**NUTRIENT DYNAMICS AND EUTROPHICATION ASSESSMENT IN THE
TROPICAL RIVER SYSTEM OF SAIGON – DONGNAI (SOUTHERN
VIETNAM)**

Tuyet T.N. Nguyen^{a,b*}, Julien Némery^{a,b}, Nicolas Gratiot^{a,b}, Emilie Strady^{a,b}, Viet Quoc
Tran^b, An Truong Nguyen^b, Joanne Aimé^c, Alice Payne^b

^a Université Grenoble Alpes, CNRS, IRD, Grenoble INP*, IGE, F-38000 Grenoble,
France

*Institute of Engineering Univ. Grenoble Alpes

^b CARE, Ho Chi Minh City University of Technology, VNU-HCM, Viet Nam

^c IRD, Vietnam

*Corresponding author:

Tuyet T.N. Nguyen, Université Grenoble Alpes, CNRS, IRD, IGE, F-38000 Grenoble,
France (Email: ngoctuyet1412@gmail.com, tuyet.nguyen@univ-grenoble-alpes.fr)

Abstract

Saigon-Dongnai Rivers in Southern Vietnam is a complex lowland hydrological network of tributaries that is strongly influenced by the tidal cycles. The increasing economic, industrial and domestic developments in and around Ho Chi Minh City (HCMC) have led to serious impacts on water quality due to lack of appropriate wastewaters treatment. Drinking water production is impacted and the large aquaculture production areas may also be affected. We analyzed spatial and seasonal variability of nutrient concentrations (Phosphorus, Nitrogen and Silica) and eutrophication indicators (Organic Carbon,

Chlorophyll-*a* and Dissolved Oxygen) based on bi-monthly monitoring during two hydrological cycles (July 2015 – December 2017). Four monitoring sites were selected to assess the impact of HCMC: two upstream stations on the Saigon River and Dongnai River branches to provide the reference water quality status before reaching the urbanized area of HCMC; one monitoring station in the city center to highlight Saigon River water quality within the heart of the megacity; the fourth station downstream of the confluence to evaluate the impact of HCMC on the estuarine waters. This study points to excess nutrients in HCMC's water body with concentrations of NH_4^+ and PO_4^{3-} averaging to $0.7 \pm 0.6 \text{ mgN L}^{-1}$ and $0.07 \pm 0.06 \text{ mgP L}^{-1}$, respectively in mean over the monitored period and rising up to 3 mgN L^{-1} and 0.2 mgP L^{-1} , in extreme conditions. During the dry season, we evidenced that untreated domestic discharges leads to degradation of the Saigon River's water quality with extreme values of algal biomass (up $150 \mu\text{Chl-a L}^{-1}$) and hypoxic conditions occurring episodically ($\text{DO} < 2 \text{ mg L}^{-1}$) in the heart of the megacity. Until now, eutrophication in the urban center has had no clear effect downstream because eutrophic water mass from the Saigon River is efficiently mixed with the Dongnai River and sea water masses during the successive semi-diurnal tidal cycles.

Keywords: water quality, nutrients, megacity, eutrophication, tidal river.

1. Introduction

In the past few decades, eutrophication has become a significant issue for surface water bodies' worldwide (Hilton et al., 2006; Romero et al., 2013; Smith and Schindler, 2009; Smith et al., 1999). Eutrophication is an accelerated growth of algae caused by the enrichment of nutrients in an aquatic system, especially nitrogen (N) and phosphorus (P); which results in oxygen depletion in the water body through intense bacterial mineralization (Billen and Garnier, 1997; Nixon (2009); Volterra et al., 2002). Five decades ago, Redfield et al. (1963) proposed the Redfield stoichiometric ratio of carbon, nitrogen and phosphorus (C:N:P) as a generic tool to assess which is the limiting factor for primary production. The N:P ratio in an aquatic system is an important key which is used to verify which element will become the limiting factor to be controlled to reduce algal blooms. More recently, Billen and Garnier (2007) improved the concept to address the question of coastal waters. They showed that eutrophication is the consequence of unbalanced riverine nutrient inputs, with excess nitrogen and phosphorus with respect to silica (Si), when compared to the requirements for algal growth; stated to be C:Si:N:P = 106:15:16:1 (Brzezinski, 1985). The enrichment of riverine waters in N and P, together with decreasing suspended solids and Si, often result in eutrophication of coastal areas (Billen and Garnier, 1997; Conley et al., 1989; Howarth et al., 2011), characterized by non-diatom harmful algal blooms. The new production of non-siliceous algae can be facilitated by the imbalance between nutrient inputs.

62 Nutrients (N, P) generally originate from over fertilized agricultural soils through
63 leaching and erosion processes (Cloern et al., 2014; Lau and Lane, 2002; Singkran, 2017;
64 Trinh et al., 2015) or from untreated domestic and industrial wastewaters (Billen et al.,
65 2007; Cloern et al., 2014; Trinh et al., 2007). In industrialized European and North
66 American industrialized countries, wastewater treatment started in the 1970s in order to
67 reduce the point sources of N and P towards the hydrosystem (Van Drecht et al., 2009).
68 While the reduction of point sources pollution was shown to be efficient, diffuse inputs
69 remained a worrying source of nutrients for watersheds in these countries (Grizzetti et al.,
70 2013). The situation described for industrialized countries described above is very
71 different to that of emerging countries, especially for those located in the tropical regions,
72 such as Vietnam (Le et al., 2015). With the onset of the 21st century, the Southeast Asian
73 countries faced significant environmental challenges, such as quantitative shortages and
74 qualitative deterioration of water resources due to rapid industrialization, urbanization,
75 and agricultural intensification (Le, 2007; Vo, 2007). Indeed, sanitation network
76 development in large cities does not provide sufficient support to cover population
77 growth (Trinh et al., 2012). As a result, domestic wastewaters are released without
78 appropriate treatment into the receiving aquatic environments, causing high levels of
79 organic and nutrient pollution. In parallel with urban growth, changes in agricultural
80 practices have involved an increasing supply of fertilizers (Garnier et al., 2015). The
81 change in land-use have led to an increase of nutrient inputs to surface water and of the
82 flows to the outlets of major watersheds (e.g., the Mekong River). Moreover, high rainfall
83 intensity in the tropics leads to significant erosion rates and associated nutrient flows into

the rivers (Syvitski et al., 2014). The seasonality of precipitation, with marked alternation between the dry and wet seasons, influences the hydrological regime and promotes eutrophication during the dry season (Boulton et al., 2008).

