Nutrient budgets in the Saigon-Dongnai River basin: Past to future inputs from the developing Ho Chi Minh megacity (Vietnam)

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Abstract

Ho Chi Minh City (HCMC, Vietnam) is one of the fastest growing megacities in the world. In this paper, we attempt to analyse the dynamics of nutrients, suspended sediments, and water discharges in its aquatic systems today and in the future. The work is based on nine sampling sites along the Saigon River and one on the Dongnai River to identify the reference water status upstream from the urban area and the increase in fluxes that occur within the city and its surroundings. For the first time, the calculated fluxes allow drawing up sediment and nutrient budgets at the basin scale and the quantification of total nutrient loading to the estuarine and coastal zones (2012–2016 period). Based on both national Vietnamese and supplementary monitoring programs, we estimated the water, total suspended sediment, and nutrients (Total N, Total P, and dissolved silica: DSi) fluxes at 137 m^3 $year^{-1}$, 3,292 × 10^3 tonSS $year^{-1}$, 5,323 tonN $year^{-1}$, 450 tonP $year^{-1}$, and 2,734 tonSi $year^{-1}$ for the Saigon River and 1,693 m^3 $year^{-1}$, 1,175 × 10^3 tonSS $year^{-1}$, 31,030 tonN $year^{-1}$, 1,653 tonP $year^{-1}$, and 31,138 tonSi $year^{-1}$ for the Dongnai River, respectively. Nutrient fluxes provide an indicator of coastal eutrophication potential (indicator of coastal eutrophication potential), using nutrient stoichiometry ratios. Despite an excess of nitrogen and phosphorus over silica, estuarine waters downstream of the megacity are not heavily impacted by HCMC. Finally, we analysed scenarios of future trends (2025–2050) for the nutrient inputs on the basis of expected population growth in HCMC and improvement of wastewater treatment capacity. We observed that without the construction of a large number of additional wastewater treatment plants, the eutrophication problem is likely to worsen. The results are discussed in the context of the wastewater management policy.

KEYWORDS
budgets, nutrients, past and future scenarios, sediment, wastewater management

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1 | INTRODUCTION

In the 21st century, the impact of human activities on ecosystems has become a major concern. The application of fertilizers in agriculture and the discharge of untreated domestic and industrial wastewaters into aquatic systems is increasing significantly (Seitzinger et al., 2010; Turner, Rabalais, Justic, & Dortch, 2003). As a direct consequence, human activities have deeply changed the cycle of nitrogen (N) and phosphorus (P) at the global scale (Meybeck, 1982; Seitzinger et al., 2010; Seitzinger, Harrison, Dumont, Beusen, & Bouwman, 2005; Van Drecht, Bouwman, Knoop, Beusen, & Meinardi, 2003), as well as at the regional scale, with alarming consequences in various large rivers such as the Yangtze River (Liu et al., 2016), the Mississippi River (Turner & Rabalais, 1994), the Mekong River (Li & Bush, 2015), and numerous European rivers (Ludwig, Bouwman, Dumont, & Lespinas, 2010; Ludwig, Dumont, Meybeck, & Heussner, 2009).

An excess of nutrients leads to serious impacts on aquatic ecosystems, including eutrophication with hypoxia and fish mortality (Conley et al., 2009; Smith, 1998). Algal blooms can also cause water quality problems such as unpleasant odors and an increase in pH and dissolved organic carbon (Carpenter et al., 1998; Shen et al., 2003; Smith, 1998). In addition, some algal species such as Cyanobacteria can release harmful toxins that may affect livestock and human health (Duong, Le, et al., 2010; Duong, Vu, et al., 2010; Duong et al., 2013).

Numerous studies have reported that the main cause of eutrophication in aquatic systems is due to the increase of nutrient concentrations in both dissolved and particulate forms as well as the changes in the nutrient stoichiometry, that is, their molar ratios (Conley et al., 2009; Langenberg, Nyamushahu, Roijackers, & Koelmans, 2003; Smith, 1998; Turner et al., 2003; Winter et al., 2002). Examining the concentrations, forms, and ratios simultaneously is now recognized as a useful tool to predict the community component of undesirable algae production, both globally and regionally (Turner et al., 1998, 2003).

According to this view, an indicator of coastal eutrophication potential (ICEP) was proposed by Billen and Garnier (2007). This indicator is based on a riverine N, P, and Si inputs and can be used to determine the possible production of non-siliceous algae. Although the N:P ratio is used to identify the limiting factor, the ICEP gives information on N or P excess in regard to Si in terms of diatom growth (Conley, Kilham, & Theriot, 1989; Redfield, Ketchum, & Richards, 1963).

Vietnam, like many developing countries in the Southeast Asia, is experiencing rapid economic and demographic development, especially in urban areas, leading to water quality degradation. The nutrient sources and pathways are numerous and difficult to determine when attempting to establish global budgets. Several studies in Vietnam have examined nutrient budgets in reservoir catchments (Le et al., 2014) or large catchments and deltas such as the Red River basin (Le et al., 2005; Luu et al., 2012). However, to date, nutrient budgets including emissions in urban areas are often incomplete and therefore do not satisfy recommendation for nutrients management. The main objective of this study was to collect data from a wide variety of information sources (official statistical data, field data from a national monitoring program, complementary field data from our research group, and statistical questionnaires) in order to draw the most complete nutrient budgets possible in a densely populated urban area (including domestic and industrial treated and untreated wastewaters, atmospheric deposition, and river fluxes). To meet this objective, we focus on the Ho Chi Minh City (HCMC) in the South of Vietnam.

HCMC is the largest city in Vietnam and one of the most dynamic in the world (World Economic Forum News, January 2017). Because of urban sprawl and the lack of wastewaters treatments, the quality of the water is deteriorating, which endangers the resource as well as the human activities that depend on it (Babut et al., 2019; Nguyen et al., 2019; Nguyen, Le, Bui, Phan, & Visvanathan, 2011; Strady et al., 2017).

To better understand the current nutrient inputs and their impacts on aquatic systems, we used a database provided by the Center of Environment Monitoring (CEM) of the Department of Natural Resources and Environment (DONRE) and compared it with data collected by our group from July 2015 to December 2017. In this paper, we attempt to (a) establish the annual budget of water, total suspended sediments (TSSs) and nutrients in the river system; (b) characterize the contribution of local sources (domestic discharge, industries, and atmospheric deposition) and upstream sources to the overall nutrient budget; (c) assess possible shift of nutrient stoichiometric ratios to the downstream zone; and finally (d) explore the development of the region in 2025 and 2050 for realistic population growth and urban policy scenarios, with the establishment of new wastewater treatment plants (WWTPs).

2 | MATERIAL AND METHODS

2.1 | Description of the Saigon-Dongnai River basin

The Saigon–Dongnai River basin is located in Southeast Asia, covering an area of 31,216 km^2 (Figure 1b). The Dongnai River (basin area of 26,449 km^2) takes its source from Central Vietnam, more specifically the Southwest Plateau, and flows southward through the Tri An reservoir (Figure 1c). This reservoir was built in 1986 for hydroelectric production and water supply for domestic, industrial, and agricultural uses in the downstream provinces (an area of 323 km^2, 2,700 million m^3; Dao, Nimptsch, & Wiegand, 2016). In this basin, the Saigon River (basin area of 4,717 km^2) originates from Phum Daung in Southeastern Cambodia and flows through to the Dau Tieng Reservoir (120–270 km^2; 470–1,680 million m^3). Land use in the Saigon River basin is dominated by agricultural activities in the north (paddy rice and rubber tree farms), urban settlements in the centre of HCMC and Can Gio Mangrove forest to the south (data from Ho Chi Minh City Statistical Yearbook, 2016). The river crosses HCMC and connects with urban canals. It then confluences with the Dongnai River to form the Nha Be River, and then, it separates into two

