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Assessment of Dam Impacts on Flow and Sediment in the Sai Gon-Dong Nai River Basin, Vietnam

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Synopsis

This paper examined the impact of dams on the long-term flow regime and suspended sediment alterations in the Sai Gon-Dong Nai River Basin from the 1980s to 2021 using various statistical methods. The results show that dams in the Dong Nai and La Nga sub-basins are the main drivers of the flow alteration downstream, given that there is a discrepancy in the flow discharge variation between the upstream and downstream hydrological stations. In the Be sub-basin, the Phuoc Hoa diversion reservoir controlled the dry-season discharge reduction in the post-dam period (2011-2021), while climate variability drove the flood-season discharge decrease, exacerbated by the Thac Mo reservoir. We also found that deforestation in the Dong Nai River was the main driving force of the SSC increase at Ta Lai, while dams had insignificant effects. Differently, rainfall reduction and dams led to the SSC reduction in the La Nga River.

Keywords: Dam impact, flow regime alteration, sediment, climate change, Sai Gon-Dong Nai River Basin

1. Introduction

Sai Gon-Dong Nai (SGDN) River system (Fig. 1) is the backbone for the sustainable development of Ho Chi Minh, Binh Duong, and Dong Nai by supplying essential freshwater sources for approximately 20 million people. It discharges 32.5 billion m^3 of water to the East Vietnam Sea (Anh et al., 2022), ranked second to the Mekong River in South Vietnam.

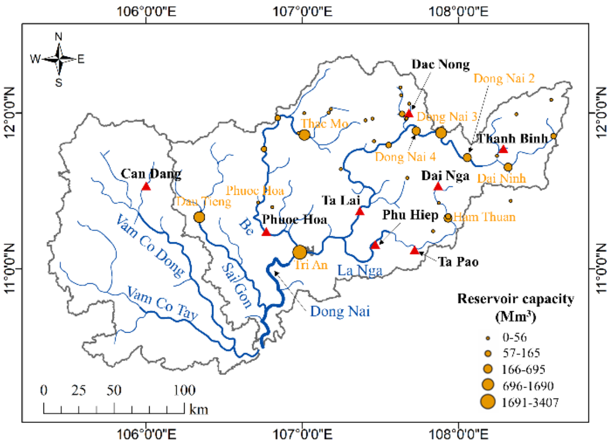

Fig. 1 The location map of the SGDN River Basin.

Flooding is an annual event in the SGDN River system. Flooding has caused enormous impacts and transport disruption in Ho Chi Minh City. Binh et al. (2019) assessed the impact of extreme rainfall and sea level rise on flood hazard maps in Ho Chi Minh City. They found that ENSO (El Niño Southern Oscillation) and PDO (Pacific Decadal Oscillation) affect the frequency and magnitude of the extreme rainfall, exacerbating flood risks in the region. Giang et al. (2022) examined long-term water level changes along the Dong Nai River, linked with urbanization, dyke, and dam construction. Water level changes in the downstream SGDN River under the effect of climate change and reduction in storage areas were examined by Luong and Bui (2019). Hung et al. (2019) assessed the impacts of climate and land-use changes on water balance alterations in the upper Dong Nai basin, whereas Truong et al. (2018) evaluated the effect of land use/land cover (LULC) changes on the flow regime alterations in the upper Dong Nai basin. The effects of LULC changes on streamflow and sediment load in the Be River basin were examined by Khoi et al. (2021).

Thirty-six large dams for irrigation, water supply, and hydropower have been built in the SGDN River basin with a total storage capacity of ~10.6 billion m^3), including several cascade dams, all of which occupy ~32.6% of the total water discharge of the river system. The operations of these dams sometimes do not guarantee flood control for large cities such as Ho Chi Minh and downstream environmental flow (i.e., necessary to control hydrological drought and salinity intrusion). A holistic understanding of the effects of dams on the hydrology and sediment in the SGDN River system is, therefore, of crucial importance for better water resource management and planning. Therefore, this study assesses long-term alterations of discharge and suspended sediment concentration (SSC) in the basin from which the driving factors are then discussed.

