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KEYWORDS

Saigon River system, C-GEM modelling, nutrients cycling, water quality, scenarios

ABBREVIATIONS

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ABSTRACT

In a context of densification of urban centers and climate change, coastal megacities in emerging countries have to face new issues about water management. With more than 9 million inhabitants, Ho Chi Minh City (HCMC), the economic capital of Vietnam, is in full demographic and economic expansion. The city does not have water treatment networks that meet the urgent needs. Indeed, in 2020, less than 15% of the population is connected to a sewerage network and treatment plant. The deterioration of water quality of Saigon River crossing the city is dramatic. Ho Chi Minh City authorities therefore plan to build new sanitation networks and ten wastewater treatment plants (WWTPs) over the next fifteen years, drawing inspiration from the centralized water management models of industrialized countries. However, the question arises of the relevance of this extremely expensive choice and not necessarily adapted to the particular conditions of this megacity in tropical monsoon zone and under the influence of tidal cycles. Using the estuarine biogeochemical model (C-GEM), this study aims at assessing the water quality of the Saigon River (oxygen depletion, nutrients concentration) in response to three scenarios of HCMC development (population growth and new water management infrastructures). In addition, projected new climatic conditions (temperature, hydrology) will be considered. The results of three scenarios show that the construction of new WWTPs is relevant. However, the rapid population growth in HCMC will make improvements support by WWTPs not sufficient to turn the water quality in Saigon River from a state of bad quality to good as expected.

1 INTRODUCTION

Accounting for more than 10% of the world's population, megacities have been attracting people and increasing population densities themselves. Notably, 67% of the megacities are distributed along estuaries and coastal areas which are known to provide numerous ecosystem services for the development of the surrounded region (Von Glasow *et al.*, 2013). In addition, estuaries are also considered to have high self-purification capacity, especially the ability to transform or remove pollutants from urban discharge (Wilk, Orlinska-Wozniak and Gebala, 2018). However, the rapid population growth coupled with the lack of investment in water environmental protection in the megacities of the developing countries threaten the safety of water resources (Kumar, 2019). In the 21st century, water pollution from megacities is well known in the Southeast Asia countries (Tran Ngoc *et al.*, 2016; Kumar, 2019). Facing the threat of water safety, these megacities have been implementing environmental rehabilitation projects, in particular the construction of municipal wastewater treatment plants (WWTPs) (Sajor and Thu, 2009; Tran Ngoc *et al.*, 2016).

Located in the most rapid urbanization area of Vietnam, Saigon River Estuary (Southern Vietnam) has been affected by urban wastewater from Ho Chi Minh City (HCMC) for many years. Canals in HCMC and the Saigon River received about 90% of untreated domestic wastewater in 2016 (Nguyen *et al.*, 2020). The high polluted loads regularly lead to excess of nutrients and intense period of anoxia in Saigon River, especially during the dry season in Saigon River (Nguyen *et al.*, 2019). Water pollution also threatens water production for the region. Over 90% of the water supply used in HCMC is taken from two raw water collection stations on the Saigon River and Dongnai River (Tran Ngoc *et al.*, 2016) (Figure 1). Under the impact of tides from the East Sea of Vietnam, some water production stations sometimes have to shut down because of the intrusion of polluted water from the inner city of HCMC as well as saline intrusion in Saigon River. Therefore, most of the water supplied to HCMC comes from the Dongnai River, as the water quality here is rated better than the Saigon River. The risk of estuarine pollution in Saigon River is expected to increase in the coming years, under the impact of megacity's development. Following the actual trend, the population of HCMC is expected to reach 23 million by 2050, and the Saigon River will then receive three times more pollution (Nguyen *et al.*, 2020). In response to the current and future major sources of urban wastewater, the HCMC is implementing an ambitious environmental sanitation project for the urban canals and Saigon River, i.e. more than eight WWTPs to treat about 80% of domestic wastewater in HCMC by 2025. However, because of the huge cost of the project (about 2 billion USD), seven WWTPs are still in stage of calling for capital investments. In this context of extremely rapid changes in pollutant loadings to the Saigon River-Estuary system, the use of models capable of describing the biogeochemical functioning of aquatic ecosystems and simulating the potential impact of improved urban water treatment is crucial.