The Saigon River is the second largest river after the Dongnai River in supplying water to Ho Chi Minh City (HCMC), the economic capital of Vietnam. Due to increasing urban sprawl in HCMC and neighboring provinces situated near the Saigon River basin, the water quality has significantly deteriorated (Nguyen et al., 2011; Strady et al., 2017; Tran Ngoc et al., 2016; Vo, 2007). Water supply demand from the Saigon River was estimated as 64 % (1.6 million m³ day⁻¹) for households in 2009 and will increase to 72 % (3.4 million m³ day⁻¹) according to future projections for 2025 (Nguyen et al., 2011). In addition, water from the Saigon River water is also used for irrigation, aquaculture and navigation.

The objectives of this study were to (i) characterize nutrients dynamics in the Saigon – Dongnai River system to evaluate the eutrophic status of water bodies and (ii) determine the controlling factors of eutrophication and the impact of HCMC on water quality downstream. We implemented a bi-monthly monitoring sampling strategy from July 2015 to December 2017 to determine and analyze physico-chemical parameters and nutrients (N, P and Si) in the dissolved and particulate phase.

2. Materials and methods

2.1. Study area

The Saigon River is a part of the Saigon – Dongnai River basin and located in Southern Vietnam. It is about 250 km long with a catchment area of 4,717 km² down to the

confluence with the Dongnai River (Figure 1a). Upstream of the Saigon River, the Dau Tieng reservoir (surface area of 270 km² and storage capacity of 1,580×10⁶ m³) was constructed in 1985 for irrigation, flood protection purposes and control of saline water intrusion (Trieu et al., 2014). The Saigon River is connected to urban canals when flowing through HCMC and then joins the Dongnai River to become the Nha Be River. It then continues its flow through Can Gio Mangrove to the East Sea. The flow direction of the Saigon River is strongly affected by the asymmetric semi-diurnal tides and the discharge is mainly controlled during the dry season by the amount of water released from the Dau Tieng reservoir.

The region falls in a tropical monsoon climate, with an average humidity of 78-82 % and a mean air temperature of 28.5 ± 1.0 °C. The year is divided into two distinct seasons (wet and dry). The wet season has an average rainfall of about 1,800 mm annually (about 150 rainy days year⁻¹), usually beginning in May and ending in November (Figure 1b). The dry season lasts from December to April.

Ho Chi Minh City is intrinsically linked with the Saigon River. The megacity's economy has developed considerably over the last ten years and HCMC is now considered the second most dynamic city in the world (World Economic Forum News, January 2017). HCMC resides on the banks of the Saigon River in a lowland floodplain area of the Saigon-Dongnai River basin and belongs to a transitional area between the South-eastern region of Vietnam and the Mekong Delta.

Land use in HCMC is dominated by agricultural activities in the north, urban settlement in the center and Can Gio Mangrove forest to the south. Can Gio forest is located - 40 km

southeast of HCMC and is recognized as a biosphere reserve by UNESCO. Agricultural land in HCMC was around 32 % in 2016, showing a decrease of 2 % in comparison to 2012 (data from HCMC Statistical Yearbook 2016).

The population of HCMC was 8.4 million inhabitants in 2016, which represents about 8.9 % of Vietnam's total population. This makes HCMC the largest and most densely populated city in the country (Figure 1c). The population of HCMC is mainly concentrated in the heart of the city (as presented in Figure 1) and 6.7 millions inhabitants live in the nineteen urban districts. The rural population was 1.5 millions in the three districts upstream of HCMC and only 230,000 in the two downstream districts. HCMC reached an urban population proportion of 88% in 2004, since then the population of HCMC and its boundary districts has increased rapidly (data from HCMC Statistical Year Book 2016).

Less than 10 % of the domestic waste water is collected and treated before being discharged directly into urban canals or rivers (Marcotullio, 2007). The main wastewater treatment plant (Binh Hung WWTP) is located south of the high population density urban area (Figure 1c). Its treatment capacity is 141,000 m³ day⁻¹ (426,000 inhabitants). Construction began in 2017 to reach a total capacity of 469 000 m³ day⁻¹ (1,390,000 inhabitants) and authorities have scheduled the building of ten new WWTPs within the next ten years (source: ATLAS Ho Chi Minh City).

Figure 1.

2.2. Monitoring and sampling strategy

A bi-monthly monitoring was undertaken at four sites from July 2015 to December 2017 in the Saigon – Dongnai River branches (Figure 1a). Two upstream stations on Saigon River (SG-up) and Dongnai River (DN-up), respectively, characterize the reference water status in the upstream of HCMC. One monitoring station in the city center (SG-city) aimed at highlighting the impact of the city. The last station was placed downstream of the confluence between the two rivers (Nha Be River – NBR) to assess the impact of HCMC on estuarine waters. Water sampling was taken at low tide for each field survey to consider the dominant fluvial flow from upstream to downstream and is illustrated in Figure 2.

Two complementary longitudinal profiles were carried out during the wet and dry seasons to understand the spatial fluctuation of water quality in the Saigon River. Total profile length was 50 km with 18 sampling points (Figure 1a). The profiles were conducted on-boat on 19th April 2017 from 8:00am to 4:30pm (dry season) and 20th October 2017 from 9:30am to 6:00pm, starting at Saigon upstream (SG-up – SG01) and ending at Saigon downstream (NBR – SG18) (Figure 1a). A GPS was used to mark longitude and latitude values of each point and to calculate the corresponding kilometric point (pK), in which $pK = 0$ was the confluence between the Saigon and Dongnai Rivers, with negative values upward and positive downward.

Figure 2.

For each sample, surface water (0-30cm below the surface) was taken by using a 2.5 L Niskin bottle in the middle of the river from either a bridge or a boat. Immediate measurements of physico-chemical parameters were realized using a multi-parameter

probe (WTW 3420[®]), e.g., temperature, pH, conductivity, salinity, and dissolved oxygen concentration and percentage of oxygen saturation. Each water sample was collected in a 5 L polypropylene recipient for Total Suspended Sediment (TSS), C, N, Si, and P measurements and Chlorophyll-*a* analysis.