2. Study area

The SGDN River system comprises two main rivers, Dong Nai and Sai Gon, in which the Sai Gon River discharges into the Dong Nai River before emptying into the East Vietnam Sea. The SGDN is one of the largest river systems that originates and flows within the territory of Vietnam. Be and La Nga are the two largest tributaries of the SGDN basin, in which Tri An and Dau Tieng are the two greatest hydropower and irrigation dams, respectively. These two dams are important for flood control and environmental flow maintenance downstream.

There are two seasons; the dry season from January to June and the flood season from July to December. The peak discharge is normally in August-September. There are seven hydrological stations, namely Thanh Binh, Dak Nong, Ta Lai, Phuoc Hoa, Dai Nga, Ta Pao, and Phu Hiep, that monitor the daily discharge from the 1980s to 2021.

3. Materials and methods

Seven hydrological stations, namely Thanh Binh, Dak Nong, Ta Lai, Dai Nga, Ta Pao, Phu Hiep, and Phuoc Hoa, are monitoring daily discharge, four of which are monitoring daily suspended sediment concentration (i.e., Ta Pao, Phu Hiep, Ta Lai, and Phuoc Hoa) in the SGDN basin (Fig. 1). The daily discharge data are available from the 1980s to 2021, while the daily SSCs are collected from the 1990s to 2021. We collected daily rainfall from climate hazards group infrared precipitation with station data

(CHIRPS) version 20 from 1981 to 2021 (Funk et al., 2015). The CHIRPS data were validated using rain gauges distributed worldwide, and it is suitable for use in Vietnam (Le et al., 2020). The CHIRPS data has a spatial resolution of 5x5 km. We also collected the gridded annual LULC data with a spatial resolution of 250x250 m from 1990 to 2020 (Phan et al., 2021). LULC data were pixel-averaged for the seven sub-basins in a way similar to the CHIRPS rainfall. We re-grouped the original ten to four LULC classes, namely forest, agriculture, built-up area, and water.

The collected discharge and SSC data were undergone quality checks before applying statistical analysis. The gridded CHIRPS rainfall data were averaged for the seven sub-basins, which were delineated by using the SRTM (Shuttle Radar Topography Mission) DEM data in the ArcGIS environment (Fig. 2). The daily discharge, rainfall, and SSC data were aggregated into monthly and annual data for statistical analysis. The cleaned data were analyzed using the Mann-Kendall test to find the long-term trend (Kendall, 1938; Mann, 1945). The change year and rate of change (i.e., slope) were found using the Pettitt test (Pettitt, 1979) and Sens slope method (Sen, 1968), respectively. Discrepancies between the upstream and downstream stations reveal the effect of climate variability and anthropogenic activities such as river damming and land use land cover changes.

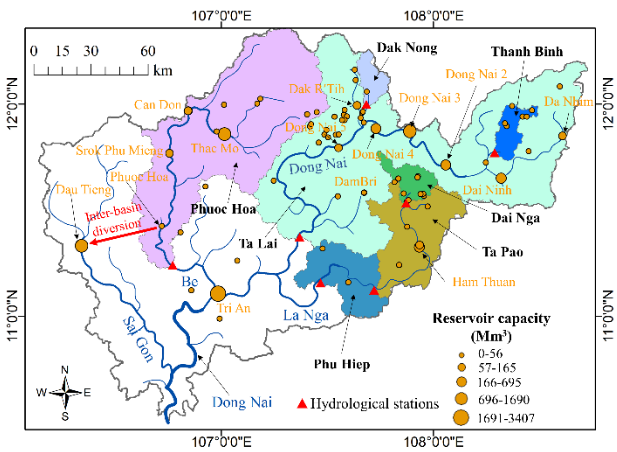

Fig. 2 Seven sub-basins and major dams in the SGDN Basin.

