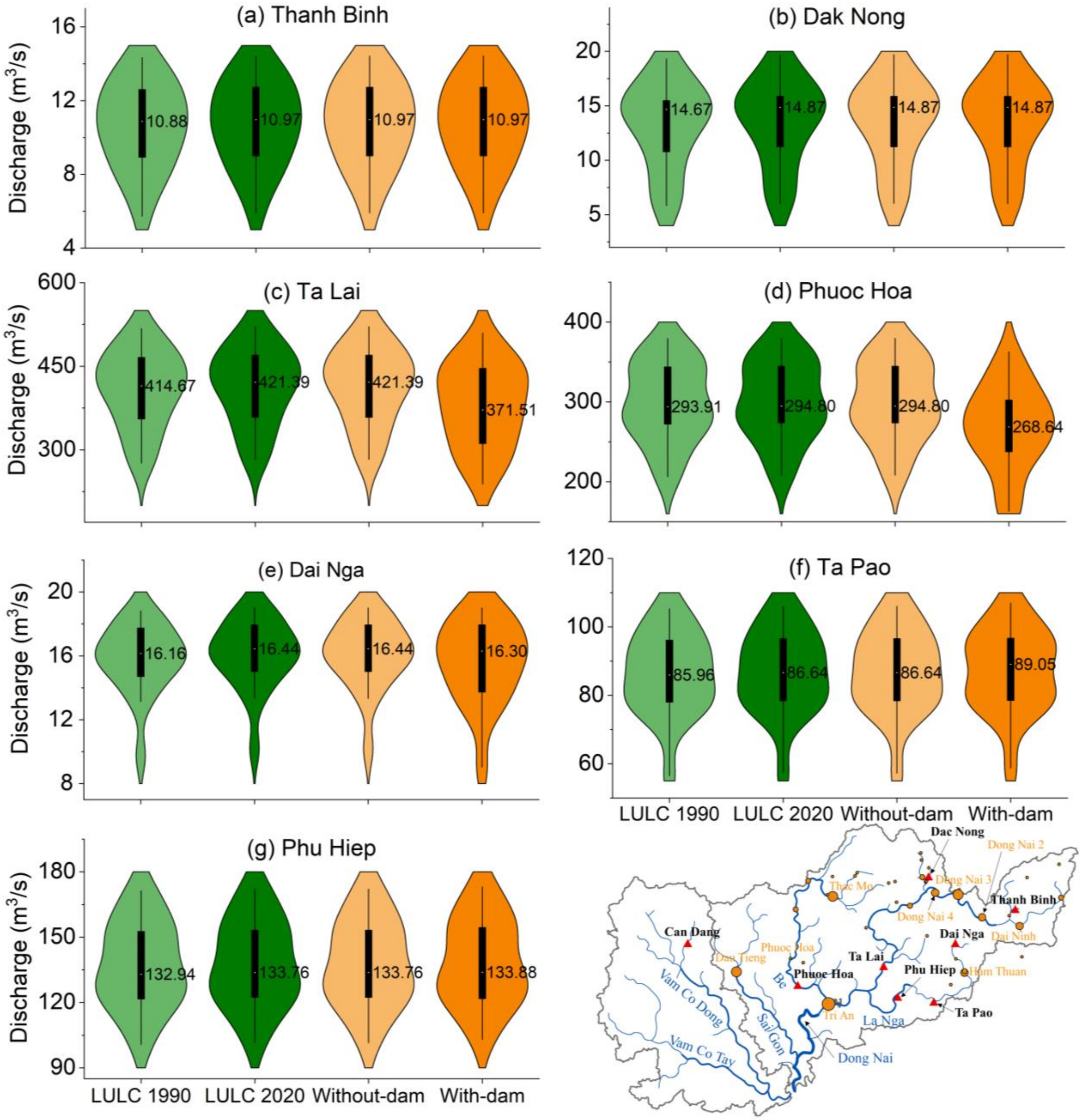

Fig. 4 Violin plot of the annual mean discharge at seven hydrological stations in four scenarios. Orange indicates the dam impact, and green presents the LULC change effect.

In the La Nga River, human activities reduced the monthly discharge in both the flood (up to −42.1% in November) and dry (up to −55.7% in January) seasons at Dai Nga (the upstream station) by 2021 (Fig. 5d). However, at Ta Pao and Phu Hiep (two downstream stations), human activities increased the dry-season discharge and reduced the flood-season discharge (Figs. 5e–f).

At Ta Pao, the dry-season discharge rose by up to +54.9% in March, whereas the flood-season discharge fell by –26.9% in November.