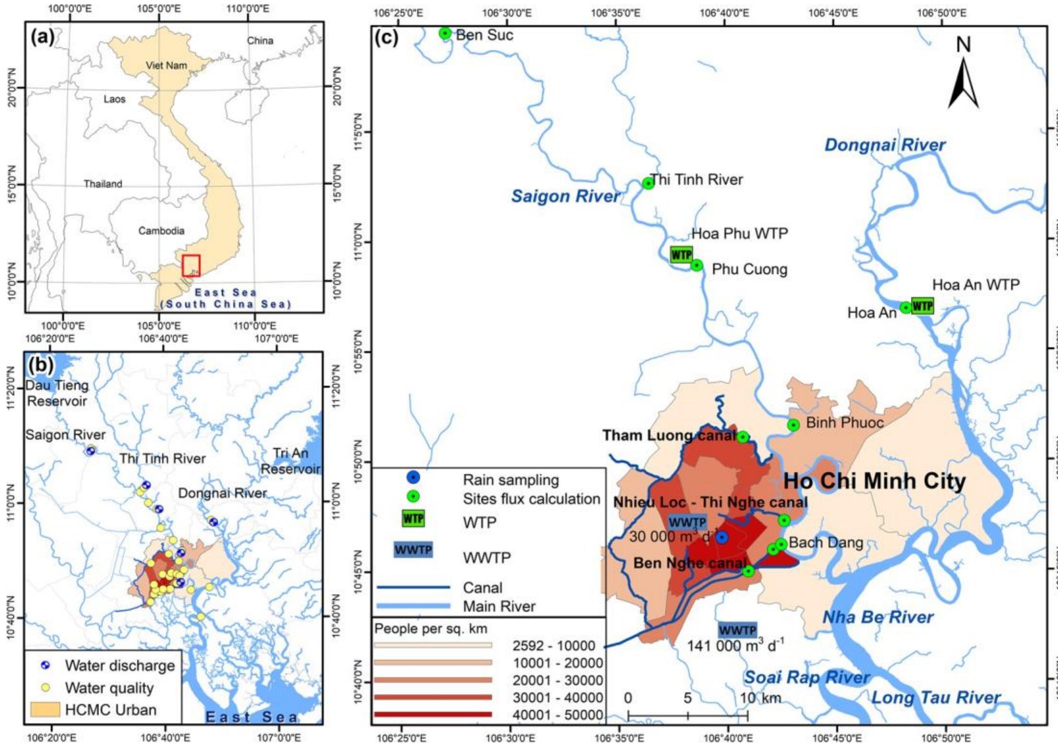

FIGURE 1 (a) Location of the Saigon–Dongnai River basin, (b) regional map of the Sai Saigon–Dongnai River basin and sampling sites, and (c) population distribution in Ho Chi Minh City and location of the sampling sites. Abbreviation: WWTP, wastewater treatment plant

branches (Soai Rap River and Long Tau River) that pass through the Can Gio Mangrove and reach the South China Sea, 20 km north of the Mekong Delta (Figure 1b). Regulation of Dau Tieng reservoir's water discharges aims at preventing the intrusion of saline water into the Saigon Water Supply Company's Hoa Phu Raw Pumping Station (or Hoa Phu Water Intake) and mitigating surface flood risks (Figure 1c). The Saigon River is highly influenced by coastal waters, in response to the tidal forcing that leads to the asymmetric flow current inversion twice a day. The basin is subjected to two distinct seasons: The rainy season usually begins in May and ends in November, whereas the dry season usually lasts from December to April.

Land use is very diverse from the north to the south of HCMC: Agricultural activities in the northwest and east (e.g., paddy rice and vegetables) and industrial parks dominate in the north, whereas the heart, the east, and the south of the inner city are dominated by urban settlement. The Can Gio Mangrove forest, which is located southeast of the city centre, has been recognized as a biosphere reserve by the United Nations Educational, Scientific and Cultural Organization.

The population in HCMC was 8.4 million inhabitants in 2016, making it the most densely populated city in Vietnam (Ho Chi Minh City Statistical Yearbook, 2016). The population density varied from 2,000 inhabitants per square kilometre in rural districts up to 50,000 inhabitants per square kilometre in urban districts (Figure 1). In recent years, less than 10% of domestic wastewater was collected and treated before release to urban canals and rivers (Nguyen et al., 2019).

2.2 | Database from the Vietnamese water monitoring survey

The Vietnamese monitoring program carries out monthly water discharge and bimonthly water quality parameter measurements at all locations within the Saigon–Dongnai River basin and urban canal network (Figure 1c). Since 2005, the CEM has been in charge of the bimonthly monitoring of the water quality at 26 sites in the Saigon and Dongnai Rivers and 16 sites in urban canals. Figure 1b,c presents the selection of sites used for this study. The CEM is also in charge of measuring the monthly river discharges at 15 sites along the Saigon and the Dongnai Rivers. Because of the asymmetric semidiurnal tides, the estimation of the residual river discharges requires hourly measurement of discharge over a minimum period of 24 hr (two tidal cycles). The mean water discharge is then deduced from the integrative flux between the tide inflow and outflow (Nguyen et al., 2019). The residual discharge corresponds to the net positive flow of the river from land to sea. Even with the low frequency measurement of the discharge (i.e., once per month), the hydrological seasonality is clearly observed (Nguyen et al., 2019). For water quality analysis, surface (20–30 cm deep) riverine and urban canal waters were collected manually during low and high tides, 4 m from the riverbank, and were filtered on preweighted filters. Temperature, pH, DO, TSS, salinity, turbidity, ammonium (NH_4^+), and phosphates (PO_4^{3-}) were measured according to the Vietnamese water quality standard (QCVN08, 2015). From this database, (a) 10 sites were selected along the Saigon River, the Thi Tinh River (a confluent), and the Dongnai River and six sites in urban canals and (b) the 2012–2016 period was selected based on the availability and reliability of data, thus providing a complete and suitable set comprising water discharge, TSS, NH_4^+, and PO_4^{3-}.

2.3 | Supplementary monitoring program

To determine the N, P, and Si fluxes, a bimonthly monitoring program was carrying out in 2015–2017 at four sampling sites along the Saigon and Dongnai Rivers to analyse additional parameters: Total N, nitrate (NO_3^-), Total P, and dissolved silica (DSi). As fully described in Nguyen et al. (2019), surface water was sampled with a Niskin bottle in the middle of the river, either from a bridge or a boat and stored in a cooler at 4°C before it was analysed in the laboratory. Surface water samples were considered integrative of the whole vertical section, as previously observed by Nguyen et al. (2019).

All samples were filtered through Whatman GF/F filters (porosity 0.7 μm) to analyse dissolved nutrients. Dissolved nutrients were analysed using standard colorimetric methods (American Public Health Association: APHA, 1995). NO_3^- and DSi were analysed using the cadmium reduction method and the silicomolybdate method, respectively. Unfiltered waters were used to measure Total N and Total P using the persulfate digestion process and the standard colorimetric method (APHA, 1995). Reproducibility for replicate measurements was better than 5% for all total and dissolved nutrients.

2.4 | Suspended sediment and global nutrient budget calculation

TSS and nutrient budgets included nutrient export by rivers and tributaries, industrial inputs, domestic inputs, and atmospheric depositions. We calculated fluxes of TSS, Total N, dissolved inorganic nitrogen (DIN including NO_3^- and NH_4^+), Total P, dissolved inorganic phosphorus (DIP, i.e., PO_4^{3-}) and dissolved silica (DSi).

2.4.1 | Nutrient export by rivers

We used nutrient and discharge data provided by CEM. We chose six monitoring sites (see Figure 1), four of which (Ben Suc, Phu Cuong, Binh Phuoc, and Phu An) are on the main course of the Saigon River. One sampling site (Hoa An) is used as the reference for Dongnai River inputs and the sixth site (Thi Tinh) is used as an indicator of input from river tributaries with agricultural and industrial activities. We built a dataset of mean discharge, TSS, and nutrient concentrations to calculate fluxes (Table A1). Due to missing data, we considered the mean concentrations from our supplementary monitoring in 2015–2017 to calculate the net flux and specific flux for 2012–2014. Based on the method proposed by Walling and Webb (1985), we calculated the net fluxes and specific fluxes as follows:

$$Flux_{annual} = \sum_{i=1}^{n} Flux_{monthly}, \text{with} Flux_{monthly} = \frac{C_{monthly} \times Q_{monthly} \times a \times 24 \times 3{,}600}{10^6}, \quad (1)$$

$$Flux_{spec} = \frac{Flux_{monthly}}{A},$$

where

- $Flux_{annual}$ is the annual flux of TSS, Total N, NO_3^-, NH_4^+, Total P, PO_4^{3-}, and DSi (ton year^{-1});
- $Flux_{monthly}$ is the monthly flux of TSS, Total N, NO_3^-, NH_4^+, Total P, PO_4^{3-}, and DSi (ton month^{-1});
- $C_{monthly}$ is the mean monthly concentrations (mg L^{-1});
- $Q_{monthly}$ is the mean monthly discharge for the period recorded (m^3 s^{-1});
- a is the number of day per month (a = 28–31), and n is the number of months (n = 12);
- $Flux_{spec}$ is the specific flux of TSS, Total N, NO_3^-, NH_4^+, Total P, PO_4^{3-}, and DSi (ton km^{-2} month^{-1});
- A is the surface area of the river basin (4,717 km^2 for the Saigon River and 26,449 km^2 for the Dongnai River).

2.4.2 | Domestic inputs

To estimate urban inputs, we assumed that untreated and treated domestic wastewaters from household and WWTPs were two main sources of TSS and nutrients. In HCMC, until recent years (before 2018), only 10% of the population had a direct connection to WWTPs, whereas 92% of the population released untreated wastewaters directly to urban canals through the sewer network (Marcotullio, 2007; Nguyen et al., 2019).