2.3. Laboratory analyses

Samples were immediately filtered through a Whatman GF/F filter (porosity 0.7µm) at the Centre Asiatique de Recherche sur l'Eau (CARE) laboratory for analysis of dissolved nutrients. Unfiltered samples were kept to measure total nutrients. TSS was measured based on the different weight of a GF/F filter after 24 hours of drying at 50 °C. Chlorophyll-*a* and Phaeopigments were measured after filtration through a second Whatman GF/F filter using acetone (90 %) extraction method followed by a spectrophotometry measurement at 665 and 750 nm absorbance (Aminot and Krouel, 2004).

Unfiltered water samples were used to measure Total N and Total P using persulfate digestion procedure and standard colorimetric method (American Public Health Association: APHA, 1995). Dissolved nutrients were analyzed on filtered water samples using standard colorimetric methods (APHA, 1995). The NH_4^+ , NO_3^- , PO_4^{3-} and Dissolved Si (DSi) were analyzed by using respectively the Nessler reactive method, the cadmium reduction method, the acid ascorbic method and the silicomolybdate method, respectively. Reproducibility for replicate measurements was better than 5 % for all total and dissolved nutrients.

A TOC (Total Organic Carbon) analyzer apparatus (TOC-V Shimadzu, CARE laboratory, Vietnam) was used to determine Dissolved Organic Carbon (DOC) in filtered water samples with accuracy higher than 5 % (Sugimura and Suzuki, 1988). Particulate Organic Carbon (POC) was measured on suspended matter retained on a GF/F filter (ignited at 550 °C). The POC content (in % of dry weight) was measured by using combustion in a LECO CS-125 analyzer (Laboratory EPOC, Université de Bordeaux, France) with precision better than 5 % (Etcheber et al., 2007). The POC concentration is calculated as the product of POC % and TSS concentration and expressed in mgC L⁻¹.

2.4. Hydrological database

Water discharges data was provided by the Center of Environmental Monitoring (CEM) of the Department Of Natural Resources and Environment of HCMC (DONRE). This national monitoring program allows the measuring of monthly discharges at different locations within our study sites. Discharges are measured every hour during a 24-hour cycle because the hydrodynamic effect of the tide is perceptible up to the dams (Figure 1a). The residual discharge is then calculated as the difference between positive and negative discharges over the tide cycle. The residual discharge corresponds to the net positive water flow of the river from land to the sea. Data was collected for the 2012-2016 period in order to characterize the mean monthly distribution of the discharge at two locations in the Saigon River (SG-city) and in the Dongnai River (DN-up) (Figure 1a).

3. Results

3.1. Seasonal hydrological variability

Water discharge distribution is mainly controlled by precipitation seasonality (Figure 1b). The wet season shows a water discharge increase from June to October followed by a decrease at the end of November in both Saigon and Dongnai Rivers (Figure 3). The mean inter-annual discharge calculated over the 2012-2016 period for the Saigon River ($50 \pm 20 \text{ m}^3 \text{ s}^{-1}$) is twelve times lower than for the Dongnai River ($613 \pm 220 \text{ m}^3 \text{ s}^{-1}$). The Saigon River discharge can be artificially controlled during the dry season by releasing water from Dau Tieng reservoir to flush out salt intrusion. Trieu et al. (2014) suggest that water release regulation from the reservoir can be up to $30 \text{ m}^3 \text{ s}^{-1}$ during the dry season. This is in good agreement with the field data provided by DONRE.

Figure 3.

3.2. Interannual variations of the water quality in the Saigon River

3.2.1. Physico-chemical parameters

Water temperature in the Saigon and the Dongnai Rivers ranged between 27 to 33 °C, with low fluctuations. Mean value was $30.0 \pm 1.2 \text{ °C}$ at four stations. As shown in Figure 4a, pH increased from upstream to downstream in the Saigon River (6.3 ± 0.2 and 6.8 ± 0.3 at SG-up and NBR, respectively), while mean pH in DN-up was 7.0 ± 0.3 . For salinity, values were almost zero in SG-up and DN-up, whereas higher values and wider ranges of seasonal fluctuations were observed in SG-city and NBR (the highest value observed was 5.0 in SG-city and 8.7 in NBR during the 2016 dry season – Figure 4b). Dissolved oxygen (DO) fluctuated at the four stations without specific variability and reached its highest value at DN-up (7.96 mg L^{-1}) and the lowest value at SG-city (0.57 mg L^{-1}) (Figure 4c). Average DO concentrations were $6.1 \pm 0.6 \text{ mg L}^{-1}$, $2.5 \pm 0.9 \text{ mg L}^{-1}$,

1.7 ± 0.8 mg L⁻¹ and 3.6 ± 1.0 mg L⁻¹ at DN-up, SG-up, SG-city and NBR, respectively. The TSS concentrations evidenced seasonal variations at SG-up and DN-up, (Figure 4d) and reached their highest values during the wet season at SG-up and DN-up (140 mg L⁻¹ in DN-up and 184 mg L⁻¹ in SG-up during the wet season). However, the mean TSS value at SG-city (98.5 ± 56.7 mg L⁻¹) was higher than at the other stations (36.8 ± 26.4 mg L⁻¹, 67.3 ± 36.7 mg L⁻¹ and 33.1 ± 25.6 mg L⁻¹ at SG-up, NBR and DN-up, respectively).

Figure 4.