The Carbon Generic Estuarine Model (C-GEM) is a generic one-dimensional, reactive-transport model which takes advantage of the relationship between estuarine geometry and hydrodynamics to minimize data requirements (Volta *et al.*, 2014). Steady-state simulations performed using C-GEM have provided accurate descriptions of estuarine hydrodynamics and biogeochemical transformations in several estuaries, especial in temperate region (Volta *et al.*, 2014, 2016; Laruelle *et al.*, 2017, 2019). The advantage of this model is the use of a minimal set of input data, but still guaranteed to simulate the biogeochemical processes occurring in an estuary system. The model allows the assessment of the estuary response to the simultaneous effects of point sources (e.g. domestic, industrial wastewater) and the effects of the estuary tidal regime (Volta *et al.*, 2014). The use if this modelling approach is particularly relevant to the urban estuary of developing countries where there is limiting extensive monitoring program.

This study aims evaluating the water quality in Saigon River Estuary under the impact of urban wastewater from HCMC's development by C-GEM application. The research results allow to evaluate the efficiency of the construction of WWTPs according to the direction of HCMC's development.

2 METHODS

2.1 Study area

The Saigon River catchment with 4717 km² is located in Southern Vietnam (Figure 1). The whole Saigon River has a length of 280 km within Vietnam. The river originates in Cambodia and is firstly controlled at Dau Tieng Reservoir, (270 km^2 and $1580x10^6$ m^3) which was designed for flood and saline intrusion control, irrigation, domestic, agricultural and industrial demands (Ngoc, Hiramatsu and Harada, 2014). From Dau Tieng Reservoir to the estuarine mouth (200 km), the Saigon River (net discharge 18 ± 14 $m^3\ s^{-1}$) in turn joins notable tributaries such as the Thi Tinh River (TT River, 20 ± 11 $m^3\ s^{-1}$) and the Dongnai River (632 ± 446 $m^3\ s^{-1}$), forming Nha Be River, it then splits into two distributaries (Soai Rap River and Long Tau River) flowing into East Sea of Vietnam (Figure 1). In addition, the Saigon River is also connected to a urban river (Vam Thuat River, 4 $m^3\ s^{-1}$) and three urban canals (total net discharge, 5.5 $m^3\ s^{-1}$) of HCMC before the confluence with Dongnai River (Nguyen *et al.*, 2020). The typical climate of this region is tropical monsoon which has two distinct seasons (dry and rainy seasons), with a relatively constant temperature (about 28^{o}C). The rainy season lasts from June to November, with an average annual rainfall of 1800 mm, whereof 80% fall in the rainy season (Nguyen *et al.*, 2019). The status of water quality in the Saigon Estuary River is spatially different. Upstream and downstream of the estuary, water quality status is considered good. The quality status of the water became moderate to bad right after connecting with the Vam Thuat River (an urban river) and urban canals of HCMC (Nguyen *et al.*, 2019). In other words, the water quality of the Saigon River has been significantly affected by the domestic wastewater from this city for many years.

Figure 1. Map and model domain of Saigon River Estuary and monitoring stations

Ho Chi Minh City's development is intrinsically linked with the Saigon River. This megacity's economy has developed considerably over the last decades and HCMC was considered one of the most dynamic cities in the world in 2017 (World Economic Forum News, January 2017). In 2015, Department of Natural Resources and Environment reported that land use in HCMC is dominated by agricultural activities in the north (41% of HCMC's area), urban settlement in the center (23%) and mangrove forest to the south (26%). The population growth rate in Ho Chi Minh City is about 3.48% per year (Ho Chi Minh City Statistical Yearbook, 2017), leading to the city having the highest population density in Vietnam. However, the development of water treatment systems is not in line with that population growth. In the early 2000s, HCMC discharged about 532.000 m^3d^{-1} domestic wastewater of about 6 million inhabitants (80−130 liters per capita per day) and 51.300 m^3d^{-1} industrial wastewater of 18 industrial parks which were mainly untreated (Le *et al.*, 2012). Consequently, most of the water quality variables exceeded Vietnamese surface water quality standards (QCVN 08:2015/BTNMT). In addition, the influence of tides causes saline intrusion as well as pollutant transport from urban area to the upstream area. This caused temporally shutdown of drinking water treatment plants in the dry season in 2004 and 2005 (Le *et al.*, 2012).