Gross nutrient inputs from urban areas

To account for Total N and Total P fluxes from untreated urban wastewater, we assumed that the per capita human N emission ranged from 10 to 12 gN capita^{-1} day^{-1} and from 0.8 to 4.0 gP capita^{-1} day^{-1} for P emissions (Triet, Hung, & Dan, 2008). We considered the mean values for further calculation (i.e., 11 gN capita^{-1} day^{-1} and 2.4 gP capita^{-1} day^{-1}). These values are in good agreement with the values proposed by Sung (1995) for Vietnamese (10.08 gN capita^{-1} day^{-1} for N and 1.7 gP capita^{-1} day^{-1} for P) and Meybeck, Chapman, and Helmer (1989) at a global scale (9.04 gN capita^{-1} day^{-1} for N and 1.1 gP capita^{-1} day^{-1} for P). The per capita values in this study come from Vietnamese sources but in the literature, there were other close or lower values (e.g., 1.5–1.7 gP capita^{-1} day^{-1}, Naden et al., 2016). The difference in P per capita is due to the use of polyphosphates in washing powders that can differ from one country to another. Gross nutrient inputs were calculated using the per capita human nutrient emissions and the population of HCMC that is not connected to WWTPs Equation (2).

$$\mathrm{Flux}\left(\mathrm{ton\,year}^{-1}\right) = \frac{E \times \mathrm{Inhab} \times 365}{100{,}000}, \quad (2)$$

where

- Flux is the annual flux of Total N and Total P (tons year^{-1});
- E is Total N and Total P in pollutant emissions (g capita^{-1} day^{-1});
- Inhab is the total population of HCMC that is not connected to WWTPs (capita).

Net nutrient inputs from WWTPs

HCMC has only two WWTPs. Their treatment capacities are 141,000 m^3 day^{-1} (426,000 inhabitants) for Binh Hung WWTP and 30,000 m^3 day^{-1} (120,000 inhabitants) for Binh Hung Hoa WWTP (see Figure 1c). WWTP inputs were calculated with the WWTPs' discharge capacity and mean output concentrations after treatment (see Table A2 and Equation (3).

$$\mathrm{Flux}\left(\mathrm{ton\,year}^{-1}\right) = \frac{C \times Q \times 3{,}600 \times 24 \times 365}{10^6}, \quad (3)$$

where

- Flux is the annual flux of TSS, Total N, NO_3^-, NH_4^+, Total P, or PO_4^{3-} (ton year^{-1});
- C is the mean annual concentrations in wastewater (mg L^{-1});
- Q is the mean annual wastewater discharge (m^3 s^{-1}).

Net flux from urban canals to rivers

Two main urban canals (Tham Luong canal in the north and Ben Nghe canal in the south of HCMC) receive untreated wastewaters (Figure 1c). The large Nhieu Loc–Thi Nghe canal in the centre of HCMC was recently protected from most direct untreated discharges when a large sewerage system was built in 2012 (World Bank Sanitation project, 2012). Influent loading was estimated using the annual domestic water discharges and the mean annual TSS and nutrient concentrations within the canals, which were calculated from the data supported by CEM-DONRE (2012–2016). The untreated wastewater discharge was estimated from the number of people living near these three canals (Ho Chi Minh City Statistical Yearbook, 2016) and the per capita water consumption of ~150 L inhab^{-1} day^{-1} proposed by Triet et al. (2008; Table A2). Annual flux was the product of annual water discharges and annual mean concentrations at low tide in urban canals (see Table A2).

2.4.3 | Industrial inputs

Several large industrial zones exist in the Saigon–Dongnai River with different activities. To estimate industrial inputs, we gathered information on companies within HCMC concerning their production, discharge effluents, and water quality variables (e.g., TSS and nutrients). Our approach comprised (a) selection of the companies with organic and nutrient emissions (paper, chemical/fertilizer, food processing, textile, pharmaceutical chemistry and cosmetic, detergent, and personal hygiene products) and (b) elaboration of a questionnaire sent to all the companies selected. This questionnaire was sent to 183 companies, requesting them to provide information on (a) wastewater effluent discharge and production and (b) quality of wastewater (TSS and nutrient concentrations) and (c) how effluents were discharged (directly to the rivers, into canals or stored in basins). We received 41 answers, only 11 of which could be used for the calculations.

We assumed that industrial inputs can be estimated using two approaches: (a) based on data from questionnaires to calculate nutrient input from sectors such as the paper industry, chemical/fertilizer industry, food processing industry, and pharmaceutical chemistry industry (first group) and (b) based on HCMC Export Processing and Industrial Zones Authority data and the Vietnamese industrial water quality regulation (QCVN40, 2011) to calculate input from the textile, cosmetic, detergent, and personal hygiene product industries (second group).

For the first group, annual nutrient fluxes were the product of mean wastewater discharge and mean TSS and nutrient concentrations for each sector (see Table A3 and Equation (3)). For the second group, we hypothesized that daily water discharges can be estimated based on the discharge of each industrial zone and the percentage from the textile company or the cosmetic, detergent, and personal hygiene products companies (see Equation (4)). TSS and nutrient fluxes were calculated from daily discharges and concentrations (see Equation (3)), in which TSS and nutrient concentrations were extracted from QCVN40 (2011; see Table A4).

$$Q = Q_{IZ} \times \frac{N_{sector}}{N_{IZ}}, \quad (4)$$

where

- Q and Q_{IZ} are the daily discharge of professional and industrial zones (m^3 day^{-1}), repsectively;
- N_{sector} and N_{IZ} are the numbers of textile companies or cosmetic, detergent, and personal hygiene product companies and the total number of companies in each industrial zone, respectively.

2.4.4 | Atmospheric depositions

Atmospheric depositions were evaluated through the collection of rainwater during the 2017 rainy season on the roof of the CARE laboratory in an urban area of HCMC (Figure 1). These deposition were monitored from May 2017 to December 2017 (rain during this period accounts for more than 90% of yearly precipitation). The volume of rainwater was collected using an oven-type gauge (AFNOR NF X 43-014) and measured after each rain event. The samples from Monday to Sunday were combined to provide one composite sample per week. These samples were analysed for TSS, Total N, NO_3^-, NH_4^+, Total P, PO_4^{3-}, and DSi. We considered that the impervious surface of HCMC was 27,142 ha in 2016 (Nguyen, Chi-Farn, Cheng-Ru, Bui-Xuan, & Tran-Hau, 2017). The annual flux was calculated as the product of weekly cumulative rain and weekly concentrations (see Table 1 and Equation (5).

$$\text{Flux}_{\text{annual}} = \frac{27142 \times \sum_{i=1}^{n} \text{Flux}_{\text{weekly}}}{1000}, \text{with } \text{Flux}_{\text{weekly}} = \frac{C_{\text{weekly}} \times Q_{\text{weekly}} \times 10^4}{10^6}, \quad (5)$$

where

- $\text{Flux}_{\text{annual}}$ is the annual flux of TSS, Total N, NO_3^-, NH_4^+, Total P, PO_4^{3-}, or DSi (ton year^{-1});
- $\text{Flux}_{\text{weekly}}$ is the specific flux of TSS, Total N, NO_3^-, NH_4^+, Total P, PO_4^{3-}, or DSi (kg ha^{-1});
- C_{weekly} is the weekly concentration in rainfall (mgL^{-1});
- Q_{weekly} is the weekly cumulative rainfall for the period recorded (mm);
- n = 35 and 27,142 (ha) is the impervious surface of HCMC in 2016 (Nguyen et al., 2017).

2.4.5 | Assumption on TSS and nutrient budgets

The TSS and nutrient budgets were built based on industrial and domestic inputs (treated and untreated nutrient inputs) and atmospheric deposition, as described above. The estimations were based on many data source, as well as on several hypotheses. Data from questionnaires may be partial because all answers from companies were not always correctly registered. Moreover, due to the lack of data, Total N and Total P fluxes in domestic inputs were estimated from data reported in the literature.

Another important type of data needed to establish a complete budget is the NO_3^- flux in WWTPs and industrial discharges, and Total N and Total P fluxes in canals. The estimation of these fluxes was based on two assumptions. Generally, N exists in organic and inorganic forms; the Total N concentration is the sum of dissolved inorganic nitrogen (NO_3^- and NH_4^+), dissolved organic nitrogen, particulate organic nitrogen, and particulate inorganic nitrogen (e.g., NH_4^+ adsorbed onto particles). However, according to QCVN14 (2008) and QCVN40 (2011), level of organic nitrogen in domestic and industrial wastewater after treatment is rather low, close to 0.003 mgN L^{-1}. We can therefore ignore organic nitrogen in treated wastewater. We assumed that N in wastewater only comprises NO_3^- and NH_4^+. The difference between Total N and NH_4^+ input was considered as NO_3^- input from WWTPs and industrial discharges.

