



Scenario-based numerical simulation to predict future water quality for developing robust water management plan: a case study from the Hau River, Vietnam

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Abstract

Rapid population growth, urbanization, industrialization, and climate change are the key drivers causing serious water pollution around the globe. Considering the impacts of these key drivers, this study employed the Water Evaluation and Planning (WEAP) simulation tool to simulate the future water quality in a nearly 60-km stretch of the Hau River, Vietnam. The business-as-usual (BAU) scenario; scenarios with measures (WM), i.e., wastewater treatment plants (WWTPs) for treating 75% (WM75) and 100% (WM100) of total future wastewater generated; and the optimistic scenario (WM_Opt., i.e., WM100+additional treatment plants for river water (RWTPs)) to achieve the desired water quality, were applied to simulate the future Hau River water quality for the year 2030. Result suggests that the average values of biochemical oxygen demand (BOD), total coliform (TC), nitrate (NO_3^-), and phosphate (PO_4^{3-}) in the wet season of 2030 under BAU scenario will be increased by 16.01%, 40.85%, 30.49%, and 20.22%, respectively, in comparison to those of the current year, i.e., 2018. In the dry season, these rates will be increased by 27.80%, 65.94%, 31.05%, and 20.64%, respectively. Under the scenario with measures (WM75 and WM100), although the Hau River water quality was improved but did not reach the desired limits, especially for BOD and PO_4^{3-} levels in the downstream region. However, under the WM_Opt. scenario, the average simulated values of both BOD and PO_4^{3-} will be significantly declined by 76.53% and 63.96%, respectively as compared to the current situation and help to achieve river water quality under class A. This study is providing policy-relevant scientific information, vital for sustainable water resource management.

Keywords Water pollution · Biochemical oxygen Demand · Total coliform · Nitrate · Phosphate · Water quality modeling · River water and wastewater treatment · The Hau River · Vietnam

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1 Introduction

Water resources are intrinsically linked to the sustainable and inclusive development of human societies (Heinemann et al. 2002; FAO AQUASTAT 2016). This natural resource even signifies its importance in the development of developing countries/regions like South East Asia (SEA) (Moglia et al. 2012). Accessibility to safe water for humans is a major challenge, which is well recognized under the United Nations Sustainable Development Goals (SDGs) (Dell'Angelo et al. 2018; Avtar et al. 2020). However, many SEA countries, including Vietnam, have currently faced several challenges posed by the increasing demand for clean water supplies. The situation is exaggerated by periodic droughts and contamination of both surface and groundwater (Wakida and Lerner 2005; UNDP 2006; Moglia et al. 2008). Rapidly developing urban centers are acting as the focal point for this clean water scarcity (Grohmann 2009; Henriques 2011). This has implications for better policies, planning, and management processes required to secure adequate safe water supplies for the future (UNDP 2006).

Water resources management (WRM), especially for the river bodies is a complex task in growing urban areas with a great number of difficulties and challenges (Phung et al. 2015; Hoekstra et al. 2018; Trung et al. 2019a). The key difficulties and challenges are rapid population growth, urbanization and industrialization; unsustainable agriculture; inadequate wastewater management infrastructure; the lack of awareness and common practices; and poor governance. Besides, water security is further skewed with extreme weather conditions, viz., floods and droughts, induced due to climate change (Konings 2012; Mukate et al. 2018; Trung et al. 2019a). Therefore, it is a challenging task for developing countries to maintain the sustainable water supply and achieve the SDGs due to their unplanned and indiscriminating WRM policies with the absence of larger socio-economic factors (Downing 2012). Therefore, inclusive and transdisciplinary research is a timely and critical need to achieve urban water security in the future (Kumar 2019).