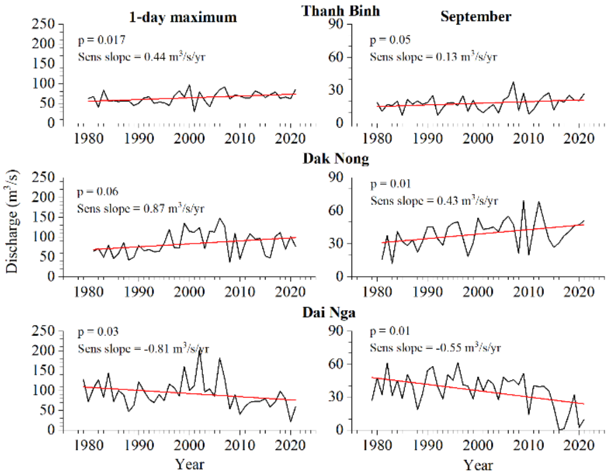

Fig. 3 1-day maximum and September mean discharges at three upstream sub-basins: Thanh Binh, Dak Nong, and Dai Nga hydrological stations.

4. Results and discussions

4.1 Alterations in the flood discharge in the upstream sub-basins

The flood-season discharge (including the monthly and extreme values) at Thanh Binh hydrological station has statistically increased (Fig. 3). The most increasing rate is in the 1-day maximum discharge with 0.44 m^3/s/year. However, the flood-season rainfall has remained mostly stable or has non-statistically changed (Fig. 4). On the other hand, LULC in the Thanh Binh sub-basin has changed from forest to agriculture and built-up area (Fig. 5). Notably, the built-up area has statistically increased by 38.1 ha/year from 1990 to 2020. These results imply that although rainfall primarily controls the streamflow, LULC changes have substantially driven the increasing trend in the streamflow at Thanh Binh over the period of 1990-2020. We further quantified the effect of rainfall and LULC changes on the annual discharge and found that annual rainfall contributes to 98% of the discharge, while the remaining 2% is driven by LULC changes. Notable, we did not have the monthly LULC data; if they were available, the contribution of LULC changes on the flood-season discharge at Thanh Binh would be higher.

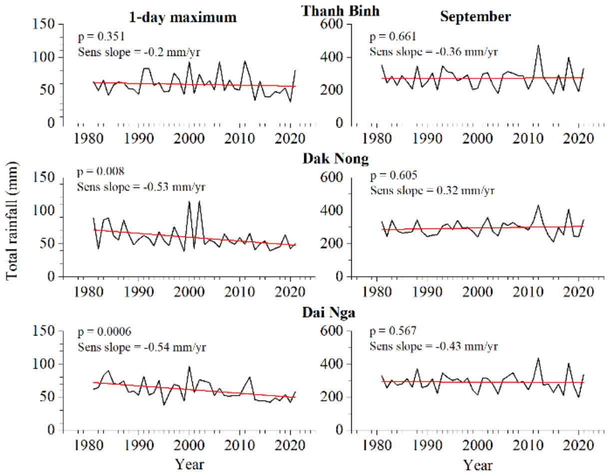

Fig. 4 Spatially-averaged 1-day maximum and September total rainfall in Thanh Binh, Dak Nong, and Dai Nga sub-basins.

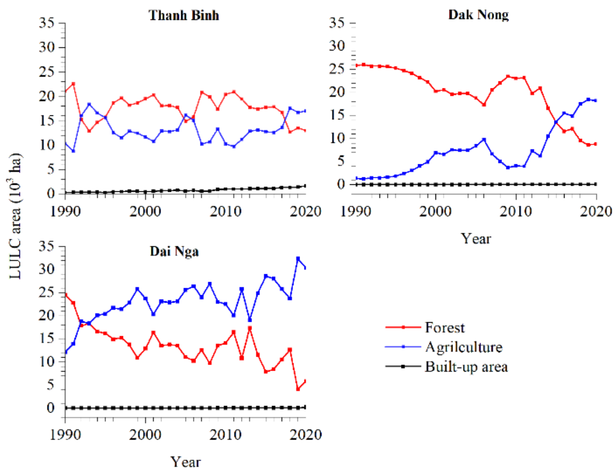

Fig. 5 Spatially total annual LULC areas in Thanh Binh, Dak Nong, and Dai Nga sub-basins.