TABLE 1 Mean annual concentrations and specific fluxes of TSS and nutrients from atmospheric depositions in 2017

Parameters	Concentration (mg L^{-1} ± SD)	Specific flux (kg ha^{-1})[a]
TSS	7.94 ± 8.43	4.19
N-NH_4^+	0.21 ± 0.16	0.13
N-NO_3^-	0.30 ± 0.13	0.24
Total N	1.66 ± 0.71	1.17
P-PO_4^{3-}	0.01 ± 0.004	0.007
Total P	0.03 ± 0.015	0.018
DSi	0.12 ± 0.07	0.08

Abbreviation: TSS, total suspended sediment.
[a]Cumulative rain in 2017 of 1,969 mm (from May to December).

2.4.6 | Expected nutrient inputs in 2025, 2040, and 2050

To estimate nutrient fluxes in the future, we assumed that HCMC's population would increase 3% per year (according to ADB (Asian Development Bank), 2010, and Ho Chi Minh City Statistical Yearbook, 2016) and inhabitant's water consumption could reach approximately 200 L inhab^{-1} day^{-1} in 2025 (Nguyen et al., 2011). By 2020–2025, the total capacity of wastewater to be treated will be 1.3 million m^3 day^{-1} (DONRE, pers. comm.). All the current sewage treatment plants in HCMC use the conventional activated sludge technique without specific biological or chemical nutrient removal (QCVN 14, 2008). The average Total N and Total P removal is therefore about 40–50% and 10–15%, respectively (Metcalf and Eddy/AECOM, 2014).

With the nutrient concentration and nutrient removal efficiency dataset, the population as well as the number and treatment capacity of WWTPs and gross nutrient inputs were calculated based on per capita human nutrient emissions and the population of HCMC (Equation (2)). Net nutrient inputs by WWTPs were calculated based on the expected population connected to WWTPs per capita human nutrient emissions and nutrient removal efficiency (Equation (6) and Table 2).

$$\text{Flux}\left(\text{ton year}^{-1}\right) = \sum \frac{E \times \text{Inhab}_{\text{WWTP}} \times 365 \times C}{100{,}000}, \quad (6)$$

where

- Flux is the annual flux of Total N and Total P (ton year^{-1});
- E is Total N and Total P in domestic emissions (g capita^{-1} day^{-1});
- $\text{Inhab}_{\text{WWTP}}$ is the population of HCMC that is connected to WWTPs (capita);
- C is the nutrient removal efficiency (%).

3 | RESULTS

3.1 | Seasonal variation of TSS and nutrient concentrations

The spatial variation of TSS and nutrients was averaged at each site for the dry and wet seasons of the 2012–2016 period (Figure 2a). For

TABLE 2 Treatment capacity and nutrient removal efficiency of WWTPs from past to future

Year	2012-2016	2025	2040	2050
Population (inhabitant)[a]	8,441,902	11,014,767	17,160,649	23,062,447
Number of WWTPs[b]	2	4	12	12
Treatment capacity (m^3 day^{-1})[b]	171,000	1,253,000	2,813,000	2,813,000
% Population connected to WWTPs	10	57	82	61
Nutrient removal efficiency[c]				
Nitrogen (%)	40-50	40-50	40-50	40-50
Phosphorus (%)	10-15	10-15	10-15	40-50[d]

Abbreviation: WWTPs, wastewater treatment plants.
[a]Population growth, 3% per year from ADB (Asian Development Bank), 2010, Ho Chi Minh City Statistical Yearbook, 2016.
[b]Planning of the building of new WWTPs from Tran Ngoc et al., 2016.
[c]Nutrient removal efficiency in conventional active sludge treatment process from Metcalf and Eddy/AECOM, 2014.
[d]Expected improvement of P retention through precipitation process.

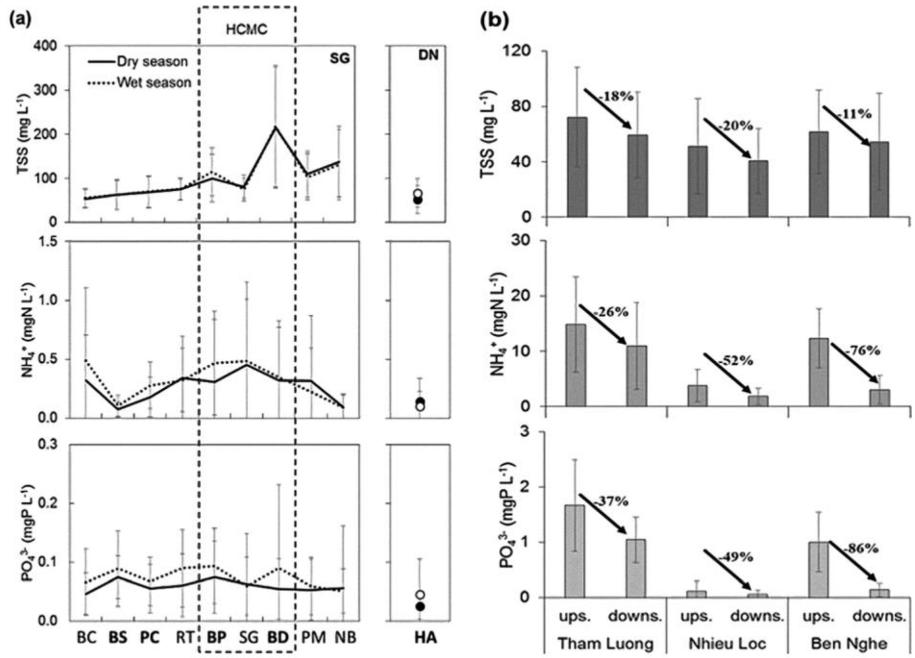

FIGURE 2 Mean total suspended sediment (TSS), NH_4^+, and PO_4^{3-} concentrations over the 2012–2016 period: (a) along the Saigon River (SG) and the Dongnai River (DN) during the wet and dry seasons and (b) in urban canals of Ho Chi Minh City (HCMC); BC, BS, PC, RT, BP, SG, BD, PM, NB, and HA are 10 sampling sites within the Saigon-Dongnai River basin (Ben Cui, Ben Suc, Phu Cuong, Rach Tra, Saigon, Bach Dang, Phu My, Nha Be, and Hoa An, respectively). In Figure 2a, bold legends represent sampling sites chosen for the budget calculation

the river sites, no difference was, on average, observed for the dry and wet seasons. However, the standard deviation revealed high variability for both seasons at all sites. The spatial variation of the TSS concentration clearly showed an increase in the HCMC sector. The highest averaged TSS concentration was approximately 215 mg L^{-1} at the city centre. NH_4^+ and PO_4^{3-} concentrations only slightly varied from upstream to downstream along the Saigon River. However, NH_4^+ values appeared slightly higher in the residential sector of HCMC (0.48 ± 0.67 mgN L^{-1}); elsewhere lower values (0.2 ± 0.1 mgN L^{-1}) were observed. PO_4^{3-} concentrations fluctuated slightly, around 0.07 ± 0.02 mgP L^{-1} from upstream to downstream (Figure 2a).

High concentrations of PO_4^{3-} and NH_4^+ were found in urban canals (Figure 2b) with value 10 and 20 times higher than in the Saigon and Dongnai Rivers (Figure 2a). This undoubtedly indicates inputs of untreated domestic wastewaters. With such high concentrations, Tham Luong canal (2,494,983 inhabitants) and Ben Nghe canal (2,409,606 inhabitants) can be considered as wastewater collectors draining HCMC. A decrease in TSS, NH_4^+, and PO_4^{3-} concentrations was observed, from upstream to downstream, which indicates a possible accumulation of the domestic pollution emitted into the canals (Figure 2b).

2| Seasonal and interannual variations of river fluxes and the effect of hydrological conditions

1. | Seasonal variation of river fluxes

Seasonal fluctuations of TSS and nutrient fluxes distinguish two distinct hydrological phases, with a wet season that lasted 7 months, from May to November, and a dry season characterized by low flow conditions from December to April (5 months). Seasonality is much more pronounced for the Dongnai River than for the Saigon River (Figure 3).

Whereas net water discharge in the Saigon River ranged from 4.18 to 222 $m^3\ s^{-1}$, in the Dongnai River, net water discharge fluctuated from 85.4 to 2,524 $m^3\ s^{-1}$ (Figure 3a). The mean discharge is thus 12 times lower in the Saigon River (50 $m^3\ s^{-1}$) than in the Dongnai River (632 $m^3\ s^{-1}$).

During the monitoring period considered (2012–2016), TSS specific flux in the Saigon River ranged from 1.5 to 20 tonSS km^{-2} $month^{-1}$; in the Dongnai River, lower values were observed (from 1.1 to 9.2 tonSS km^{-2} $month^{-1}$; Figure 3b). De facto, similar to the monthly water discharges for both rivers, the maximum TSS specific flux also extended from May to November (Figure 3b). The peak of TSS specific flux accounted for 77% of the annual TSS specific flux in the Saigon River and 80% of the annual TSS specific flux in the Dongnai River during this period.