3.2.2. Dissolved and total nutrients

Total N reached its highest value at SG-city (3.4 ± 0.9 mgN L⁻¹) and lowest at DN-up (1.5 ± 0.4 mgN L⁻¹; Figure 5a). Total N tends to significantly increase from upstream (SG-up) to Saigon City Center (SG-city) before slightly decreasing downstream of Saigon (NBR). NO₃⁻ was lower than 2 mgN L⁻¹ in all samples (except one point in SG-city in July 2015), averaging 0.6 ± 0.3 mgN L⁻¹, 0.7 ± 0.5 mgN L⁻¹, 0.6 ± 0.3 mgN L⁻¹ and 0.5 ± 0.2 mgN L⁻¹ for SG-up, SG-city, NBR, and DN-up, respectively. NO₃⁻ concentrations at DN-up fluctuated slightly with no evident seasonality. At SG-city, NO₃⁻ presented much more fluctuation from 0.0 to 2.4 mgN L⁻¹ (Figure 5b). NH₄⁺ was low at DN-up (< 0.5 mgN L⁻¹), but reached peak value up to over 3 mgN L⁻¹ (Figure 5c) at SG-city. Average NH₄⁺ was 0.3 ± 0.2 mgN L⁻¹, 0.8 ± 0.6 mgN L⁻¹, 0.1 ± 0.1 mgN L⁻¹ and 0.1 ± 0.1 mgN L⁻¹ at SG-up, SG-city, NBR and DN-up, respectively.

Figure 5.

Total P and PO_4^{3-} did not present specific seasonal variations. Total P was dramatically high in SG-city, $0.3 \pm 0.2 \text{ mgP L}^{-1}$ on average and up to 0.8 mgP L^{-1} for peak values (Figure 5d). Average Total P was $0.2 \pm 0.1 \text{ mgP L}^{-1}$, $0.1 \pm 0.1 \text{ mgP L}^{-1}$ and $0.1 \pm 0.1 \text{ mgP L}^{-1}$ in SG-up, NBR and DN-up, respectively. The PO_4^{3-} concentration (Figure 5e) was low in DN-up (experienced at $0.04 \pm 0.02 \text{ mgP L}^{-1}$ on average). Mean PO_4^{3-} value was $0.04 \pm 0.03 \text{ mgP L}^{-1}$, $0.07 \pm 0.06 \text{ mgP L}^{-1}$ and $0.03 \pm 0.02 \text{ mgP L}^{-1}$ in SG-up and NBR, respectively.

A seasonal DSi concentration fluctuation was observed at the four sites from 6 to 8 mgSi L^{-1} during the wet season down to values below 1 mgSi L^{-1} during the dry season. Average DSi concentrations were $2.6 \pm 2.1 \text{ mgSi L}^{-1}$, $1.7 \pm 1.8 \text{ mgSi L}^{-1}$, $1.8 \pm 1.8 \text{ mgSi L}^{-1}$ and $2.0 \pm 1.8 \text{ mgSi L}^{-1}$ at DN-up, SG-up, SG-city and NBR, respectively (Figure 5f).

3.2.3. Organic carbon, chlorophyll-a, and phaeopigments

The DOC concentrations were $2.4 \pm 0.7 \text{ mg L}^{-1}$, $2.5 \pm 1.9 \text{ mg L}^{-1}$, $3.6 \pm 1.1 \text{ mg L}^{-1}$ and $3.8 \pm 0.7 \text{ mg L}^{-1}$ on average at DN-up, SG-up, SG-city and NBR, respectively (Figure 6a). As compared with other parameters measured during this study, DOC concentrations were remarkably stable at the four sites during the observation period, except in March 2017 with a peak of DOC observed in SG-up and DN-up. POC reached its highest value at SG-city, with an average of $4.3 \pm 1.6 \text{ mg L}^{-1}$ and lowest value at the other sites, making up $1.3 \pm 0.5 \text{ mg L}^{-1}$, 1.7 ± 0.8 and 1.6 ± 1.0 on average at DN-up, SG-up and NBR, respectively (Figure 6b).

Figure 6.

Chl-*a* concentrations varied from 0.01 $\mu\text{g L}^{-1}$ to 147 $\mu\text{g L}^{-1}$ at SG-city (Figure 6c). Chl-*a* and phaeopigments exhibited contrasted variability both spatially and seasonally for the whole survey period. The mean value of pigments at SG-city ($29.6 \pm 32.4 \mu\text{g Chl-}a \text{ L}^{-1}$ and $19.5 \pm 16.7 \mu\text{g phaeopigments L}^{-1}$, respectively) was higher than at DN-up ($4.7 \pm 3.8 \mu\text{g Chl-}a \text{ L}^{-1}$ and $5.7 \pm 5.3 \mu\text{g phaeopigments L}^{-1}$), SG-up ($3.2 \pm 5.5 \mu\text{g Chl-}a \text{ L}^{-1}$ and $4.9 \pm 4.8 \mu\text{g phaeopigments L}^{-1}$) and NBR ($1.6 \pm 1.1 \mu\text{g Chl-}a \text{ L}^{-1}$ and $2.6 \pm 1.7 \mu\text{g phaeopigments L}^{-1}$).

3.3. Longitudinal profile in the Saigon River

The longitudinal profile was divided into three sections (i.e., was defined according to population density distribution) to assess the impact of urbanization on the Saigon River water quality: (i) the upstream section was from Phu Cuong Bridge (SG01) to Thanh Da canal (SG06), (ii) the middle section was representative of the high urban system extending from Thanh Da canal (SG07) to Bach Dang Harbor (SG11) and (iii) the downstream section was from Bach Dang Harbor (SG12) to Binh Khanh Ferry (SG18). The Saigon River water quality changed considerably between the profiles realized during the dry and wet seasons (Figure 7). The pH increased gradually from land to the ocean (with more acid water during the wet season from 5.8 to 6.2) than during the dry season (6.3 to 7.2) (Figure 7). DO values varied between moderate to severe hypoxic conditions (as low as 0.5 mg L^{-1} in the upstream section and rose up to 4.7 mg L^{-1} in the downstream section). During the wet season, DO increased rapidly from extremely low concentrations at upstream of HCMC (SG01 to SG06 during the wet season with DO values below 2 mg L^{-1}) to high values after City Center (point SG13, with DO values

above 4 mg L⁻¹). Saline water intrusion during the dry season was observed up to about 40 km from the confluence between the two rivers. Salinity was nearly 0 during the wet season in the three sections. The magnitude of TSS fluctuations was higher during the wet season with a peak of 71.5 mg L⁻¹ at SG03, a minimum of 17.6 mg L⁻¹ at SG09 and a new maximum downstream with a value of 78.6 mg L⁻¹ at SG17.