The monthly and extreme flood discharges at Dak Nong have statistically increased from 1981 to 2-2021 with the most increase in the 1-day maximum discharge of 0.87 m^3/s/year (Fig. 3). August has the most statistically increasing rate by 0.64 m^3/s/year. Although not completely consistent, the increased discharge at Dak Nong is driven by the increases in the respective rainfall (Fig. 4). However, some months have decreased rainfall but the increased discharge. For instance, the total rainfall in July has statistically decreased ($p = 0.004$) by 2.87 mm/year, while the respective discharge has statistically increased ($p = 5.1\text{x}10^{-6}$) by 0.58 m^3/s/year. The inconsistency between the discharge and rainfall can be attributed to the influence of LULC change. In the Dak Nong sub-basin, LULC has statistically changed from forest to agriculture and built-up area (Fig. 5). We estimated that the forest area has reduced from 94% of the total area of the Dak Nong sub-basin in 1990 to only 32.4% in 2020, most of which was converted to agricultural land (from 5% in 1990 to 66.8% in 2020). Quantification of the drivers of mean annual discharge changes from 1990 to 2020 reveals that the mean contribution of rainfall is 96%, whereas the remaining 4% is due to LULC change.

Unlike Thanh Binh and Dak Nong, the monthly and extreme flood discharge at the Dai Nga hydrological station has statistically decreased (Fig. 3). The most significant reduction is in the 1-day maximum (0.81 m^3/s/year, $p = 0.03$), August (0.56 m^3/s/year, $p = 0.05$), and September (0.55 m^3/s/year, $p = 0.01$) discharges. Such reduction is consistent with decreases in the respective total monthly and extreme rainfall (Fig. 4). Rainfall reduction in the 1-day maximum ($p = 0.0006$) and July ($p = 0.002$) was statistically significant. LULC in the Dai Nga sub-basin has changed from forest to agriculture and built-up areas (Fig. 5), which should cause an increase in the water yield in the basin, leading to an increase in the discharge. However, such changes in the LULC could not make a corresponding increase in the discharge. It is therefore concluded that long-term decreases in flood-season discharges in the Dai Nga sub-basin are mainly driven by decreases in the respective rainfall, whereas LULC change buffers the discharge alterations. Annual rainfall in the sub-basin explains an average of 96% of the annual discharge generation at the Dai Nga hydrological station.

4.2. Discrepancy in the discharge alteration between upstream and downstream showing dam impact in the Dong Nai River

In the upstream of the Dong Nai River, the discharge at Dac Nong and Thanh Binh (Fig. 1) increased in both flood and dry months from 1981 to 2021 (Fig. 6). The increases in the monthly discharge at these two stations are all statistically significant at 5% significance level, except for June, October, and November at Thanh Binh. For instance, the discharge in February at Dac Nong and Thanh Binh increased by 0.09 $m^3/s/yr$ ($p < 0.001$) and 0.03 $m^3/s/yr$ ($p = 0.01$), respectively. The respective values in September are 0.43 $m^3/s/yr$ ($p < 0.05$) and 0.13 $m^3/s/yr$ ($p = 0.05$). The increases in the discharge at these two stations are driven by natural phenomena, i.e., increases in rainfall (Fig. 7).

However, the flood discharge at Ta Lai (downstream station) has decreased, while the dry discharge has increased from 1987 to 2021 (Fig. 6). In September, for instance, the discharge statistically decreased by 8.97 $m^3/s/yr$ ($p < 0.05$). The discrepancy between the upstream and downstream stations shows that the cascade dams in the Dong Nai River (e.g., Dong Nai 2, 3, and 4 dams) have strongly regulated the natural flow in the upper Dong Nai basin.