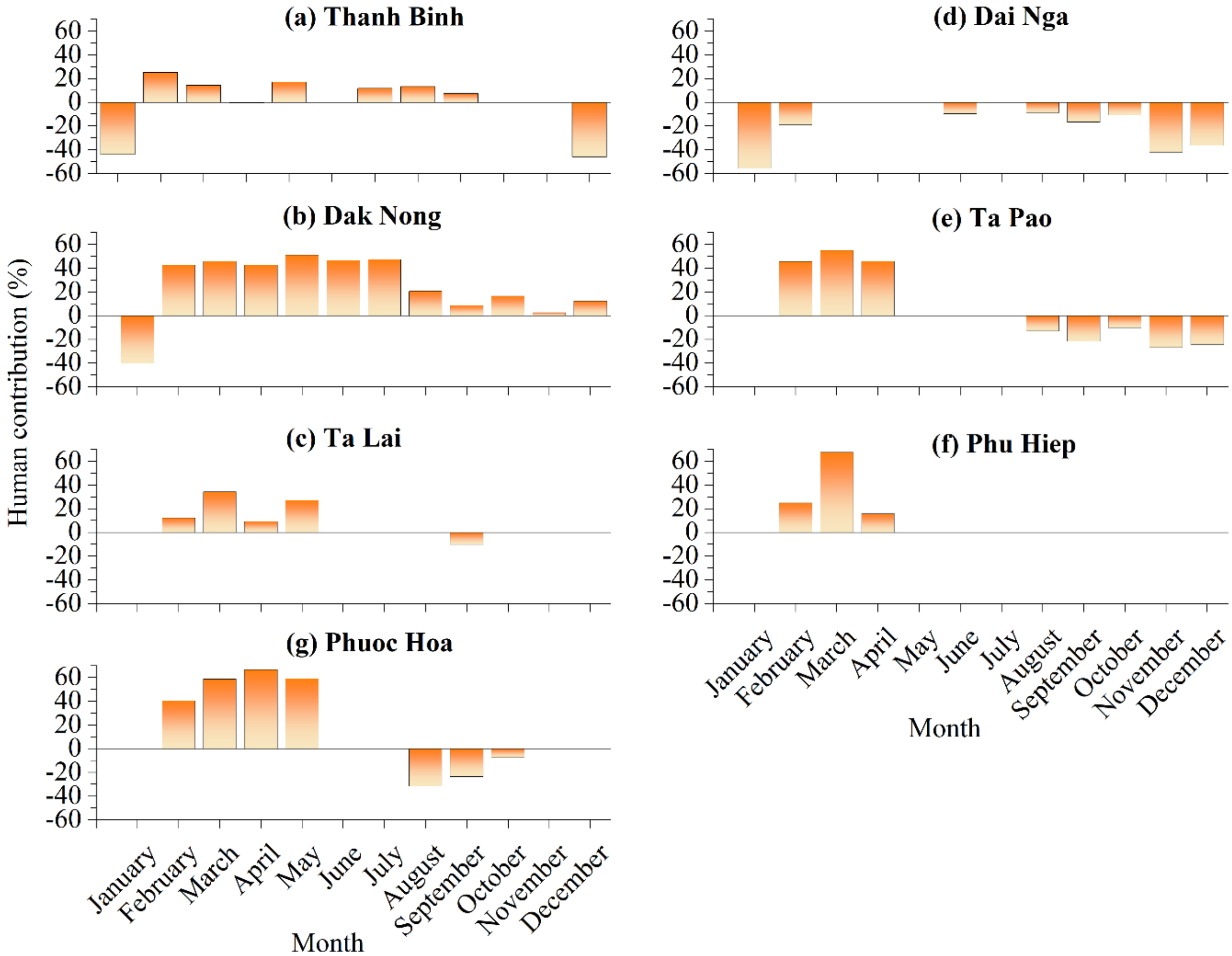

Fig. 5 Contribution of human activities to the monthly discharge changes in the seven subbasins by 2021. The quantification was performed for months with statistically significant trends.

At Phuoc Hoa in the Be River, human activities increased the dry-season discharge (from +40.4% to +66.5% in February–May) but reduced flood-season discharge (from –7.5% in October to –31.8% in August) by 2021 (Fig. 5g).

5 Discussion

5.1 Impacts of climate and human activities on discharge alterations

Generally, no consistent changes exist between the discharge and rainfall in the Thanh Binh, Dak Nong, and Ta Lai subbasins in the Dong Nai River (Fig. 3). This suggests that human activities, such as LULC changes and dam construction, are the primary drivers of flow alterations. Forest conversion to agricultural and built-up areas (Figs. S2, S3) contributed to the discharge increase at Thanh Binh and Dak Nong, where no major dams exist (Figs. 1a, 4a-b, S5a-b)). With continued deforestation for urbanization and population growth, coupled with extreme rainfall increases due to climate change (Anh et al. 2023), flooding in these subbasins is likely to worsen.