In Vietnam, Dong Thap, Vinh Long, and Can Tho are not only three of the most crucial developing cities but also the regional urban centers in the Vietnamese Mekong Delta (VMD). Moreover, Can Tho is also considered one of the five nation's largest economic centers (Konings 2012; Moglia et al. 2012). With their enormous river and canal networks (more than 3,405 km), water is the center of everyday life and underpins these cities' economies, including agriculture, aquaculture, industry, transportation, services, and tourism (Konings 2012; Nguyen et al. 2016). Currently, the Hau River supplies the main source of water for these three cities. Being the main tributary of the Mekong River, the Hau River flows across the entire area of Can Tho City and the large parts of Dong Thap and Vinh Long Cities' areas with a total length of nearly 60 km. However, the fast urbanization and industrialization, population growth, and climate change (mainly change in rainfall) have placed enormous pressure on these river water resources, especially the water quality. The situation gets worse with the low levels of residents' awareness, lack of sufficient regulations, and inadequate water infrastructure (Quan et al. 2013; Trung et al. 2019a). Noticeably, although wastewater is rapidly increasing due to the population growth, rapid urbanization, industrialization, and changes in water consumption behavior, the investment for the water management infrastructure does not keep pace with the developing demand (Long and Cheng 2018; Trung et al. 2019a). Moreover, these cities' wastewater management is limited to the collection of wastewater from both point and non-point pollution sources through open and underground sewer lines, and disposal of untreated wastewater into the rivers (Trung et al. 2019a). Thus, a huge amount of untreated wastewater from

both domestic and industrial activities of these cities is directly discharged into the Hau River and its diversion network (CTCPC 2019b). As a result, the Hau River is getting contaminated with physical, chemical, and biological pollutants, exceeding the desired surface water quality of class A of the National Technical Regulation on Surface Water Quality (NTRSWQ) (CTCPC 2019b; DOC 2019).

Since the systems of the natural environment and anthropogenic sources are multivariate and complex, river water quality management requires a fundamental understanding of spatial and temporal variations in the water characteristics, including hydro-morphological, chemical, and biological parameters (Phung et al. 2015). For this purpose, diligent monitoring of water quality is a necessity for maintaining a clear water environment and reducing the financial burden to local government in managing polluted water at the later stage (Simeonov et al. 2004; Shrestha and Kazama 2007). Moreover, to design a robust management plan, there is a requirement for both current water quality conditions and also possible future scenarios. The formulation of water quality management strategies requires an interdisciplinary analysis of various potential causes of water quality degradation as well as corresponding solutions (Kannel et al. 2007; Mishra et al. 2017). With the above-mentioned facts, computer-based mathematical models have been developed since the 1980s to assess and predict water quality. In WRM, the favorable approaches vary from simplified conceptual, empirical to data-based ones. Most models can provide detailed insight into water quality conditions in a river system such as SWAT, QUAL2K, and MIKE. However, there has mostly been an absence of policy-setting issues in detail (Mishra et al. 2017; Kumar 2019). Specifically, the Integrated Water Resource Management (IWRM) model targets different components of water resource governance (socio-economic status, hydro-meteorological factors, agriculture, industries, wastewater, etc.) and thereby integrates them for the policy- and decision-making processes (Blanco-Gutiérrez et al. 2013; Frija et al. 2015). Several IWRM numerical models like RIBASIM (River Basin Simulation Model), SWMM (Storm Water Management Model), VENSIM (The System Dynamic Model), WEAP (Water Evaluation and Planning), and WBalMo (Water Balance Model) have been developed and widely used to address water security issues (Sieber and Purkey 2015; Kumar 2018; Trung et al. 2019a). The application of an optimal water quality model depends on data availability, calculation time, and intended output variables.