2.2 C-GEM model

2.2.1 Model description

C-GEM is a one-dimensional, reactive transport model. This model was developed to minimize the data requirement while ensuring the accurate description of estuarine hydrodynamics, salt transport and biogeochemistry (Volta et al., 2014). Three main modules of C-GEM (geometry, hydrodynamics, and transport - reaction modules) were implemented following the set-up protocol proposed by Volta et al. (2014). Hydrodynamic module was solved by using a finite difference scheme applied along a one-dimensional grid, with a grid size of 2000 m and an integration time step of 300 seconds. Transport-biogeochemical reaction module was solved by the operator-splitting method within a single time step (Regnier, Wollast and Steefel, 1997). The application of C-GEM in Saigon River Estuary required a spin-up of 180 days to reach a steady-state condition.

2.2.2 Model set-up and calibration

The C-GEM version in this study was adapted from the steady state version of Volta et al. (2016) to simulate the water quality along 200 km of Saigon River Estuary (see Figure 1 for the model domain and monitoring stations).

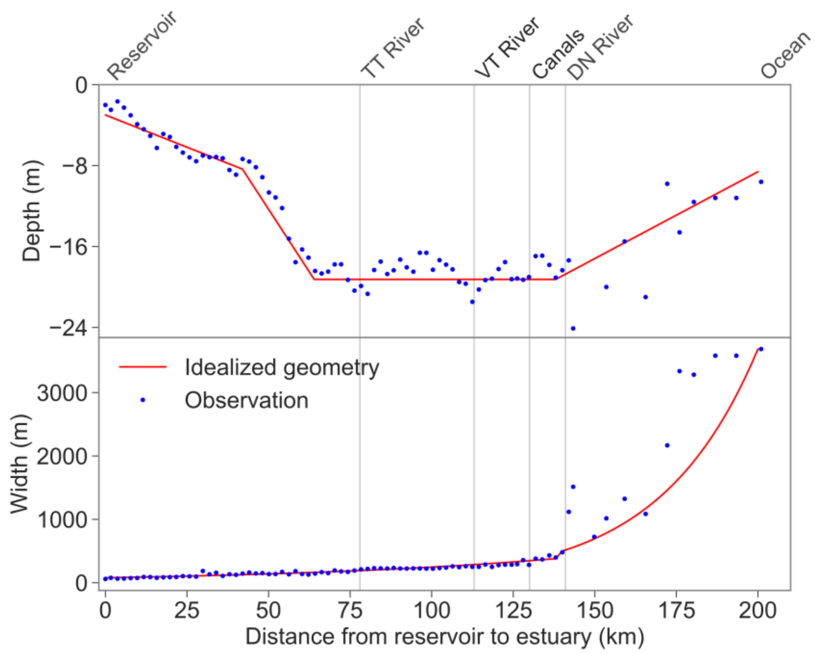

Figure 2. Idealized geometry of Saigon River Estuary using in C-GEM. The vertical lines are the main tributaries and canals

Idealized geometry

C-GEM used an idealized representation of the estuarine geometry which can describe the estuarine width by an exponential equation along the estuary gradient. The estuarine width ranges from 60 m to 350 m from Dau Tieng Reservoir to km 140, and rapidly increases to 3 687 m at the estuarine mouth. The model geometry was validated with the mean depth and width of 83 cross-sections along the 200 km Saigon River Estuary (Figure 2). The observed geometry data was extracted from bathymetry survey by SIWRR Vietnam in 2008.

Hydrodynamics module

The hydrodynamics along 200 km long reach along Saigon River Estuary was described by the one-dimensional hydrodynamic module of C-GEM based on the continuity and cross-sectional integrated momentum equations (see Volta et al. (2014, 2016) for detailed description).

Water elevation at estuarine mouth and freshwater discharge at the upstream limit were required to solve the hydrodynamic module. Tidal period and tidal amplitude were also needed to calculate the variation of elevation at the estuarine mouth. Chézy coefficient was the only parameter used for the calibration of the hydrodynamic module. The Chézy coefficient was calibrated based on the comparison between simulated tidal amplitude profiles and mean tidal amplitude observations at seven stations along Saigon River Estuary 2014 - 2017 (Figure 3). The observed tidal level data were provided by Center of Environment Monitoring (CEM). Data and methods of hydrological measurement were presented in Nguyen et al. (2020). Calibrated results showed that the Chézy coefficient applied Saigon Estuary should range from 15 to 60 $m^{1/2}\,s^{-1}$.