Discharge in both the dry and flood seasons at Dai Nga significantly decreased, mainly due to rainfall reductions (Fig. 3). Similar effects of climate change on flow alterations have been reported in the upper Yellow River (Cui et al. 2020) and the upper Yangtze River (Zhang et al. 2021). LULC change through deforestation, which typically increases discharge, was not a factor in these reductions, while the Dai Nga diversion reservoir (Figs. 1a, 4e, S5c) played a key role. Therefore, dry-season water availability in the Dai Nga subbasin will likely be adversely affected by climate change and human activities, increasing water pressure on local communities and authorities. This aligns with SWAT model projections by Nguyen et al. (2024).

Human activities are the primary drivers of the increased dry-season discharge and decreased flood-season discharge at Ta Lai (Dong Nai River), Ta Pao and Phu Hiep (La Nga River), and Phuoc Hoa (Be River), as the discharge and rainfall trends are inconsistent (Fig. 3). While forest conversion to agriculture and built-up areas may have contributed to the increased flood-season discharge, river damming was the dominant factor in discharge reductions at these stations (Figs.

4c-d, f-g). Similar human-driven flow alterations have also been widely reported in rivers worldwide, including the Mekong River (Binh et al. 2020), Vu Gia Thu Bon River (Nguyen et al. 2023), Rietspruit River (Banda et al. 2022), Yellow River (Gao et al. 2011), and the United States (Chalise et al. 2021).

We found that dams in the Dong Nai, Be, and La Nga Rivers, which tend to reduce flood-season discharge, may have dampened the impact of LULC change, which tends to increase the flood-season discharge. This is evident in the discharge discrepancies between upstream (e.g., Thanh Binh and Dak Nong) and downstream (e.g., Ta Lai) areas (Figs. 4, S5). The damping effects of dams may continue until 2100 (Nguyen et al. 2024). This finding agrees with that of Chalise et al. (2021), who reported that dams dampened climate-driven discharge changes in the United States. Additionally, the diversion functions of the Da Nhim and Dai Ninh reservoirs (Fig. 1a) likely had minimal effects on flow at Ta Lai in the Dong Nai River (Fig. 4c), whereas the Phuoc Hoa Reservoir may have contributed to flood reductions in the Be River (Fig. 4d).

5.2 Comparison with other river systems

We found that human activities are the main drivers of the statistically significant flow alterations in the SGDN Basin, except for the Dai Nga subbasin, where climate variability and the Dai Nga diversion reservoir may have controlled the flow. These findings align with those of global studies (Banda et al. 2022; Han et al. 2019). Banda et al. (2022) reported that urban settlements drove 75% of the increased streamflow in the Rietspruit subbasin. In the upper MRB, human activities accounted for 95% of the discharge changes from 2008–2014 (Han et al. 2019). Soil and water conservation measures contributed 86.03% of runoff reductions in the Liuhe River Basin, surpassing climate change effects (Li et al. 2024). Yang et al. (2018) estimated that human activities contributed 59.3–64.7% of the preflood magnitude and 30.4–45.9% of the postflood magnitude in the Sha River. Similarly, land use changes have reduced streamflow by 10–35% in the Piranga River Basin (Reis et al. 2024), and human contributions to flow alteration have been reported at 31% in the upper Yangtze River Basin (Zhang et al. 2021) and 17.8% in the Yellow River Basin (Gao et al. 2011).

5.3. Implications for river basin management

Flow alterations can have a significant impact on flood occurrence and severity, water availability, soil moisture, and groundwater recharge, exacerbating droughts. The cumulative effects of climate change and human activities on flow regimes are complex (Chalise et al. 2021; Yang et al. 2018). For example, while climate change is expected to increase floods in the MRB, river damming tends to reduce floodwater through reservoir trapping (Binh et al. 2020). These challenges require integrated and proactive water management strategies to ensure sustainable and effective resource use (Yang et al. 2018).

In Ho Chi Minh City (an important city downstream of the SGDN Basin), flooding is increasing due to rising rainfall, tides, and high discharge from the Sai Gon River (Camenen et al. 2021). We found that dams in the Dong Nai and La Nga Rivers may have had a positive function in controlling floods by trapping flood-season discharges. In addition, the Phuoc Hoa diversion reservoir (Fig. 1a) may partially increase floodwater in the Sai Gon River, contributing partially to the increased flooding in Ho Chi Minh City (Camenen et al. 2021). Drawing insights from the Tennessee Valley Authority in the United States, prioritizing flood control functions of dams and reservoirs is vital (Meo 1991), potentially saving billions of dollars in damage prevention (Miller et al. 1996).