While Total N and NO₃⁻ concentrations were stable from the upstream to downstream sections, NH₄⁺ tended to increase in the middle section during the wet season. Total P concentrations were high in the upstream and middle section before decreasing in the downstream section, especially during the dry season. The PO₄³⁻ concentrations fluctuated from the upstream to downstream sections during both seasons. The DOC, POC, Chl-*a* and phaeopigments varied in the same range. Chl-*a* content was stable and lower than 2 µg L⁻¹ for Chl-*a* and 5 µg L⁻¹ for phaeopigments during the wet season, while Chl-*a* and phaeopigments concentrations reached their highest values at the transition between upstream and middle sections during the dry season (110.3 µg Chl-*a* L⁻¹ at SG06 and 72.2 µg phaeopigments L⁻¹ at SG07). DSi values were rather low in the upstream section (1mg DSi L⁻¹) but increased locally to 2 mg DSi L⁻¹ in the middle (dry season) or downstream sections (wet season).

Figure 7.

3.4. Nutrients ratios

We have assembled a data set of dissolved nutrients (N, P and Si) concentrations at the four sampling sites in the Saigon and Dongnai Rivers. These dissolved nutrient concentrations were used to calculate the Redfield ratio (N:P:Si ratios). When the graph

was plotted according to the Si:N and Si:P ratios, the theoretical lines represented a theoretical nutrients ratio and the graph was separated into four areas (Figure 8). Each area represented, respectively, from the lower right quadrant counter-clockwise: an area with N in limiting amounts and Si in excess; an area with N in limiting amounts and Si deficiency; an area with P in limiting amounts and Si deficiency; and an area with P in limiting amounts and Si in excess (Billen and Garnier, 2007). Figure 8 showed that the four sampling sites in the Saigon – Dongnai River system were distributed in overlapping clusters. From bi-monthly monitoring, we can observed that the Saigon – Dongnai River system was characterized by a N:P ratio above the Redfield value and by a substantial excess of Si over both P and N. Additionally, the molar Si:P ratio was higher than 15 and reached the maximum value of 200 (Figure 8), indicating that Si still exceeded diatom growth requirement, and could therefore limit the development of non-diatoms algae in this environment.

Figure 8.

4. Discussion

4.1. Level of nutrients contamination

The level of nutrients measured in the Saigon and Dongnai Rivers was compared to the European standard of water quality (Water Framework Directive, 2000). The European standard of water quality has five surface water quality assessment categories (high, good, moderate, bad and very bad status). Vietnamese water quality regulation (QCVN08, 2015) is not complete enough for nutrient assessment and only provide water

quality legislation for industrial and domestic usage, but this standard does not include the general health of the ecosystem.

Nitrogen. In the whole Saigon and Dongnai basin, NO_3^- concentration was lower than 2.5 mgN L^{-1} , which is equivalent to good (0.5-2.5 mg. L^{-1}) and high status ($< 0.5 \text{ mgN L}^{-1}$) (WFD, 2000). The NH_4^+ concentration was around 0.1 mgN L^{-1} (good status $< 0.4 \text{ mgN L}^{-1}$, WFD 2000) at upstream Dongnai River (DN-up) and downstream Saigon River (NBR). This was not the case for Saigon City Center (SG-City), as it is affected by urban wastewater discharge, NH_4^+ concentration being on average 0.7 mgN L^{-1} and rising up to 3 mgN L^{-1} (moderate, 0.4-1.6 mgN L^{-1} to bad status, 1.6-3.9 mg L^{-1} , WFD 2000). The Saigon River was then highly polluted by ammonium in the dense urban area but less by nitrates, which indicates low emissions from agricultural practices (Grizzetti et al., 2012).

Concentrations of NO_3^- and NH_4^+ in the Saigon River were not only higher than in the very polluted urban Nhue River in Hanoi, Northern Vietnam: 0.0-0.1 $\text{mgN-NO}_3^- \text{ L}^{-1}$ and 0.02-0.15 $\text{mgN-NH}_4^+ \text{ L}^{-1}$ (Trinh et al., 2015) but also than in other major tropical rivers, such as the Lower Mekong River (Vietnam): $0.15 \pm 0.05 \text{ mgN-NO}_3^- \text{ L}^{-1}$ and $0.03 \pm 0.03 \text{ mgN-NH}_4^+ \text{ L}^{-1}$ (Li and Bush, 2015), the Senegal River (Senegal): 0.042-0.17 $\text{mgN-NO}_3^- \text{ L}^{-1}$ and 0.005-0.03 $\text{mgN-NH}_4^+ \text{ L}^{-1}$ (Mamadou et al., 2016), Chap Phraya River (Thailand): 1.3 mgN L^{-1} and 0.08 mgP L^{-1} (Jens et al., 2001) and the Yangtze River (China): 0.019-0.027 $\text{mgN-NO}_3^- \text{ L}^{-1}$ and 0.003-0.005 $\text{mgN-NH}_4^+ \text{ L}^{-1}$ (Liu et al., 2016). Land use in boundary areas of HCMC is dominated by agriculture, while the upstream parts of both the Saigon and Dongnai Rivers are more populated compared to

downstream of HCMC; the heart of HCMC being the most densely populated (Figure 1c). NO_3^- originates principally from the leaching of agricultural soils (Billen et al., 2010). However, in rivers influenced by urban wastewater discharges, it can originate from the ammonium nitrification process (Garnier et al., 2007; Herbert, 1999; Xia et al., 2009). In HCMC, due to the lack of wastewater treatment plants, most of the untreated domestic waste water is discharged directly into the three main urban canals connected to the Saigon River (Figure 1c). Therefore, the untreated domestic waste water becomes the principal source of NH_4^+ .

Indeed, NH_4^+ is a good indicator of domestic pollution among all nitrogen forms. NH_4^+ concentrations increased considerably in Saigon City Center evidencing pollution by effluents from HCMC and its suburbs (Figure 7). At the Saigon – Dongnai River confluence, NH_4^+ concentrations returned close to the values observed in upstream Dongnai River showing the spatially limited NH_4^+ pollution of HCMC on its river further downstream. NO_3^- concentrations also decreased at the confluence and we hypothesized that they (NH_4^+ and NO_3^-) played a major role in the stimulation of primary production by phytoplankton in the Saigon River aquatic system (Dugdale and Goering, 1967).