Particularly, the WEAP model is not data-intensive and free of charge, and thus, it has been widely used in water quality modeling, especially in data-scarce developing countries (Slaughter et al. 2014; Sieber and Purkey 2015). Besides, this integrated model has also been widely used to analyze the efficiency of different planned adaptation and mitigation measures for improving the water resources in the future (Kumar 2018; Mirauda and Ostoich 2018). Noticeably, despite the lack of detailed water quality variables like several other models, the WEAP model supports scenario formation functionalities. These scenarios can be built with the involvement of policy and strategic plans in this model, based on different variables such as population growth, industrialization, and urbanization, climate change, land use land cover (LULC) change, the status of treatment plants and sewerage network, hydropower generation, etc. (Mishra et al. 2017; Kumar 2018). Moreover, the WEAP hydrology module also allows the estimation of rainfall-runoff and pollutant travel from a catchment to water sources (Ingol-Blanco and McKinney 2013).

With the aforementioned facts, this research aims to quantify the current conditions and future outlook of water quality for the year 2030 in the Hau River flowing through Can Tho, Dong Thap, and Vinh Long Cities, Vietnam, based on four possible scenarios. The first scenario is BAU, where the effects of all possible key factors (population growth, urbanization, and climate change) affecting the Hau River water quality are considered.

The others are scenarios with measures, in which water treatment plants are considered as the mitigation measure for improving the river water environment. The second scenario denoted by “WM100” refers to an ideal situation considering 100% completion of the WWTPs of capacity planned in the cities’ master plans, whereas the third scenario, i.e., “WM75” refers to 75% completion of the planned WWTPs because of some delay in the project completion in the cities. Considering the existing gap to achieve the desired water quality with WM100, a fourth scenario named “WM_Opt.” with the same characteristics and components as the MW100 scenario and the addition of RWTPs at serious water pollution centers along the Hau River was applied.

2 Study area

The study area comprised Can Tho (north latitudes/east longitudes: 9° 55′ 08″–10° 19′ 38″/105° 13′ 38″–105° 50′ 35″), Dong Thap (10° 07′ 59″–10° 58′ 22″/105° 12′ 00″–105° 56′ 01″), and Vinh Long (9° 52′ 45″–10° 19′ 50″/105° 41′ 25″–106° 17′ 00″) Cities, the main regional urban center locating in the middle of the VMD (CTCPC 2020; MOPI 2020) (Fig. 1). Can Tho City has nine districts, including five urban districts and four rural ones, with a total area of nearly 1,440 km² (CTCSO 2019). The total areas of Dong Thap and Vinh Long Cities are approximately 3,384 km² (including two urban districts and ten rural ones) and 1,526 km² (one urban district and seven rural ones), respectively (VNCSO 2018). Can Tho is also the fourth most populous city in Vietnam (nearly 1.283 million in 2018 and projected to be 2.1 million by 2030), with approximately 67% living in urban and peri-urban areas (CTCSO 2019; UN DESA 2019). Similarly, Dong Thap and Vinh Long are also considered populous cities in Vietnam with nearly 1.694 and 1.052 million people in 2018, respectively (VLCSO 2018; VNCSO 2018).

Located in the middle of the Lower Mekong Basin, the altitude of these cities is at a maximum of 1 m above mean sea level and lower from the east-north (+1 m) to west-south (+0.8 m). In terms of weather, all these cities lie in a tropical and monsoonal climate with two distinctive seasons, i.e., rainy (May to November) and dry (December to April). Its average annual humidity is 83%, and annual rainfall ranges between 1,500 and 1,800 mm (of which 90% of rainfall occurs during the rainy season) (Konings 2012). The northeast of Can Tho City and the southwest of Dong Thap and Vinh Long Cities are bordered by the Hau River, one of the two main branches of the Mekong River flowing in Vietnamese territory (Fig. 1). During the rainy season (September to October), the average water flow in the Hau River reaches 15,000–16,000 m³/s. In contrast, during the dry season, this flow drops to 1,600–1,700 m³/s leading to water shortages in the cities (Neumann et al. 2011).