4.3. Discrepancy in the discharge alteration between upstream and downstream showing dam impact in the La Nga River

In the upstream of the La Nga River, the discharge at the Dai Nga hydrological station (Fig. 1) decreased in both flood and dry seasons from 1979 to 2021 (Fig. 8). Most of the monthly discharge decreases were statistically significant at 5% significance level, except for March-May and July. Such discharge decreases were consistent with the rainfall reduction at the Dai Nga station from 1981 to 2021 (Fig. 9). However, at the downstream stations at Ta Pao and Phu Hiep (Fig. 1), the discharge increased in the dry season and decreased in the flood season (Fig. 8), whereas the respective monthly rainfall data were mostly unchanged at these two stations. Such upstream-downstream discrepancy shows dam impact (e.g., by the Ham Thuan dam) on the flow discharge in the La Nga River.

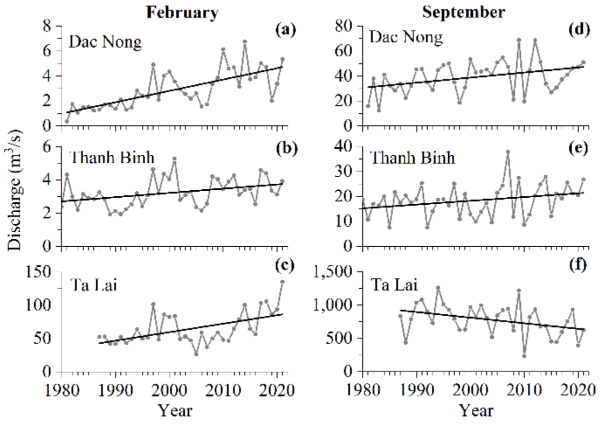

Fig. 6 Long-term trends in the discharge at Dac Nong, Thanh Binh (upstream), and Ta Lai (downstream) in February and September along the Dong Nai River.

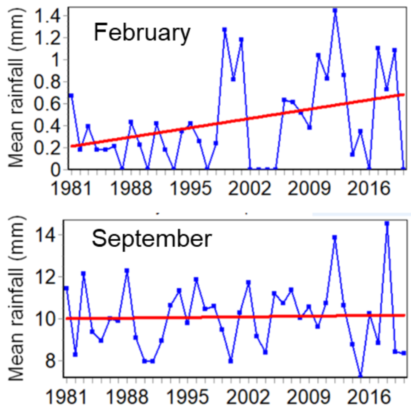

Fig. 7 Increasing trends in the rainfall in February and September at Dak Nong station.

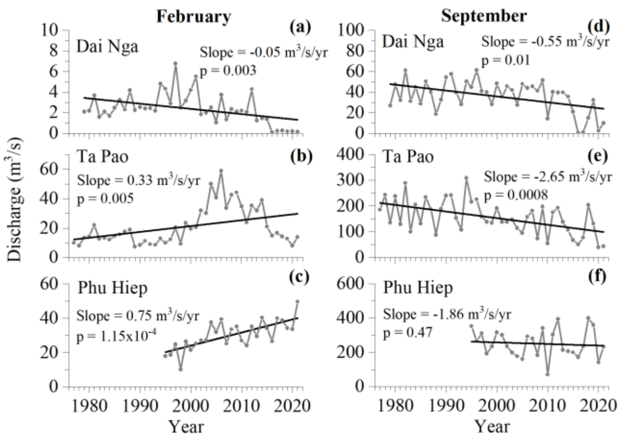

Fig. 8 Discrepancy in the discharges in both flood and dry seasons between the upstream (at Dai Nga) and downstream (at Ta Pao and Phu Hiep) stations along the La Nga River.

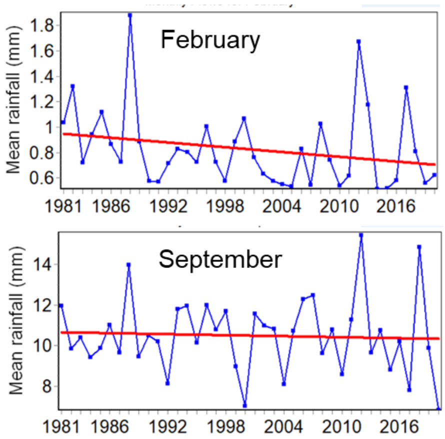

Fig. 9 Decreasing trends in the rainfall in February and September at Dai Nga station.