The high values of Total N, NO_3^- and NH_4^+ specific fluxes similarly extended during the May to November period for the two rivers (Figure 3c). During the wet season, the Saigon River delivered 0.71 tonN of Total N, 0.14 tonN of NO_3^-, and 0.17 tonN of NH_4^+, which was 68%, 66%, and 82% of total annual specific fluxes, respectively. These specific fluxes were 0.8 tonN of Total N, 0.09 tonN of NO_3^-, and 0.07 tonN of NH_4^+ exported by the Dongnai River. Based on the monthly specific fluxes of Total P and PO_4^{3-} in the two rivers, it appears that most of the annual specific flux was again exported during the wet season, that is, 67% and 83% of total annual Total P and PO_4^{3-} specific fluxes for the Saigon River and 71% and 86% for the Dongnai River, respec- tively (Figure 3d).

3.2.2 | Interannual variations of river fluxes

Whatever year is considered, the difference between Saigon and Dongnai tributaries predominated over interannual variations (Figure 4). During the 2012–2016 period, the mean fluxes of TSS, NH_4^+, and PO_4^{3-} in the Dongnai River were 5, 6, and 3 times higher than those in the Saigon River, respectively, with a factor of 10 for discharge. The lowest TSS fluxes (19×10^3 tonSS $year^{-1}$), NH_4^+ (23 tonN $year^{-1}$), and PO_4^{3-} (32 tonP $year^{-1}$) were observed at Ben Suc in 2012, when the minimal water discharge was recorded. Conversely, the maximum yearly fluxes occurred at higher discharge, that is, 1.43×10^6 tonSS $year^{-1}$ (in 2013) for TSS, 4.65×10^3 tonN $year^{-1}$ for NH_4^+, and 1.44×10^3 tonP $year^{-1}$ for PO_4^{3-} (in 2016; Figure 4). The Saigon River transported about 60% DIN and 20% DIP of the total N and total P, whereas the Dongnai River transported only 24% DIN and 63% DIP, respectively.

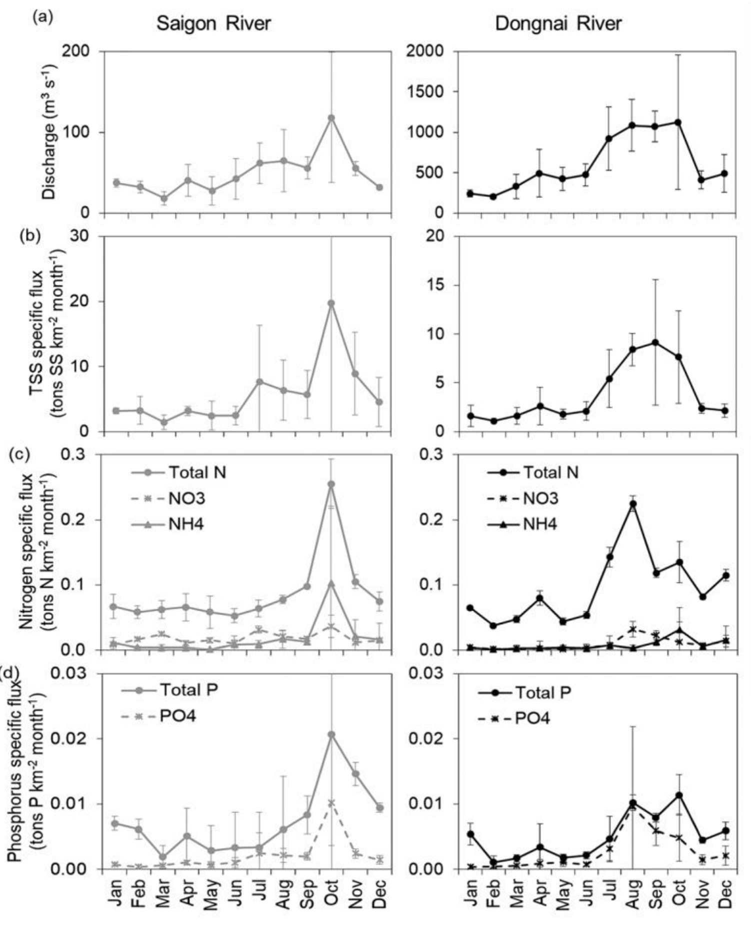

FIGURE 3 Seasonal variations of (a) discharges (b) total suspended sediment (TSS) and (c–g) nutrient fluxes in the Saigon (Bach Dang station) and Dongnai (Hoa An station) River system (2012–2016)

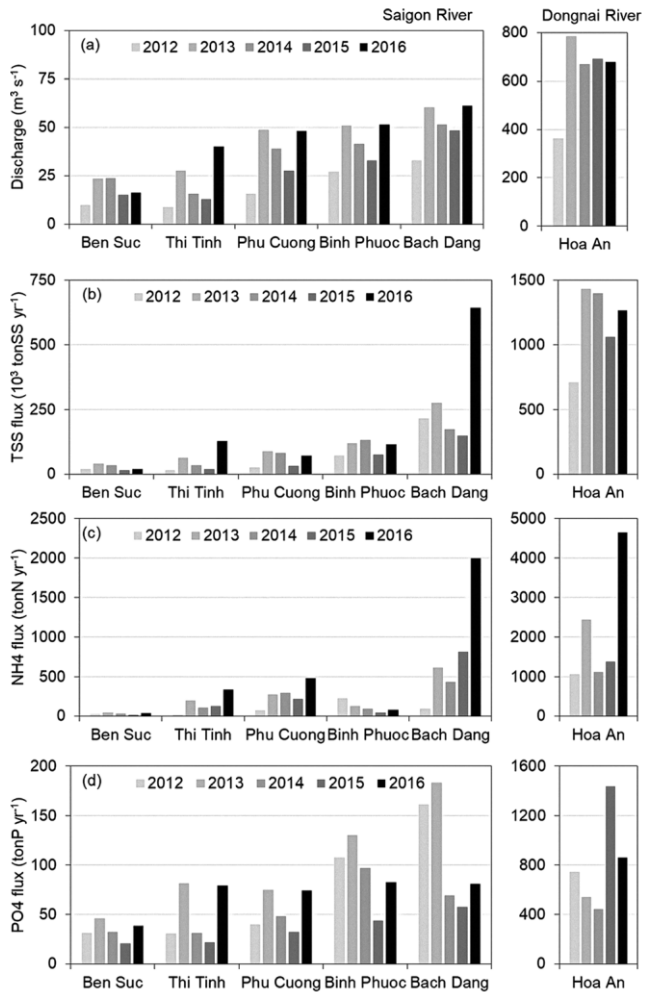

FIGURE 4 Interannual discharges and fluxes of total suspended sediments (TSS), NH_4^+, and PO_4^{3-} in the Saigon–Dongnai River system (2012–2016)

3 | TSS and nutrient budgets in the Saigon River

1. | Water budget

The discharge contribution was calculated independently for each site (and tributaries) and appeared balanced (Figure 5a). Urban waters accounted for 20% of the Saigon River discharge on average over the 2012–2016 period, indicating a potential impact of untreated wastewaters. Knowing that the Saigon River is around 200 m wide and 10 m deep in the city, the mean residual water discharge of the Saigon River was rather small (51 $m^3 s^{-1}$).

3.3.2 | TSS budget

The mean annual TSS flux delivered by the Dongnai River was around 1.18×10^6 tonSS year^{-1}, about 4 times higher than the amount exported by the Saigon River. Crossing of HCMC, the TSS flux in the Saigon River increased over tenfold to reach 290×10^3 tonSS year^{-1} in comparison with the watershed's upstream value (26×10^3 tonSS year^{-1}; Figure 5a).

3.3.3 | Nitrogen budget

The Saigon River delivered 5,323 ± 378, 1,928 ± 59, and 791 ± 727 tonN year^{-1} for Total N, NO_3^-, and NH_4^+, respectively, during the 2012–2016 period, whereas the Dongnai River exported 31,030, 2,963, and 2,132 tonN year^{-1}, respectively. The urban canals contributed to a maximum of about 2,200 tonN year^{-1}, which means that 90% of Total N emitted through untreated wastewaters was retained or lost in urban canals (mostly for the NH_4^+ form [see Figure 5b] nitrified in NO_3^- and subsequently denitrified in N_2).