The whole VMD region, including three cities, is characterized by flat terrain with a dense waterway network, which is essential to people’s livelihoods. Here, water is central to everyday life and underpins the local economy, including industry, agriculture, transport, and commerce and service (Neumann et al. 2011). In Can Tho City, noticeably, all five urban districts, namely, Ninh Kieu, Cai Rang, Binh Thuy, O Mon, and Thot Not, are located along the Hau River in the northeast of the city. Similarly, Lap Vo and Lai Vung districts of Dong Thap City and Binh Tan and Binh Minh districts of Vinh Long City are also bordered by the Hau River (Fig. 1). They are the nine most populous and crucial districts contributing to these cities’ general development. Although the area of these nine districts only accounts for nearly 20% (1,156 km²) of the total area of Can Tho, Dong Thap, and Vinh Long Cities; their population makes up nearly 34% (nearly 1.338 million

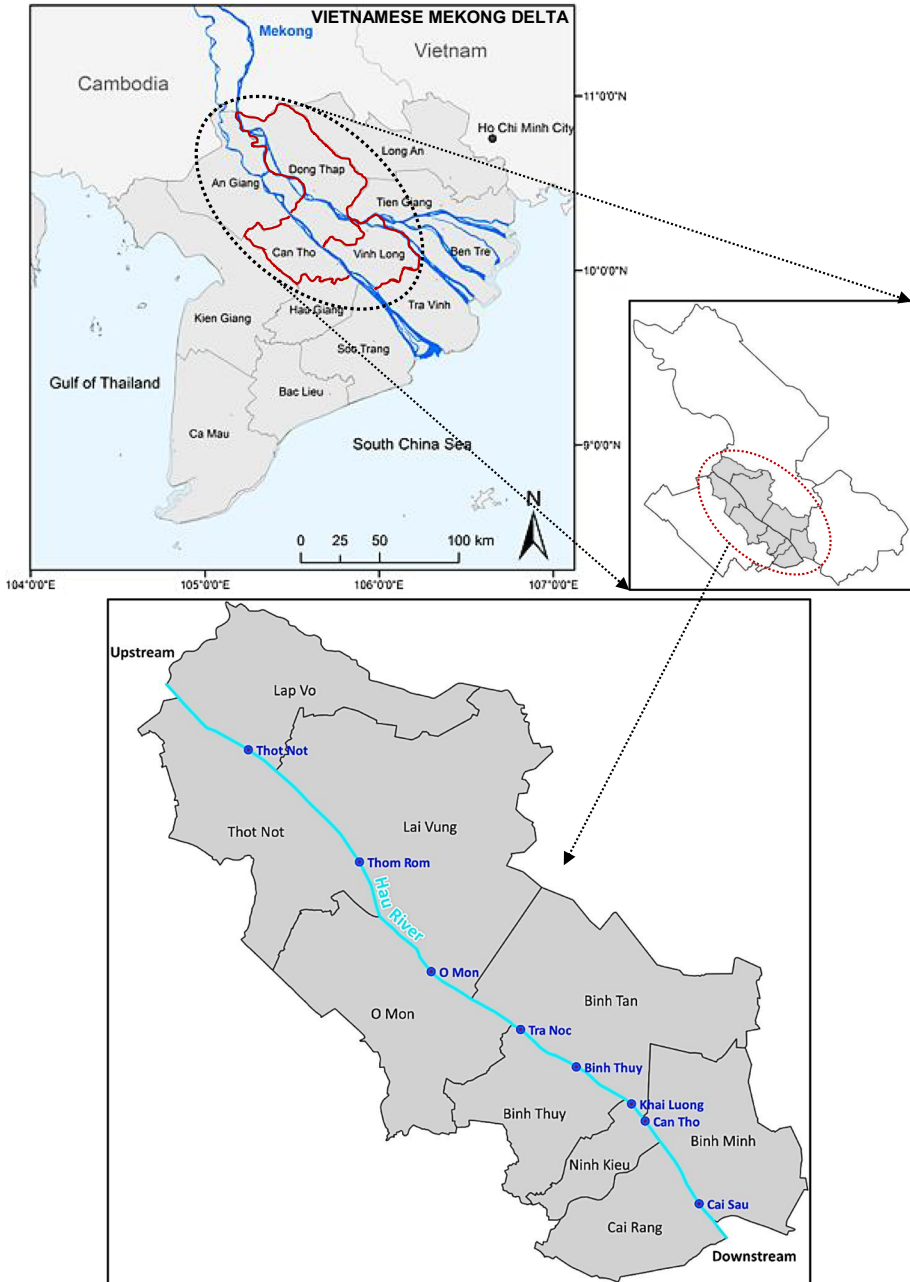


Fig. 1 The location of the study area’s nine districts along the Hau River (light blue) with several hydrological and water quality monitoring stations (dark blue) from upstream to downstream areas

people) of these cities’ total population in 2018 (CTCSO 2019). Table 1 shows the nine districts’ area and population characteristics in the study area (VLCSO 2018; VNCSO 2018; CTCSSO 2019; UN DESA 2019; MOPI 2020).

Table 1 The nine districts' area and population characteristics in the study area

Cities	Districts considered for this study	Area (km ²)	Percentage of the city's total area (%)	Total population (people)		Percentage of the city's total population (%)
				2018	2030	
Can Tho	Thot Not	121	29.18	172,786	274,878	62.94
	O Mon	132		140,712	223,853	
	Binh Thuy	71		125,739	200,033	
	Ninh Kieu	29		269,541	428,802	
	Cai Rang	67		98,320	156,413	
Dong Thap	Lap Vo	246	14.30	180,266	234,586	20.33
	Lai Vung	238		163,912	213,304	
Vinh Long	Binh Tan	158	16.94	96,327	125,353	17.75
	Binh Minh	94		90,327	117,545	
Total		1,156	19.99	1,337,931	1,974,767	33.67