5.4 Research limitations and recommendations

This research has several limitations that future studies should address. *First*, the limited number of monitoring stations restricts spatial representation. Therefore, we also employed the SWAT model to complement and support the historical data analysis; however, a denser monitoring network is recommended. *Second*, although overall hydrological changes were analyzed, specific aspects such as flooding, droughts, and irrigation require detailed investigations with potential solutions.

As climate change accelerates and extreme events become frequent (Tran and Lakshmi 2024), the effects of climate change on flow regimes may exceed dam capacity, exacerbating floods and droughts. Comprehensive studies and integrated water resource management, including watershed, reservoir, flood, drought, agricultural, and coastal management, are essential for sustainable development in the SGDN Basin.

Humans may overexploit water resources for irrigation because of urbanization and the booming population, exacerbating droughts and water stress and scarcity. Therefore, halting deforestation must be the government's top priority, supported by local communities, especially ethnic groups. Drought management should be incorporated with high priorities in reservoir regulations. As rising water demand may lead to conflicts among stakeholders (e.g., irrigation vs flood control), lessons from Brazilian river basins (Ioris, 2001) can guide sustainable management of the SGDN Basin.

6 Conclusions

Climate change and human activities are the primary drivers of river flow alterations globally, yet their contributions are less understood in smaller tropical rivers. This study examined the discharge alterations in the SGDN Basin, a tropical region in Vietnam. Some of the main findings are as follows.

1) Climate variability is the primary driver of natural flow, but human activities are essential contributors to statistically significant flow alterations.

2) In the Dong Nai River headwaters, discharges at Thanh Binh and Dak Nong increased due to LULC changes, whereas discharges at Dai Nga in the La Nga River decreased due to climate variability and the Dai Nga diversion reservoir. Downstream, discharges at Ta Lai (Dong Nai), Ta Pao, Phu Hiep (La Nga), and Phuoc Hoa (Be) decreased in the flood season and increased in the dry season, primarily due to human activities.

3) Dams and reservoirs in the SGDN Basin regulated discharge changes, with effects outweighing those of climate variability and LULC change. These changes may have dampened the effects of LULC changes on reducing flood discharge downstream. The Da Nhim and Dai Ninh Reservoirs had limited effects on flow alterations in the Dong Nai River, whereas the Phuoc Hoa Reservoir reduced flooding in the Be River but partially increased it in the Sai Gon River.

4) Human activities in the Dong Nai River contributed up to +50.9% (May at Dak Nong) of the discharge increase and up to −45.8% (December at Thanh Binh) of the decrease. In the La Nga River, human activities reduced both the flood- and dry-season discharges at Dai Nga, the upstream station (up to −55.7% in January), but increased the dry-season discharge (+54.9% in March) and reduced flood-season discharge (−26.9% in November) at Ta Pao (the downstream station). In the Sai Gon River (at Phuoc Hoa), human activities increased the dry-season discharge by up to +66.5% (April) and decreased the flood-season discharge by up to −31.8% (August).

Acknowledgments

We thank the Vietnam Meteorological and Hydrological Administration for sharing the hydrological data.

Author contributions

All the authors contributed to the study conceptualization and methodology. Funding acquisition and supervision were performed by D.V.B, S.A.K, and T.S. Data collection and material preparation were performed by D.V.B, M.H.L, V.N.D, T.V.N, and N.T.L. Software, data curation, and formal analysis were conducted by D.V.B, B.Q.N, T.T.H.N, X.H.L, L.A.T, V.N.D, N.T.L, M.H.L, and M.F.A. All the authors have read, reviewed, edited, and approved the final manuscript.

Funding

This paper was funded by Vietnamese-German University under grant number DTCS2022-002. Binh Quang Nguyen is supported by the JSPS Postdoctoral Fellowships Program (Fellowship ID: P24064). We acknowledge the collaborative research project (Grant number 2023IG-01) of the Disaster Prevention Research Institute of Kyoto University and the Asia-Pacific Network for Global Change Research (APN) under project reference number CRRP2023-04MY-Doan Van (Funder ID: https://doi.org/10.13039/100005536) for partially supporting the paper.

Data availability

The data will be made available upon request.

Declarations

Ethical approval: Not applicable.

Consent to participate: Not applicable.

Consent to publish: The authors agree to publish in the journal.

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

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