3.3.4 | Phosphorus budget

The Saigon–Dongnai river system delivered 2,103 and 917 tonP year^{-1} for Total P and PO_4^{3-}, in which the Saigon River exported 21% and 13% of total annual flux of Total P and PO_4^{3-}, respectively. Interestingly, total P input from domestic waste was 25 times higher than the outflow from the canal. Total P outflow was mainly as PO_4^{3-} (Figure 5c). In this study, to increase confidence on per capita P loading, we calculated a new scenario based on other per capita (1.5–-1.7 gP capita^{-1} day^{-1} from Naden et al., 2016; see Figure 5c, value in italics). We observed that our budget was unbalanced for Total P flux, whatever the per capita considered.

3.3.5 | Silica budget

The Saigon–Dongnai river system delivered 66,500 tonSi year^{-1}, in which the Dongnai River exported 94% of the total annual flux of DSi (Figure 5d). Taking into account the wastewater discharge (industrial, WWTPs, and canal inputs), we estimated DSi input by taking the average DSi concentration of the river upstream. Indeed, DSi input by industrial zones, WWTPs, and urban canals accounted for about 30% of the DSi flux in the Saigon River.

3.4 | Future nutrient inputs

The higher population will also affect net nutrient inputs from canals to rivers, which are expected to fluctuate substantially. We observed a decrease from about 18×10^3 tonN year^{-1} in 2016 to 10×10^3 tonN year^{-1} in 2040 prior to an increase to 30×10^3 tonN year^{-1} in 2050 and from about 5×10^3 tonP year^{-1} in 2016 to 3×10^3 tonP year^{-1} in 2040 prior to an increase to 8×10^3 tonP year^{-1} in 2050 (see Table 3). Over four different investigation periods, the proportion of N and P retention in the urban area decreased from 30% to 26% for N and from 32% to 19% for P. These N and P retention percentages reached the highest value in 2040,

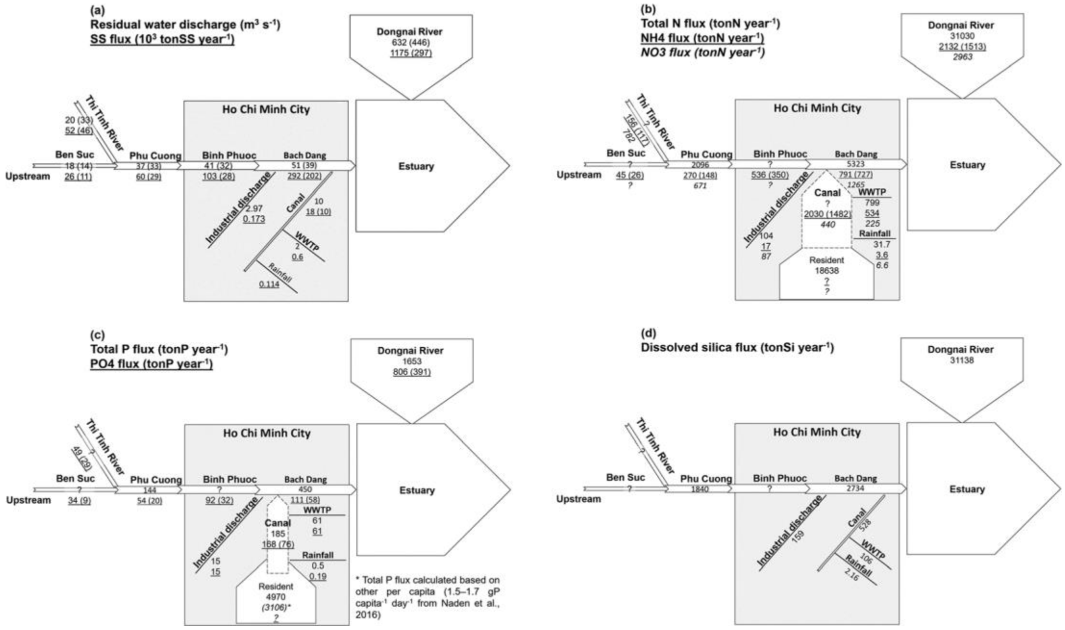

FIGURE 5 (a) Mean annual water discharge (±*SD*) and annual suspended sediment (±*SD*) budget (underlined values), (b) annual nitrogen (±*SD*) budget, (c) annual phosphorus (±*SD*) budget, and (d) annual dissolved silica (±*SD*) budget within the Saigon–Dongnai River system (2012–2016). Abbreviation: WWTP, wastewater treatment plant

accounting for 37% for N and 66% for P, and decreased to 27% for N and 40% for P in 2050.

4 | DISCUSSION

4.1 | TSS and nutrient budgets in HCMC for the 2012-2016 period

Water discharge during the wet season accounted for 73% of the annual discharge at the Saigon River and 73% for the Dongnai River.

TABLE 3 Gross nutrient inputs and net nutrients inputs from urban canals to river (past and future)

Year	2012-2016	2025	2040	2050
Gross nutrient inputs				
Total N flux (tonN year^{-1})	27,732	36,184	56,373	75,760
Total P flux (tonP year^{-1})	7,395	9,649	15,033	20,203
Net nutrient inputs from WWTPs				
Total N flux (tonN year^{-1})	799	11,319	25,412	25,412
Total P flux (tonP year^{-1})	61	3,641	2,373	4,335
Net nutrient fluxes from canals to rivers				
Total N flux (tonN year^{-1})	18,638	15,603	10,169	29,557
Total P flux (tonP year^{-1})	4,970	4,161	2,712	7,882

Since the Dau Tieng and Tri An reservoirs were built in the Saigon and Dongnai Rivers, the discharge in each river has been regulated for water demand and use (Trieu, Hiramatsu, & Harada, 2014). The discharge by Dau Tieng reservoir is up to 30 $m^3 s^{-1}$ during the dry season to prevent saline intrusion in the Saigon River (Trieu et al., 2014). In contrast, TSS and nutrient concentrations were similar in dry and wet seasons and fluxes increased with increasing water discharge, in almost similar proportions.

4.1.1 | TSS budget

TSS urban inputs from canals cannot totally explain the global TSS increase, even when considering industrial discharge, WWTPs, and rainfall rather negligible (Figure 5a). Thus, local bank erosion is likely to be responsible for the difference, considering that sediment trapping probably occurring in the Dau Tieng reservoirs could be compensated downstream by river bank erosion (Kondolf, 1997).

It appeared that the specific TSS flux in the Saigon–Dongnai river system was around 47.1 tonSS km^{-2} $year^{-1}$ and was over 4 times lower than that of the Mekong River (Wolanski, Huan, Dao, Nhan, & Thuy, 1996), the Red River (Le et al., 2005, 2007), and the Changjiang River (Liu et al., 2016; see Table 4). The TSS specific flux in the Saigon and Dongnai Rivers thus appeared to be within the low range of those observed worldwide. This can be explained by the high potential for sediment retention within the two reservoirs as well as by the storage within this low land elevation basin (knowing that the river is around 100–200 m wide and 8–12 m deep), as previously observed in the Red River basin in Vietnam (Luu et al., 2012). In a recent study, Marchesiello et al. (2019) demonstrated high coastal erosion

TABLE 4 Specific fluxes of TSS and nutrients in the Saigon–Dongnai River system and in some rivers in the world

River	Area (km^{-2})	Specific discharge ($10^3 m^3 km^{-2} year^{-1}$)	TSS specific flux ($tonSS km^{-2} year^{-1}$)	Specific TN flux ($kgN km^{-2} year^{-1}$)	Specific TP flux ($kgP km^{-2} year^{-1}$)	References
Saigon River	4,717	335	62	1,129	95	This study
Dongnai River	26,499	751	45	1,171	62	
Saigon–Dongnai River basin	31,216	689	47	1,165	67	
Mekong River	790,000	595	215	238	24	Wolanski et al., 1996; Li & Bush, 2015
Red River basin	156,451	1,104	280	855	325	Le et al., 2005, 2007
Changjiang River (China)	1,808,500	9,285	4819	346	145	Zhang, 1996; Liu et al., 2016

Abbreviation: TSS, total suspended sediment.

downstream of the Saigon River estuary and also assumed that erosion was a consequence of sediment trapping by dams in the Saigon and Dongnai Rivers (Marchesiello et al., 2019).