Phosphorus and silica. PO_4^{3-} concentrations ranged from 0.05 up to 0.2 mgP L⁻¹ in Saigon City Center (SG-city) corresponding to good-to-moderate status (WFD, 2000) but Total P concentrations were much critical up to 0.96 mgP L⁻¹ (bad status, WFD, 2000). In the other upstream locations (SG-up) and downstream (NBR) of the Saigon River and upstream of the Dongnai River (DN-up), PO_4^{3-} concentrations were lower than 0.1 mgP L⁻¹ (good status, WFD, 2000) and Total P concentrations were lower than 0.4 mgP L⁻¹

(good to moderate status, WFD, 2000). These results indicated a high level of phosphorus within the city center, especially Total P. The proportion of particulate P in Total P was high (mean of 78 ± 6 % in mean) indicating a strong interaction with suspended sediments. PO_4^{3-} concentrations in the Saigon River were higher than in other rivers, e.g., the Lower Mekong River (Vietnam): 0.02 ± 0.04 mgP L⁻¹ (Li and Bush, 2015) and the Senegal River (Senegal): 0.003-0.013 mgP L⁻¹ (Mamadou et al., 2016). Moreover, we observed that DSi fluctuated between four sampling sites during the 2015-2017 period. The sources of DSi were mainly from diffuse origins (e.g., weathering and erosion of natural rocks) or from point sources (e.g., urban runoff, domestic and industrial waste waters) (Sferratore et al., 2006). Particulate silica can then be dissolved to become a source of DSi, which could explain the fluctuation of DSi observed at the four sampling sites.

Due to the very poor sanitation in HCMC, Total P inputs are mainly from industrial and domestic sources, so that the Total P load in the Saigon – Dongnai River is rather constant over the year. Less than 10% of domestic effluents and less than 50 % of industrial effluents are treated before being discharged directly into the river (Marcotullio, 2007). The theoretical domestic P concentration can be estimated at 30 mgP L⁻¹ from the equivalent per capita (4 gP inhab.⁻¹ day⁻¹ and 150 L inhab.⁻¹ day⁻¹; Lam et al., 2008 and Ministry of Construction, 1998) and total wastewater flux at about 10 m³ s⁻¹ (considering the total unconnected urban population at 6 million inhabitants, i.e., 90% of the 6.7 million inhabitants living in urban districts). Untreated wastewaters would contribute to about 20 % of mean annual discharge of the Saigon River (50 m³ s⁻¹) and

untreated wastewaters P concentrations would be 100 times higher than P concentrations measured in the Saigon River (mean of 0.3 mgP L⁻¹ in mean). Domestic inputs are then constant over the time regardless of the season and could maintain P concentrations at a high level within the Saigon River.

During the wet season, the river flow was higher than during the dry season (Figure 3); P input was diluted by rainfall and there was a P depletion with regards to Si. During the dry season, most of the Saigon River water discharge comes from the Dau Tieng reservoir, modifying the nutrients balance. Despite inputs being less diluted during the dry season, the decrease of PO₄³⁻ concentrations, especially effective at this time can be due to algal growth (Causse et al., 2015). In addition, the canal system in HCMC is the main drain for untreated effluents from the urban catchment area so that P can be stored within the sediments. Urban areas include houses, roads, and other public areas, are regularly flooded with a mix of storm water and wastewater leading to the sediments being flushed out by the overflow under rainy conditions (Tran Ngoc et al, 2016). Indeed, high levels of PO₄³⁻ in water and Particulate P in sediment were observed in urban canals in HCMC (Strady et al., 2017) indicating an intense adsorption process of dissolved P onto sediment. This accumulation in the sediment was evidenced in the urban canals of Bangkok (Thailand), which presents similar geography, demography and wastewaters management to HCMC (Færge et al, 2001).

Nutrients proportions. We observed from bi-monthly monitoring data that the dissolved inorganic nitrogen proportion (%DIN) at four sampling sites fluctuated slightly from 38 ± 24 % at NBR to 49 ± 22 % at SG-up during the 2015-2017 period. Whilst PO₄³⁻

proportion was lowest at SG-city (32 ± 27 %), Dongnai River experienced the highest proportion (49 ± 31 % at DN-up). The change in proportion of primary nutrients (N, P and Si) can lead to a change in the Redfield ratio N:P:Si, affecting the risk of eutrophication in aquatic systems. In turn, phytoplankton uptake affects nutrient concentrations (Redfield, 1958 and many others since then); furthermore, the increased anthropogenic nutrient inputs necessarily change the proportion of nutrients for phytoplankton growth (Turner and Rabalais, 1991). It means that the feedback effect between nutrients and phytoplankton uptake, can control phytoplankton dynamics (e.g., dominant species, successions from diatoms to non-diatoms).

The seasonal variability of water quality in the Saigon River was explored from the bi-monthly monitoring. Seasonality is of most important in terms of the eutrophication problem because phytoplankton development is naturally controlled by factors that follow seasonal cycles (Le et al., 2015). Surprisingly, there was no clear seasonality of all observed parameters. The relation between water discharge and nutrient variation is not relevant in this system as the discharge is controlled by the tide and water release from Dau Tieng reservoir (Trieu et al 2014). The parameters monitored and presented in Figures 4 to 6 showed that the salinity was by far the one that exhibits the strongest seasonality. We can actually clearly distinguish the two peaks during the 2016 and 2017 dry seasons, but we can also clearly see that their magnitudes are very different. Based on statistical analyses, we observed that some nutrients fluctuated seasonally (p-value < 0.05), e.g., NO_3^- (p-value = 0.015) and NH_4^+ (p-value = 0.04) in SG-up; Total P (p-value = 0.026) in DN-up or NO_3^- (p-value = 0.049) in SG-city. Other nutrients such PO_4^{3-} did

not vary seasonally with $p\text{-value} > 0.05$, especially in SG-city. Therefore there is no evidence of hydrological seasonality to explain the variability of most of the nutrient concentrations.

Concerning the spatial fluctuation of nutrients in the Saigon River, our results clearly showed the impact of HCMC on nutrient concentrations, which is presented by an increase of Total N, NH_4^+ , Total P and PO_4^{3-} (Figure 7).