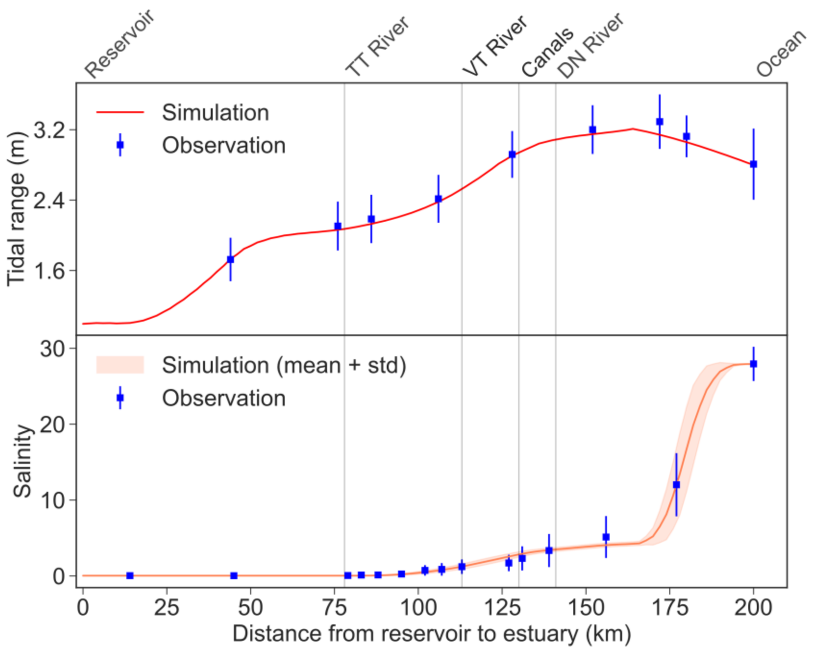

Figure 3. Comparison between observed and simulated profiles for tidal amplitude, salinity along the Saigon River Estuary.

Coupling reaction and transport module

The coupling of mass transport and biogeochemical reactions was described by using a one-dimensional, tidally resolved advection–dispersion equation:

$$\frac{\partial C}{\partial t} + \frac{Q}{A}\frac{\partial C}{\partial x} = \left(AD\frac{\partial D}{\partial x}\right) + P$$

where C is the concentration of solutes, D is the effective dispersion coefficient [$m^2\ s^{-1}$] which is automatically calculated following the geometry (see Volta et al. (2014) for details), P is the net biogeochemical processes related to the solutes C(x,t). Transport module was calibrated by comparison between salinity simulation and observations during the dry seasons 2014 – 2017. The salinity distribution agreement between simulation and observations in dry seasons 2014-2017 has ensured the precise transport of solutes along the Saigon River (Figure 3).

The current version of C-GEM in this study can simulate the concentrations of eight state variables, namely ammonium (NH_4), nitrate (NO_3), phosphate (PO_4), total organic carbon (TOC), Silica (DSi), dissolved oxygen (DO), phytoplankton (diatoms and non-diatoms) and Total Suspended Solid (TSS). Seven biogeochemical processes are considered in C-GEM, including oxygen exchange, aerobic degradation (organic carbon mineralization), nitrification, denitrification, primary production, phytoplankton mortality and TSS erosion/deposition. The rate constants of these processes were adjusted in the limit of their values from experimental or literature determination based on 49 estuarine biogeochemical model applications (Volta *et al.*, 2016).

Water quality data to calibrate biogeochemical parameters were obtained from bi-weekly monitoring data of Center of Environment Monitoring (CEM, Vietnam) and Center Asiatique de Recherche sur l'Eau (CARE, Vietnam) from 2014 - 2017. The sampling and analytical methods were described by Nguyen et al. (2020). Most of the observed data were BOD_5 but not the TOC. There were however 3 stations (at km 88, 130 and 156) where we measured BOD_5 and TOC. Therefore, TOC used in model was the converted BOD_5 concentrations using a relationship equation $TOC = 1.4 \times BOD_5 + 0.6$ ($R^2 = 0.67, n = 87$).