4.1.2 | Nitrogen budget

The specific Total N flux was 1,164 kgN km^{-2} $year^{-1}$, 1 to 5 times higher than for the Red River (Le et al., 2005, 2007), the Changjiang River (Liu et al., 2016; Zhang, 1996), and the Mekong River (Li & Bush, 2015; see Table 4). This indicates the high impact of the megacity of HCMC on the total N flux. Figure 5b clearly shows that untreated domestic wastewaters were responsible for the high level of N input. Untreated domestic wastewaters dominated the fluxes of NO_3^- and NH_4^+, accounting for 77% and 58% of total N urban fluxes, respectively, whereas industrial discharge and rainfall were negligible. The fluxes in urban canals were extremely high, about 10 times higher than the fluxes from other inputs. The results showed that the residents living near urban canals released 18,638 tonN $year^{-1}$. This means that a large proportion of Total N was stored in urban canals or in individual septic tanks that are common in the old urban centre (Marcotullio, 2007). Consequently, a large amount of N may be lost in the septic tank and removed through cleaning. According to urban policy building in HCMC, septic tanks are widely used for most habitations, for a total storage capacity of 250–350 wet tons per day (Nguyen, Tran, & Nguyen, 2013). Septic tanks sludge presents high TSS and organic compounds (55–80% of dry weight) including N (Total N = 1,500–1,800 mg L^{-1} according to Nguyen et al., 2013). Septic tanks are dredged every 1–10 years using small vehicles, and sludge is used as organic fertilizer after treatment. Moreover, the HCMC Urban Drainage Company and the Office of Waterway Management are in charge of dredging canals in the inner city for navigation, tourism purposes, and improving drainage (JICA, 2001). The total amount of dredged sediment is estimated at 1,750 m^3 day^{-1} along 57 km of canals used as the drainage network (Nguyen et al., 2013). The surface layer (30–50 cm) is highly polluted, whereas the bottom layer is mainly sand and coarse particles. Urban rivers and canals play an important role in N sink through sediment–water exchange, as mentioned in the Nhue and Day River systems in Hanoi in the north of Vietnam, similar to the Saigon River system (Trinh, Meysman, Rochelle-Newall, & Bonnet, 2012). Dredged sludge from canals is transported to the Solid Waste Treatment Company of HCMC for composting for the most part, but within the limits of treatment capacity, or even "open dumping" without treatment (Nguyen et al., 2013; Urban Drainage Company, pers. comm.). Overall, canal and septic tank sludge collection likely explains the high removal rate evidenced in our N budget.

In addition, once N enters the river system, in-stream N transformations, such as NH_4^+ nitrification followed by NO_3^- denitrification continue as the result of both physicochemical and biogeochemical processes (Van Drecht et al., 2003). The corresponding N removal within the aquatic system accounts for approximately 70% of all the inputs of NH_4^+. Nitrification, denitrification, and algal uptake are suspected to occur at a high rate, with the warm weather conditions in this tropical environment favouring biological activities (Luu et al., 2012; Nguyen, Nguyen, Bui, & Khoa, 2007). The low level of NH_4^+ in rivers compared with urban canals and further compared with the total N inputs largely as NH_4^+, confirm the role played by the nitrification process, followed by denitrification (Nguyen et al., 2019).

4.1.3 | Phosphorus budget

The specific Total P flux was 67.4 kgP km^{-2} $year^{-1}$ and was 2 to 5 times lower than in the Red River Delta (Le et al., 2005, 2007) and the Changjiang River (Zhang, 1996; Liu, Zhang, Chen, & Zhang, 2005; Liu et al., 2016. High retention of particulate P within the river systems can explain this finding. P is known to adsorb easily onto suspended sediment and the fate of particulate P is closely related to the TSS flux. As an illustration, the Red River Delta retained 50% of the incoming flux of P from upstream (Luu et al., 2012). Figure 5c shows that Total P and PO_4^{3-} fluxes from untreated wastewaters accounted for 71% and 69% of the total annual fluxes of urban area into river. We observed that residents annually released 4,970 tonP into canals. Again, a low percentage (3.7%) of Total P flux was transferred into the Saigon River, indicating that about 96% of Total P may be stored in the canals. This Total P storage also concerned PO_4^{3-}, which may strongly adsorb onto sediment. This sediment accumulation was evidenced in the urban canals of Bangkok, which presents a similar geography, demography, and wastewater management as HCMC (Færge, Magid, & Penning de Vries Frits, 2001). As mentioned above, dredging of the urban canals can explain the high removal of P from the system, sediment being much richer in P in canals (Strady et al., 2017). This conclusion is in line with the observations made by Babut et al. (2019) on the disappearance of organic pollutants in the Saigon River.

4.2 | Nutrient flux ratios as an indicator of potential eutrophication

The ICEP proposed by Billen and Garnier (2007) is particularly relevant to evaluate the new production of non-siliceous biomass potentially sustained in the estuarine zone by either N or P delivered in excess over Si (Garnier, Billen, Némery, & Sebilo, 2010). The ICEP was based on the Redfield molar C:N:P:Si = 106:16:1:20 (Redfield et al., 1963), with the equations described in Garnier et al. (2010). For the purposes of river-to-river comparison, it is scaled to the river basin area, expressed in specific flux in kgC km^{-2} day^{-1}. Depending on the nutrient considered, either N-ICEP or P-ICEP can be defined, following relationships (6) or (7), respectively:

- If NFlux/PFlux < 16 (N limiting), where N:Si and C:N are the Redfield ratio,

$$N-ICEP = \left[\left(\frac{NFlux}{14} - \frac{SiFlux}{28} \times \frac{N}{Si}\right) \times \frac{C}{N} \times 12\right]; \quad (6)$$

- if NFlux/PFlux > 16 (P limiting), where P:Si and C:P are the Redfield ratio,

$$P-ICEP = \left[\left(\frac{PFlux}{31} - \frac{SiFlux}{28} \times \frac{P}{Si}\right) \times \frac{C}{P} \times 12\right]; \quad (7)$$

where NFlux, PFlux, and SiFlux are the mean specific fluxes of Total N, Total P, and DSi, delivered at the outlet of the river basin, expressed in kgN km^{-2} day^{-1}, kgP km^{-2} day^{-1}, and kgSi km^{-2} day^{-1}, respectively. A negative N-ICEP or P-ICEP value illustrates that N and P are not in excess over silica and thus characterize the limitation of the eutrophication phenomenon, with a possible dominance of desirable diatoms well palatable for the higher trophic level. Positive values indicate an excess of either N or P over the requirements for diatom growth, a condition for potentially harmful non-siliceous algal development such as cyanobacteria or dinoflagellates, possibly producing toxins.

We observed that the Saigon River, under high human pressure, was characterized by N:P ratios above the Redfield ratio (N:P > 16, Nguyen et al., 2019), which indicated an excess of N over P with respect to algal growth requirements. Thus P becomes a potential limitation of primary production. Furthermore, both the P-ICEP and N-ICEP provided positive values for the Saigon–Dongnai Rivers (9.8 and 21.6 kgC km^{-2} day^{-1}, respectively; see Table 5), indicating that excess in N and P could lead to a high potential for coastal eutrophication. Specifically examining the Saigon River, the P-ICEP and N-ICEP were also positive. This eutrophication risk is confirmed from our measurements, chlorophyll *a* often being higher than 25 μg L^{-1} and up to 150 μg L^{-1}, far beyond a good trophic value (Nguyen et al., 2019). Eutrophication has not yet occurred downstream of the Saigon River-Soai Rap estuary, probably because of the high nutrient metabolism potential of the Can Gio Mangrove, as recently demonstrated (David, Marchand, Thiney, Nhu-Trang, & Meziane, 2019).

4.3 | Future nutrient emissions from HCMC by 2025-2050

During the 2012–2016 period, the proportion of urban households connected to the main sewage treatment system was low (only 10%). In addition, the population should increase by about 270% between 2016 and 2050 (Table 2). According to HCMC authorities, an ambitious environmental sanitation project aims at building a drainage basin inside the city and establishing 10 new WWTPs (Tran Ngoc

TABLE 5 Specific nutrient fluxes delivered by Saigon–Dongnai River basin and the indicator of coastal eutrophication potential (ICEP)

Parameters	Saigon River basin (4,717 km^2)	Dongnai River basin (26,499 km^2)	Saigon-Dongnai River basin (31,216 km^2)
N:P (FluxN:FluxP)	29	27	27
P specific flux (kgP km^{-2} day^{-1})	0.49	0.39	0.40
N specific flux (kgN km^{-2} day^{-1})	6.49	4.72	4.98
Si specific flux (kgSi km^{-2} day^{-1})	1.59	3.22	2.97
P-ICEP (kgC km^{-2} day^{-1})	16.7	8.5	9.8
N-ICEP (kgC km^{-2} day^{-1})	33.2	19.5	21.6

et al., 2016). Very recently in 2018, the treatment capacity increased by 21% of the population with the construction of two new WWTPs and the increase of the treatment capacity of the Binh Hung WWTP. We estimated that about 57% of the city's inhabitants will have access to wastewater treatment systems in 2025 versus approximately 82% in 2040. With a stable water treatment capacity from 2040 to 2050, the population in HCMC connected to sewage treatment systems will decrease to 61%, because of the increase of the number of inhabitants. Moreover, wastewater collection by WWTPs would decrease the net nutrient fluxes from urban canals to the river at the 2040 horizon prior to an increase of these fluxes from 2040 to 2050, assuming that the collected volume will not exceed the WWTP capacity.