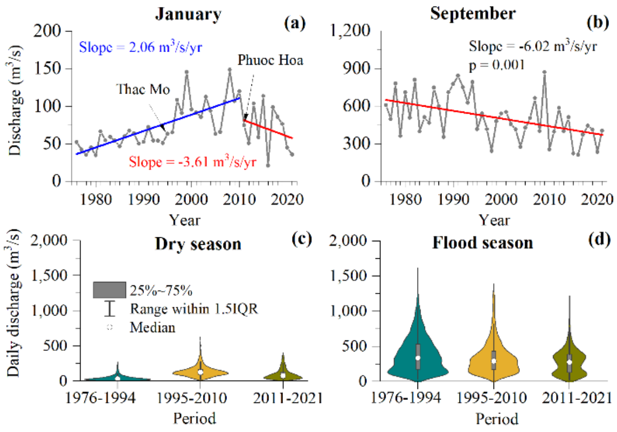

Fig. 10 Flow alterations in the dry season (a and c) and flood season (b and d) at the Phuoc Hoa station.

4.4. Dam impact on the discharge alteration in the Be River

There is only one hydrological station monitoring the discharge in the Be River, namely Phuoc Hoa (Fig. 1). Fig. 10 shows that the dry-season discharge increased from 1976 to 2010 and decreased from 2011 to 2021. The change year of the trends was consistent with the completion of the Phuoc Hoa reservoir (Fig. 10a). To clarify, we divided the time series into three periods according to the completion year of the Thac Mo (in 1995) and Phuoc Hoa (in 2011). It was found that the dry-season discharge at the Phuoc Hoa station increased in the 1995-2010 period and decreased in the 2011-2021 period, compared with the pre-dam period (1976-1994) (Fig. 10c). On the other hand, the dry-season rainfall at the Phuoc Long meteorological station (Fig. 1) had an increasing trend (Fig. 11a), which was inconsistent with the trend of the dry-season discharge. Therefore, it is concluded that the Phuoc Hoa diversion reservoir is the main driver of the dry-season discharge alterations downstream of the Be River.

In the flood season, the discharge decreased at the Phuoc Hoa hydrological station (Fig. 10b and d), which is consistent with the decreasing trend in the rainfall at the Phuoc Long meteorological station (Fig. 11b). Therefore, it is concluded that climate variability controls the flood-season discharge alteration in the Be River. Moreover, the reduction in the flood-season discharge is further exacerbated by the Thac Mo hydropower and Phuoc Hoa diversion reservoirs.

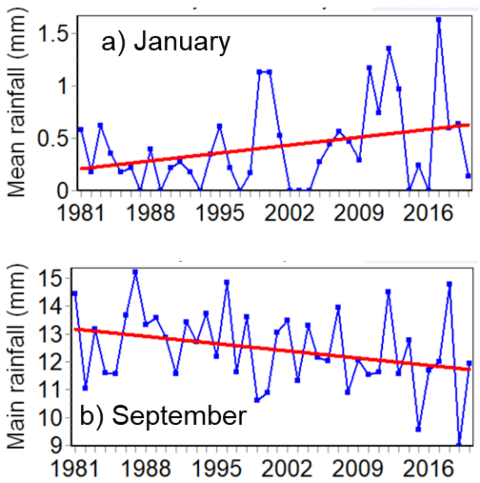

Fig. 11 Trends of the rainfall in the dry season (a) and flood season (b) at the Phuoc Long meteorological station.

4.5. Changes in the sediment in the SGDN Basin

In the Dong Nai River, the SSC at Ta Lai has increased in all months (some months in both flood and dry seasons are statistically significant) from 1999 to 2021, except for a decreasing trend in July (Fig. 12). In February, the SSC at Ta Lai statistically increased by 1.05 g/m^3/yr ($p < 0.05$). It indicates that the sub-basin between Thanh Binh-Dac Nong and Ta Lai contributes a significant amount of sediment, mainly from deforestation causing more sediment erosion (Fig. 5). Although there is a cascade of dams in the Dong Nai River (Fig. 1), these dams are not the main driver of the SSC increase at Ta Lai because these dams are mainly run-of-the-river, which have small sediment trapping capacity.