4.2. Eutrophication status and limiting factors

According to the eutrophication classes proposed by Dodds et al. (1998) and Dodds and Welch (2000), we classified the water quality of the Saigon and Dongnai River branches upstream and downstream of the City Center as mesotrophic, and being clearly eutrophic in the SG-city site (Table 1). To identify the principal limiting factor of algal blooms in the system, we used the N:P molar ratio presented in Figure 8. A molar ratio of N:P lower than 16 indicates that P is the limiting factor for algal growth, while a ratio higher than 16 shows that N is the key element. When observation that the molar N:P ratio is higher than 16:1 in the Saigon – Dongnai River system, P is indicated as the limiting factor. More precisely, the molar N:P ratio in the Saigon River ($\text{N:P} = 69.7 \pm 44.8$ on average) was higher than that of the Dongnai River ($\text{N:P} = 45.5 \pm 22.9$ on average). In May 2017, the N:P ratio peaked at 258, showing that N was largely in excess in comparison to P. It would seem that in order to reduce eutrophication in the Saigon River, the control of the key element P is necessary.

Table 1.

The relationship between POC and Chl-*a* was analyzed at the four sampling sites to verify the origin of organic carbon. This relationship observed with $R^2 < 20\%$ indicates that the main composition of organic carbon in the Saigon River is not phytoplankton. Furthermore, POC/Chl-*a* weight-to-weight ratio values were calculated for each site and were all higher than 200 (e.g., 1573 ± 1600 , 517 ± 770 , 1564 ± 1620 and 524 ± 620 at SG-up, SG-city, NBR and DN-up, respectively), characterizing a detrital or degraded material (Cifuentes et al., 1988). This means that the origin of the organic matter within the river was principally allochthonous and likely from untreated wastewaters. Moreover, the average C:N ratios calculated at the four sampling sites were all lower than 12 (3.0 ± 2.5 , 4.5 ± 4.7 , 2.6 ± 3.2 and 2.8 ± 4.5 at SG-up, SG-city, NBR and DN-up, respectively). These findings supported the assumption of allochthonous organic matter inputs from wastewaters (Hedges et al., 1986; Hedges and Oades, 1997; Balakrishna and Probst, 2005; Zafirah et al., 2017). Nevertheless, values of POC/Chl-*a* ratio decreased in SG-city where algal development is maximum. It indicated that in this part of the river, the proportion of autochthonous organic matter is increasing due to eutrophication.

4.3. Impact of HCMC on the water quality of the Saigon River

Since the early 1990's, HCMC has been experiencing an economic boom (Du and Fukushima, 2010; Vo, 2007). This growth has been accompanied with a rapid urbanization, the urban surface area has indeed quintupled between 1990 and 2012; with about 660 km² of surface becoming urbanized during that period (Kongtis et al., 2014). Since the study of Gurby et al. (2002), urbanization has continued to expand along the Saigon River (North and South), with a population density that can exceed 30,000

inhabitants per km² (see Figure 1c). This economic and demographic evolution has created new challenges for the city in terms of water quality management (Vo, 2007). Policy makers are now being forced to find new solutions to reduce pollution and restore the aquatic ecosystem of the Saigon River.

The monitoring conducted at our four stations for more than two hydrological years underlines a critical eutrophication observed each year at SG-city. The three episodes of eutrophication observed during our survey lasted several weeks, but were not easily correlated with dry or wet hydrological seasons; even if the highest peak of eutrophication was observed in the middle of the dry season in January 2017 (Chl-*a* > 150 µg L⁻¹, Figure 6c).

Figure 9 proposes a synthetic view of population distribution along the Saigon River and the level of the trophic status in order to highlight the connections between urbanization and eutrophication. The snapshot presented in Figure 9a shows a rapid deterioration of water quality, from oligotrophic waters in the upper 5-10 km of monitoring (pK-55 to pK -48) to mesotrophic (pK-48 to pK-40) and eutrophic waters downstream (pK -40 to pK -12). The water quality is then restored quite rapidly and recovers an oligotrophic status around pK-10, i.e., ten kilometers before the confluence of Saigon and Dongnai Rivers.

Figure 9.

For the upper stretch of the river (from pK-55 to pK-10), Figure 9 shows a good match between the increase in eutrophication and the density of inhabitants, which demonstrates the direct effect of untreated urban wastewater release on river quality. The restoration of water quality beyond pK-10 can appear surprising, but it is supported by two

assumptions: first, the restoration of water quality can be attributed (at least partially) to the positive effect of the Binh Hung wastewater treatment plant, which collects and treats a part of the wastewaters from the south of the City Center (district 5, district 7); second, water quality improvement is more likely due to the dilution of polluted water from the Saigon River as it mixes with seawater and the Dongnai River waters. The water quality monitored at station NBR indeed presented a good water quality status ($\text{Chl-}a < 10 \mu\text{g L}^{-1}$) throughout the 30 months of monitoring. During the dry season, this water body mixes daily with the Saigon River and progressively diffuses upstream. This is demonstrated by the saline intrusion observed at SG-city station in Figure 4b.

Furthermore, during the dry season survey (19th April 2017), the DO level was high due to photosynthesis processes by a high level of phytoplankton, reaching its highest value at $110 \mu\text{g Chl-}a \text{ L}^{-1}$. During the wet season, the upstream and middle sections of the Saigon River were deoxygenated ($\text{DO} < 2 \text{ mg L}^{-1}$, see Figure 7) because of oxygen consumption by biological activities (not only degradation of organic matter but also nitrification). At these locations, the water body contains large amounts of organic matter which is quantified by high DOC and POC concentrations (making up above 3 mgC L^{-1}) and NH_4^+ concentrations higher than 0.2 mgN L^{-1} (cf. Figure 7).