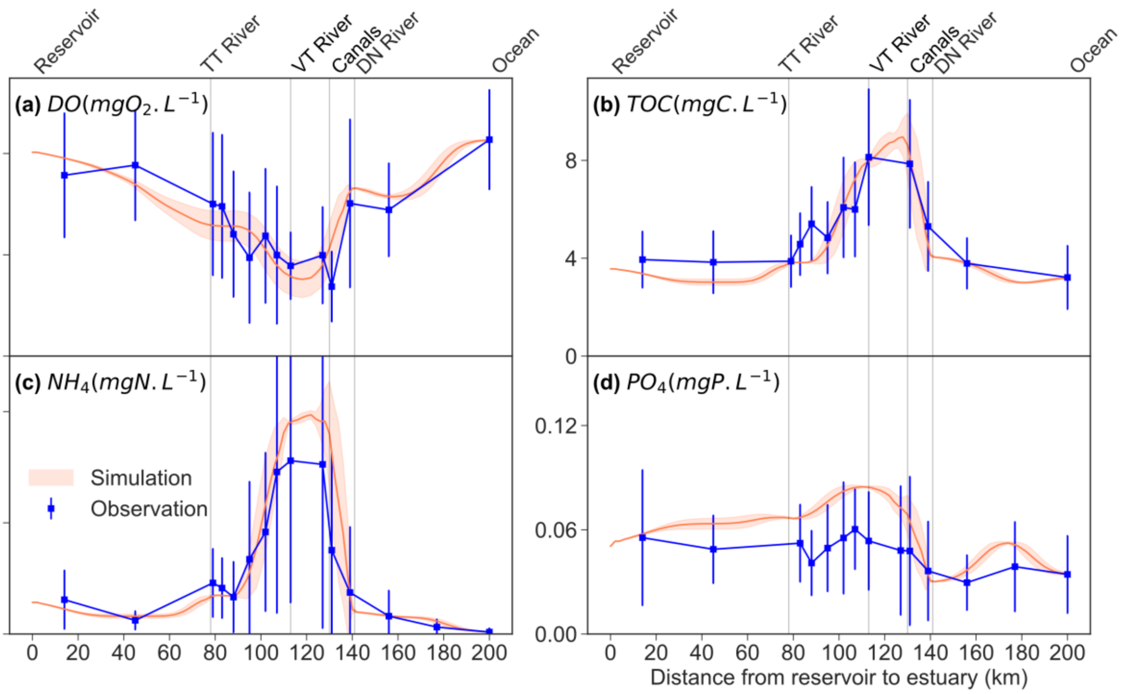

Figure 4. Comparison of observed and simulated results of water quality variables along Saigon River Estuary in dry seasons 2014 – 2017.

The water quality simulation results were compared with monitoring data of 13 stations along Saigon River Estuary in the dry seasons 2014 - 2017 (624 samples in total) (Figure 4). Although the current C-GEM model allows for the simulation of eight environmental variables, only four of them (DO, TOC, NH_4, PO_4) are discussed in this study because they are of particular interest for the municipal WWTPs construction plan in HCMC. In addition, the two monitoring programs of CARE and CEM provided the most complete data sets of these variables for the calibration and validation process in C-GEM. Statistical analysis for model performance shows that the simulation results and observation data of

13 monitoring stations have a coefficient correlation (R^2) from 0.6 to 0.9, the percentage bias is less than 20% for most of variables (except PO_4). PO_4 simulation has a percent bias of 37% (0.02 $mgPL^{-1}$), which is just equivalent to experimental error of PO_4 (0.01 $mgPL^{-1}$, standard colorimetric methods). These simulation results show that C-GEM model has good ability to simulate water quality at Saigon River. In addition, C-GEM allows determining the intensity of biogeochemical processes such as nitrification, organic carbon aerobic degradation affecting the concentration of these environmental parameters. Nitrification is the process with the largest consumption of dissolved oxygen in the Saigon River when it receives the high concentration of NH_4 from urban canal discharge (results are not shown in this study).

2.3 Scenarios

The calibrated and validated model was used to evaluate the responses of the Saigon River Estuary under the impact of changes in pollution levels from 2014 to 2050 according to HCMC's development plan as well as projections of climate change in 2050. The three scenarios in turn were tested by the C-GEM model respectively as follows (see also Table 1):

Scenario 1: With two WWTPs 2014 – 2017 (using observed data 2014 – 2017 for model input)

Scenario 2: With four WWTPs 2025 and increase of the population (130% compare to 2015)

Scenario 3: With twelve WWTPs 2050 and having the effect of climate change (increase tidal amplitude, temperature) and increase of the population (273% compare to 2015).