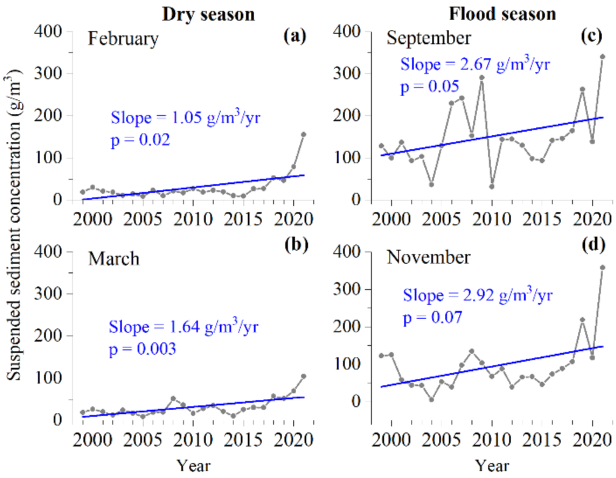

Fig. 12 Increases in the SSC at Ta Lai in the Dong Nai River due to deforestation.

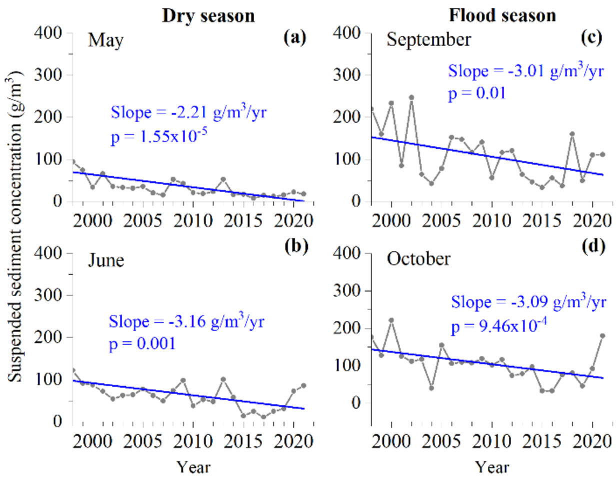

Fig. 13 Decreases in the SSC at Ta Pao in the La Nga River due to climate and dams.

In the La Nga River, the SSC at Ta Pao decreased (statistically significant in the flood months) during 1996-2021 (Fig. 13), which is consistent with the decreasing trend in the long-term (1979-2021) discharge at Dai Nga (Fig. 8). In September, the SSC at Ta Pao decreased by 3.01 g/m^3/yr ($p < 0.05$). Such SSC decrease is mainly because of a reduction in the rainfall in the sub-basin, while the Ham Thuan reservoir (Fig. 1) may contribute partially to the reduction.

5. Conclusion

In the upper Dong Nai basin at Dak Nong and Thanh Binh, the flood and dry discharge have increased due to rainfall increase. However, the flood discharges downstream at Ta Lai have decreased, caused mainly by cascade dams. In the La Nga sub-basin, the discharge decreased in both flood and dry seasons in the upstream station at Dai Nga but increased in the dry season and decreased in the flood season in the downstream stations at Ta Pao and Phu Hiep, showing the impacts of dams. In the Be River, the Phuoc Hoa diversion reservoir is the main driver of the dry-season discharge reduction in 2011-2021, while climate variability controls the flood-season discharge decrease, exacerbated by the Thac Mo reservoir.

The SSC has increased at Ta Lai and decreased at Ta Pao hydrological stations. We found that deforestation in the Dong Nai River controls the SSC increase at Ta Lai, while dams have a negligible effect. On the other hand, rainfall reduction and dams are the two main factors of the SSC decrease in the La Nga River.

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