In addition to the high level of NH_4^+ in the middle section, NO_3^- was also low in this area (Figure 7). There was a slight decrease in NH_4^+ concentrations during the dry season from upstream to downstream of HCMC, while there was a drastic increase in NH_4^+ levels at the City Center during the wet season due to the discharge of untreated domestic waste water from urban zones. By contrast, NO_3^- concentration increased at the City

Center during the wet season, whereas their values decreased during the dry season (Figure 7). During the dry season, NH_4^+ slightly decreased at the same time as NO_3^- indicating a dilution by the Dongnai River or seawaters. On the contrary, during the wet season, there was a strong nitrification process with a rapid decrease of NH_4^+ at City Center occurring at the same time as an increase in NO_3^- (Figure 7). The nitrification process was likely initiated with the input of oxic waters up to pK -10 (Figure 7). The result highlights the potential capacity of the estuary to metabolize the pollution emitted by HCMC (Flemer, 2006).

In general, anthropogenic activities (e.g., agricultural and industrial activities, poor domestic wastewater treatment) have led to eutrophication of water bodies with an expected impact on water quality and drinking water production. To deal with these problems, wastewater planning and management is needed. It is critical that wastewater management becomes a fundamental part of urban planning and watershed management. HCMC authorities have already planned to build ten new WWTPs able to treat most of the domestic waters in the next ten years (Tran Ngoc et al., 2016). HCMC must also urgently incorporate principles of ecosystem management from the watershed into the coastal ocean. The natural ecosystem can be used to provide water more sustainably; with this in mind, wetland management is an essential option to sustain the water cycle and hence, to decrease nutrient and organic pollution (Gupta et al., 2016).

5. Conclusions

Our two-and-a-half year survey of water quality was the first time to evaluate global nutrient levels in the Saigon – Dongnai Rivers. As outlined above, the values observed in

the upstream of HCMC were close to those observed in the downstream of HCMC, which showed the low anthropogenic impact in the more rural areas. We did not take into account nutrient input from diffuse sources (e.g., agricultural activities) due to lack of data. However, we assumed that nutrient input from diffuse sources is of second order in comparison to high nutrient input from point sources in the urban areas of HCMC. Indeed water in the heart of HCMC was polluted and exhibited high nutrient concentrations (especially phosphorus) due to untreated effluents from residential and industrial areas. The Saigon River experienced extreme eutrophication episodes. We can therefore conclude that there are numerous problems and challenges with regards to water quality management in HCMC. The question we need to ask is how to revise, improve and implement the current legal system regarding the water sector in general, and wastewater management in particular. Appropriate quantification of the eutrophication status is a first step in which scientists and policy makers need to work together using operational modelling tools to move from observation to mitigation. We need to understand how water quality in downstream of HCMC is recovered. This should be further investigated when looking at dilution between the Saigon River, the Dongnai River and seawater within the whole salinity gradient down to the coastal area. A modelling approach of the hydrodynamics and biogeochemistry of the estuary is currently conducted to identify the predominance of each of the internal biogeochemical processes.

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Figure 1. (a) Map of Saigon – Dongnai Rivers and location of sampling sites, (b) distribution of monthly rainfall and temperature from 2011 to 2016, (c) population density distribution in Ho Chi Minh City (source: HCMC Statistical Year Book 2016).

Figure 2. Water level during (a) the dry season (April 2017) and (b) the wet season (October 2017) at HCMC (source: tide4fishing.com; black points indicate bi-monthly monitoring and black lines correspond to the time period during which longitudinal profiles were carried out).

Figure 3. Distribution of mean monthly discharges (period 2012-2016) in the Saigon and Dongnai Rivers (data source: DONRE; see Figure 1a for the location).

Figure 4. Seasonal variations of (a) pH, (b) salinity, (c) DO and (d) TSS at the four stations during the period from July 2015 to December 2017. Gray color represents the dry season, which lasts from December to April and white color is the wet season from May to November.

Figure 5. Seasonal variations of (a) Total N, (b) NO_3^- , (c) NH_4^+ , (d) Total P, (e) PO_4^{3-} and (f) DSi measured at the four sites from July 2015 to December 2017.

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816 **Figure 6.** Seasonal variations of a) DOC, b) POC, c) Chl-a and d) phaeopigments
817 measured at the four sites from July 2015 to December 2017 (MD is missing data).

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819 **Figure 7.** Longitudinal profile in the Saigon River during dry season (19th April 2017)
820 and wet season (20th October 2017); from top to bottom and from left to right: pH,
821 DO, salinity, Total N, NO₃⁻, NH₄⁺, Total P, PO₄³⁻, DSi, TSS, DOC, POC, Chl-a
822 and Phaeopigments. Last panel represents the longitudinal profile divided into
823 three sections.

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825 **Figure 8.** Molar ratios of Si:N and Si:P (log scale) at four sampling sites in Saigon –
826 Dongnai River system from July 2015 to December 2017.

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828 **Figure 9.** Seasonal variations of the trophic status of the Saigon River with population
829 density. (a) Snapshot of the eutrophic level during the dry season (19th of April
830 2017); spatial distribution of population density (see also Figure 1c). The patch of
831 Chl-a presented in Figure 9a is corrected from the upstream-downstream
832 oscillation of water masses with tides. Depending on tidal level, water masses can
833 oscillate with an amplitude of 6 km around their mean locations during spring

tides and (b) Intercomparison of snapshot trophic situations for dry (black solid line) and wet (grey dashed line) seasons.

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865 (f) DSi measured at the four sites from July 2015 to December 2017.

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899 **Table 1.** Classification of trophic levels of rivers and assessment of levels for the four
900 sampling sites in the Saigon – Dongnai Rivers.

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902 Table 1. Classification of trophic levels of rivers and assessment of levels for the four
 903 sampling sites in the Saigon – Dongnai Rivers.

Site	DO (mg L ⁻¹)	Total N (mg L ⁻¹)	Total P (mg L ⁻¹)	Chl-a (µg L ⁻¹)	Trophic status classification
According to Dodds et al., 1998 and Dodds and Welch, 2000					
	>5	<0.7	<0.025	<10	Oligotrophic
	1-5	0.7-1.5	0.025-0.075	10-30	Mesotrophic
	0-1	>1.5	>0.075	>30	Eutrophic
Classification of trophic levels of four sampling sites in Saigon – Dongnai Rivers					
SG-up	2.5	1.8	0.15	3.2	Mesotrophic
SG-city	1.7	3.4	0.30	29.6	Eutrophic
NBR	3.6	2.2	0.12	1.6	Mesotrophic
DN-up	6.1	1.5	0.09	4.7	Oligotrophic

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