Table 1. Three scenarios for C-GEM application in Saigon River Estuary

Scenarios	**2014 - 2017**	**2025**	**2050**
Population [a] (inhabitant)	8,441,902	11,014,767	23,062,447
Number of WWTPs[b]	2	4	12
WWTPs treatment capacity (m^3d^{-1})[b]	171 000	1,253,000	2,813,000
Population connected to WWTPs (%)[c]	10%	57%	61%
TN flux from canals to river ($kgNd^{-1}$)[d]	51,062	42,768	80,957
TP flux from canals to river ($kgPd^{-1}$)[d]	13,651	11,405	21,600
TOC flux from canals to river ($kgCd^{-1}$)[d]	10,973	7,171	22,550
Temperature (°C)	28	28	28+1.5[e]
Tidal Range (m)	2.80	2.80	2.80 + 0.02[f]
Freshwater inflow (m^3s^{-1})[g]	17.6	17.6	17.6

[a] Population growth 3.4% Ho Chi Minh City Statistical Yearbook, 2017.
[b] Planning of the building of new WWTPs from (Tran Ngoc *et al.*, 2016).
[c] Percentage of population connected to WWTPs is equal to WWTPs volume capacity divided by the total water consumption (200 liters/capita/day).
[d] Calculated based on removal efficiency, 40–50% of TN, TP and 85% of TOC in conventional active sludge treatment process from Metcalf and Eddy/AECOM, 2014 for the WWTP outlet and with the linear dilution of untreated wastewater from the inner urban to the outlet of canals.
[e] Increase in sea surface temperature of 1.5°C by 2050 under RCP8.5 scenario, which adapted for HCMC (MONRE *et al.*, 2016).
[f] Increase of tidal amplitudes by 2050 (Bindoff *et al.*, 2019).
[g] The upstream boundary condition discharge Dau Tieng Reservoir is maintained for all three scenarios. The increase in water demand in HCMC in future will be addressed by increasing additional water sources which are mainly from Dongnai River (net discharge 613 m^3 s^{-1}) (Tran Ngoc *et al.*, 2016).

These scenarios were based on plans to develop WWTPs in HCMC as well as forecasts of temperature and sea level rise in the Saigon River (MONRE et al., 2016). Number of WWTPs and their capacity were after the decision n°24/QD-TTg which was approved by the Prime Minister of Vietnam on January 6th, 2010. Under this plan, a total of 12 WWTPs will ensure efficient domestic wastewater treatment for 12 basins in HCMC. Three scenarios (2015, 2025, 2050) allow to predict the effect of WWTPs on water quality in the Saigon Estuary under the impact of increased waste loads (population growth in HCMC). Therefore, the model parameters in all three scenarios remain the same except for the wastewaters source from urban discharge and climate parameters for the year 2050.

The concentration of pollutants from the canals was calculated based on the research results of Nguyen et al. (2020), from which we forecasted the total amount of wastewater from the inner canal, including total nitrogen (TN), total phosphorus (TP) and TOC. However, C-GEM model did not consider TN and TP and their values thus needed to be converted to NH_4 and PO_4 in accordance with the model implementation. The NH_4/TN and PO_4/TP ratios were calculated from CARE's bi-weekly monitoring program from 2015 to 2017. These data were presented according to Nguyen et al. (2019).

Scenario 1: This scenario is essentially an application of the model using the observed data from 2014 - 2017. It represents the current water quality of the Saigon River with two WWTPs (treated for 10% domestic wastewater of HCMC's population).

Scenario 2: HCMC's government plans to achieve four WWTPs by 2025. In 2020, there are three WWTPs in operation in HCMC. A fourth WWTP is under construction, the completion of this plant is expected to increase the total amount of treated domestic wastewater from 14% to 57% compared to 2015. According to the assessment of Ministry of Natural Resources and Environment of Vietnam (MONRE), the construction of two new WWTPs will create a turning point in the water quality improvement project of HCMC.

Scenario 3: By 2050, the population of the HCMC is forecasted to increase almost three times compared to the present population. In order to ensure the construction progress, the remaining WWTPs have been in the capital raising phase, including the socialization of investment from 2018. The proportion of domestic wastewater connected to 12 WWTPs can be 61% in 2050. C-GEM model was also adjusted parameters related to the impact of climate change. Tidal amplitude can be determined to increase by about 20 mm by 2050 (Bindoff *et al.*, 2019). In addition, MONRE determined that the surface temperature of the sea water of Southern Vietnam can be increase to 1.5^{o}C by 2050 (MONRE *et al.*, 2016). An increase in temperature can contribute to increased activity of biogeochemical processes in estuary which is considered intensifying the self-purification capacity.