Gross nutrient inputs are expected to double in 2040 and triple in 2050, for both Total N and Total P fluxes. The expected construction and operation of 10 new WWTPs for the additional 6 million inhabitants should lead to a decrease in Total N and P inputs. With a rise of the HCMC population up to 23 million inhabitants in 2050 and no further wastewater treatments, the net nutrient fluxes from the canals to the river could increase to about 30 tonN year^{-1} and 8 tonP year^{-1}. It seems that the increase in population from 17 to 23 million inhabitants, and hence the associated wastewater increase, has not been included to date in the sanitation management plans.

To evaluate the effect of the construction of the ten WWTPs in the future in terms of eutrophication, we estimated nutrient ratios and the ICEP index based on nutrient fluxes in 2025, 2040. and 2050. Dissolved silica comes from rock weathering; without taking into account climate change possibly increasing this process, we can assume that silica fluxes will remain stable. As discussed above, urban canals were the main source in the HCMC area, where about 48% of Total N flux and 58% of total P flux in the Saigon River originate from urban canals (Figure 5b,c). Therefore, river fluxes in the future can be considered as a sum of the present river fluxes and nutrient inputs from urban canals to rivers for the 2050 horizon explored. On this basis, we would observe a change in the P limiting factor to the N limiting factor for algal development in the Saigon River. This is presented by the N:P ratio below 16, indicating an excess of P over N with respect to algal growth requirements. Furthermore, the P-ICEP would increase from 16.7 to 369 kgC km^{-2} day^{-1} in 2050. This indicates an extremely high potential eutrophication in the Saigon River with a potential increase in undesirable algae. Eutrophication would also occur downstream of the Saigon River and the coastal zone with the occurrence of harmful algae.

5 | CONCLUSIONS AND RECOMMENDATIONS

Based on the water discharge, TSS, and nutrients (N and P) concentration data collected, we assessed that the Saigon and Dongnai Rivers delivered 1.47×10^6 tonSS year^{-1}, 36.4×10^3 tonN year^{-1}, and 2.1×10^3 tonP year^{-1}, respectively, into the estuary. Seasonal and spatial variations were closely linked to the hydrological patterns of the Saigon and Dongnai watersheds. With much higher N and P concentrations in the Saigon River, fluxes were much higher for the Dongnai River with a tenfold average discharge. The 5 years documented, including wet and dry years, provide robust estimates, despite considerable variability. The newly established budgets highlight the worrying impact of untreated domestic wastewaters released by HCMC into the estuarine system. Urban canals in HCMC were shown to be responsible for the increasing TSS, P, and N fluxes in the Saigon River. However, they appeared to be efficient biological reactors for eliminating/retaining a large part of the domestic load, and dredging in these canals seems to be an important management tool that deserves further study. As a result, the positive ICEP values at the outlet of the Saigon–Dongnai River system indicates on the eutrophication risk of the coastal zone. Even if the financing plan has not yet been consolidated, the local authorities have already started to build new WWTPs to reduce the direct release of untreated wastewaters and to recover good water quality, which is believed to be mandatory to secure the water resource. The scenarios tested, however, showed that an increasing population without appropriate treatment in WWTPs could worsen the water quality of the Saigon River in HCMC, calling for enlarging the current management plan.

For instance, a dredging plan and linked solid waste management are the major challenge for HCMC to prevent pollution emissions from urban canals to rivers. Without an awareness of the situation, the coastal zone could rapidly encounter an eutrophication problem with the occurrence of undesirable algae that may threaten aquaculture within the Can Gio mangrove area and fisheries in the coastal zone.

These results highlight the challenges that the megacity HCMC is now facing to ensure both good economic and ecological health. The estimation of future nutrient inputs clearly underlines the need to build the 10 WWTPs, as planned in the planning framework and already started, but an additional effort will be necessary with any further increase in population. HCMC is not unique and exemplifies the trajectory that many coastal megacities are experiencing, or will experience, in Asia and Africa.

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DATA AVAILABILITY STATEMENT (DAS)

Data from scientific monitoring are available on request from the authors. The data that support the findings of this study are available from the corresponding author, Nguyen Tuyet, upon reasonable request. The data from the Vietnamese monitoring program that support the findings of this study are available from DONRE. Restrictions apply to the availability of these data, which were used under licence for this study. Data are available from the authors with the permission of DONRE.

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APPENDIX A: | APPENDICES

TABLE A1 Mean annual discharges and concentrations (±*SD*) at the sampling sites within the Saigon and Dongnai river selected to draw the budgets

Sites	Ben Suc	Phu Cuong	Binh Phuoc	Bach Dang	Thi Tinh	Hoa An
pK (km)	151	106	88	64	118	53
Discharge[a] ($m^3 s^{-1}$)	18 ± 14	37 ± 33	41 ± 32	51 ± 39	20 ± 11	632 ± 446
TSS[a] ($mg L^{-1}$)	54.8 ± 18.7	62.0 ± 21.9	102.2 ± 46.3	186.3 ± 127.1	70.8 ± 35.1	57.8 ± 25.7
Total N[b] ($mgN L^{-1}$)	—	1.9 ± 0.5	—	3.4 ± 0.9	—	1.6 ± 0.3
N-NH_4^{+}[a] ($mgN L^{-1}$)	0.09 ± 0.07	0.25 ± 0.21	0.45 ± 0.52	0.42 ± 0.55	0.27 ± 0.25	0.12 ± 0.12
N-NO_3^{-}[b] ($mgN L^{-1}$)	—	0.63 ± 0.29	—	0.81 ± 0.38	—	0.14 ± 0.10
Total P[b] ($mgP L^{-1}$)	—	0.13 ± 0.06	—	0.29 ± 0.14	—	0.08 ± 0.04
P-PO_4^{3-}[a] ($mgP L^{-1}$)	0.08 ± 0.04	0.06 ± 0.03	0.08 ± 0.04	0.07 ± 0.08	0.09 ± 0.05	0.04 ± 0.04
DSi[b] ($mgSi L^{-1}$)	—	1.7 ± 1.8	—	1.8 ± 1.8	—	2.5 ± 2.1

Abbreviation: TSS, total suspended sediment.
[a]Data available for the 2012–2016 period.
[b]Date available for the 2015–2017 period, mean concentrations are extrapolated for the 2012–2014 period where no data are available.

TABLE A2 Mean annual discharges and concentrations (±*SD*) from 2012 to 2016 at the outlet of the three main urban canals and in wastewater treatment plants (WWTPs)

Canals	Tham Luong	Nhieu Loc Thi Nghe	Ben Nghe	WWTPs
Population (inhabitants)	2,494,983	769,103	2,409,606	546,000
Discharge ($m^3 s^{-1}$)	4.33	1.34	4.18	1.98[a]
TSS ($mg L^{-1}$)	59 ± 31	56 ± 23	56 ± 34	10 ± 10 [a]
N-NH_4^{+} ($mgN L^{-1}$)	11 ± 8	3.0 ± 1.5	3.0 ± 2.6	9.2[b]
P-PO_4^{3-} ($mgP L^{-1}$)	1.0 ± 0.4	0.15 ± 0.07	0.15 ± 0.12	—
Total N ($mgN L^{-1}$)	—	—	—	12.9[b]
Total P ($mgP L^{-1}$)	1.11[c]	0.18[c]	0.19[c]	0.98[b]

[a]Data from technical visit in Binh Hung WWTP 29/05/2017.
[b]Data from Center for Environmental Technology and Management in 8/2014 and from Technical report of WWTPs in 3/2015.
[c]Data from Strady et al. (2017).

TABLE A3 Mean daily discharges and concentrations of six industrial sectors (n is the number of responses per category; data synthesis from questionnaires)

Industrial sector	Discharge ($m^3 day^{-1}$)	TSS ($mg L^{-1}$)	Total N ($mgN L^{-1}$)	Total P ($mgP L^{-1}$)
Paper industry (*n* = 2)	25	65	24	5
Chemical/fertilizers industry (*n* = 3)	42	75	30	2
Food processing industry (*n* = 5)	87	40.7	32.3	4.0
Pharmaceutical chemistry industry (*n* = 1)	25	5	7.5	3.5
Textile industry (*n* = 0)	—	—	—	—
Cosmetics, detergents, personal hygiene products (*n* = 0)	—	—	—	—

Abbreviation: TSS, total suspended sediment.

TABLE A4 Levels of TSS and nutrient concentrations allowed in domestic and industrial wastewaters (from National Technical Regulation on Domestic and Industrial Wastewater)

Parameters	For domestic wastewater QCVN14 (2008)	For industrial wastewater QCVN40 (2011)
TSS (mg L^{-1})	50	50
Total N (mgN L^{-1})	—	15
NO_3^- (mgN L^{-1})	30	-
NH_4^+ (mgN L^{-1})	5	5
Total P (mgP L^{-1})	—	4
PO_4^{3-} (mgP L^{-1})	6	—

Abbreviation: TSS, total suspended sediment.