3 RESULTS

Figure 5 depicts the simulation results of water quality at the Estuary Saigon River under the three scenarios driven by the construction of WWTPs in HCMC. In general, the simulations show significant efficiency in the construction of WWTPs especially for NH_4 and TOC. According to QCVN 08:2015/BTNMT, river water quality in Vietnam can be classified into four groups according to different concentration ranges. The quality of the river water is assessed "very good" (grade A1) suitable for domestic use, aquatic life. "Good" (grade A2) can be used for domestic use but requires appropriate water treatment. "Moderate" (grade B1) and "Bad" (grade B2) are respectively used for irrigation and transport purposes. Scenarios show that some of the parameters will change positively.

From km 0 to km 80 simulation results are almost unchanged for all environmental parameters, which is explained by the lack of input changes in this area (see vertical lines in Figure 5 for the location of external inputs). Besides, the impact of tides on water quality in the upstream area is very weak. This is demonstrated through the calibration salinity process (Figure 3). The three scenarios in the upstream area allow to assess the effect of the increase of temperature to the biogeochemical processes. The results of a nearly constant concentrations show that an increase of 1.5^{o}C would produce a negligible impact in this area.

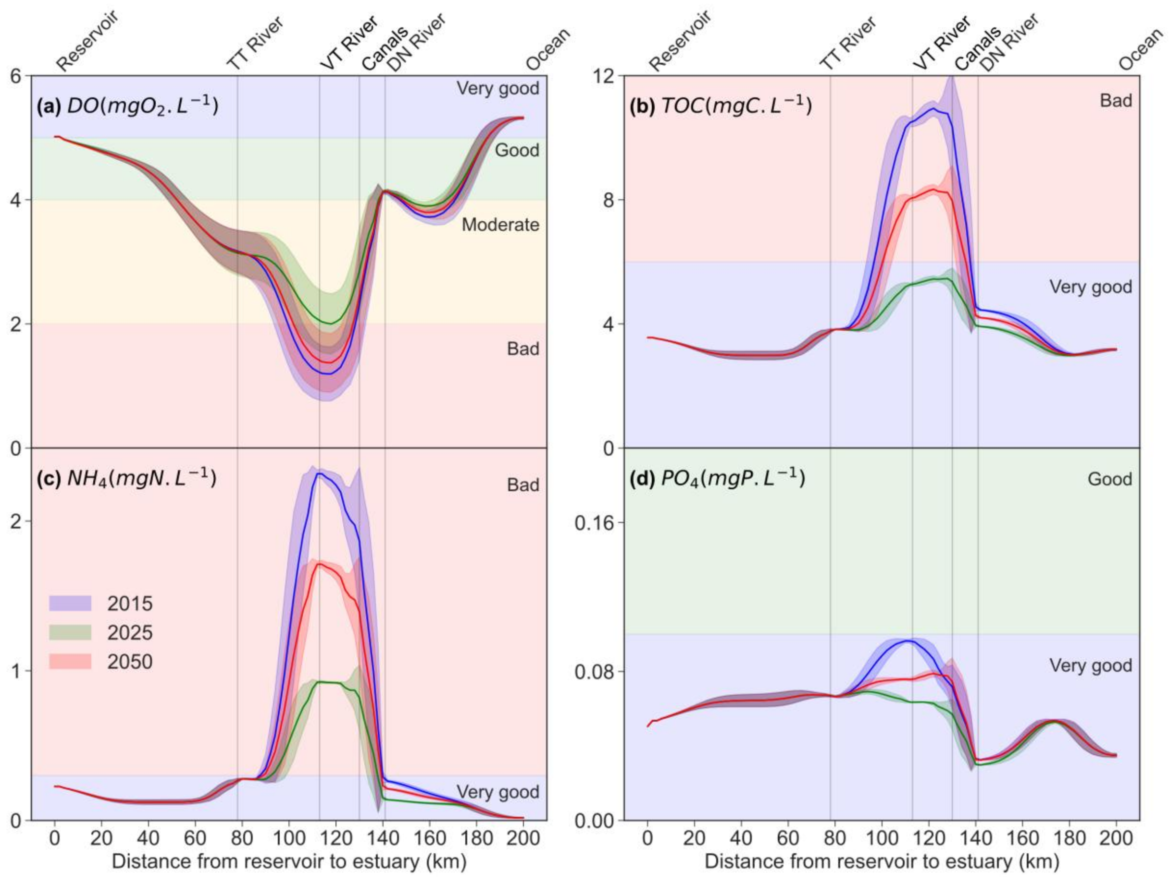

Figure 5. Simulated results of water quality variable along Saigon River Estuary in three scenarios. The background colors (red, orange, green, blue) are the concentration ranges for water quality assessment according to Vietnamese regulation on surface water quality – QCVN 08:2015/BTNMT.

From km 80 to km 140, this area is adversely affected by domestic wastewater from HCMC. All three scenarios have clear differences in the concentrations of environmental variables in this area, especially TOC and NH_4. Indeed, as forecasted by MONRE, the construction of two more WWTPs will significantly improve water quality in the Saigon River. The concentrations of NH_4 and TOC in 2025 can be reduced respectively by 52% and 37% compared to 2015. Thanks to the increase of total treatment capacity of WWTPs in HCMC (from 10% to 57%), TOC concentrations can be judged as good or very good in 2025. Likewise, DO under the 2025 scenario changes from a bad to a moderate quality. NH_4 shows a significant change in concentrations. The reduction in the inputs from wastewater in the inner city is clearly the main factor in reducing NH_4 concentrations in the river. In addition, the improvement in DO concentration enhances the nitrification efficiency which further helps to increase the NH_4 consumption. Unfortunately, NH_4 concentrations in the two future scenarios will not improve as much as TOC. This can be explained by the WWTPs treatment efficiency of TN of only about 40-50% while the TOC can be removed at 85% (Metcalf and Eddy/AECOM, 2014). Therefore, in order to improve quality of DO and NH_4 there is a need to improve the efficiency of WWTPs in nutrients treatment, and especially for nitrification NH_4 abatement. Under the 2050 scenario, all environmental variables in the Saigon River would show signs of deterioration. The concentrations of DO could be almost equivalent to the observations in 2015. DO would decrease from 2.4 to 1.4 $mgDO.L^{-1}$ between 2025 and 2050. Although the rate of connection with WWTPs reached 61% during this period, the large amount of nutrients from 23 million inhabitants (from 11 million to 23 million in 25 years) would cause significant DO consumption by nitrification and aerobic degradation. For the year 2050, three of four considered variables would return to a bad state, compared to 2025, although their concentrations would be improved compared to present. Meanwhile, PO_4 concentrations would always remain within the allowed concentration threshold of QCVN 08:2015/BTNMT regardless of the scenarios.

In the downstream area, from km 140 to km 200, the concentrations of the considered variables in the three scenarios are slightly different for NH_4 and TOC. From km 140 to km 165, the simulated results show an improvement in water quality of NH_4 and TOC. This can be explained by the improvement of water quality in the urban section of Saigon River while the water quality in Dongnai tributary remains the same according to C-GEM model implementation. In the area near downstream km 165 to 200, there is no difference although this area is likely to be affected by changes in tidal amplitude in the 2050 scenario. However, an increase of about 2 cm by 2050 may not make significant difference in the transport from the ocean to the Saigon River.

Conclusions

The application of the C-GEM model at the Saigon Estuary well reproduce the water quality parameters such as DO, NH_4, PO_4 and TOC. After calibration and validation based on the Saigon River observed data in the dry seasons 2014 - 2017, C-GEM allows to evaluate the changes of water quality in Saigon River under various conditions of pollution input. Model results for two future scenarios show a marked effect in improving river water quality by WWTPs construction, especially under scenario 2025. This result shows that the construction of WWTPs is essential for a sustainable development of HCMC. However, a population growth from about 8 million inhabitants in 2015 to 23 million in 2050 can make the water quality return to bad condition, as in 2015. Although the construction of new WWTPs could treat around 60% of the population in Ho Chi Minh City, the water quality in the Saigon River would not meet the water quality standards on surface water quality QCVN 08:2015/BTNMT. To solve this problem, improving nutrient processing technology in WWTPs, and/or implementing alternative urban wastewater management (Based Nature Solutions) is probably the effective solution in eliminating oxygen shortages or nutrient pollution (e.g. NH_4) in the urban section of the Saigon River.

Acknowledgments

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