The surface water of the Hau River is the main water source supplied for all daily activities in these nine districts, while residents in the remaining rural districts mostly use groundwater for their water demand. Although there are abundant water resources available in the Hau River to cater to these nine districts' general demand, the growth of point and non-point pollution sources in recent years has increasingly become a matter of concern, especially for this river's water quality management. Particularly, point wastewater sources generated by rapid population and industrial growth along the Hau River are considered the main reasons causing water pollution in this river (CTCPC 2019b). To support this fact, seven monitoring stations and spatio-temporal trends in BOD, TC, NO₃⁻, and PO₄³⁻ concentrations at an annual average for some monitoring stations across the study area in the period of 2009–2018 are shown in Fig. 2. As can be seen from Fig. 2b, c, d, and e, all BOD, TC, NO₃⁻, and PO₄³⁻ concentrations have mostly shown upward trends over these 10 years except for slight decreases from 2013 to 2015 thanks to a series of environmental projects (rehabilitating canal network, building an industrial WWTP, etc.) implemented during these three years (CTCPC 2014; ODAPMU 2016). However, these parameters' levels, especially BOD and TC, have significantly re-increased since 2016 due to the rapid urbanization, population growth, and land use changes in recent years (CTCPC 2019b). Noticeably, BOD and TC concentrations are much higher compared to class A of the NTRSWQ, while an opposite trend can be seen in NO₃⁻ and PO₄³⁻ levels that are within the permissible ones. Another thing to note is that the pollution status is more serious in the Hau River downstream areas, where the most populous districts of the study area are located with many residential zones, trading centers, and industrial parks.

Noticeably, despite the reticulated water supplies system, there is a lack of sufficient WWTPs to handle both domestic and industrial wastewater generated in these heavily urbanized districts (CTCPC 2019b). At present, only one domestic WWTP with a treatment capacity of 30,000 m³ per day is functional in the study area. It accounts for only more than 25% of the study area's total daily discharged domestic wastewater (CTCPC 2019b; DOC 2019). Regarding industrial wastewater treatment, although the WWTPs for industrial parks in the study area are currently being operated, the existing treatment capacity and efficiency do not meet the increasing water demand for industrial activities along the Hau River (Trung et al. 2019b). According to CTCPC (2019b),

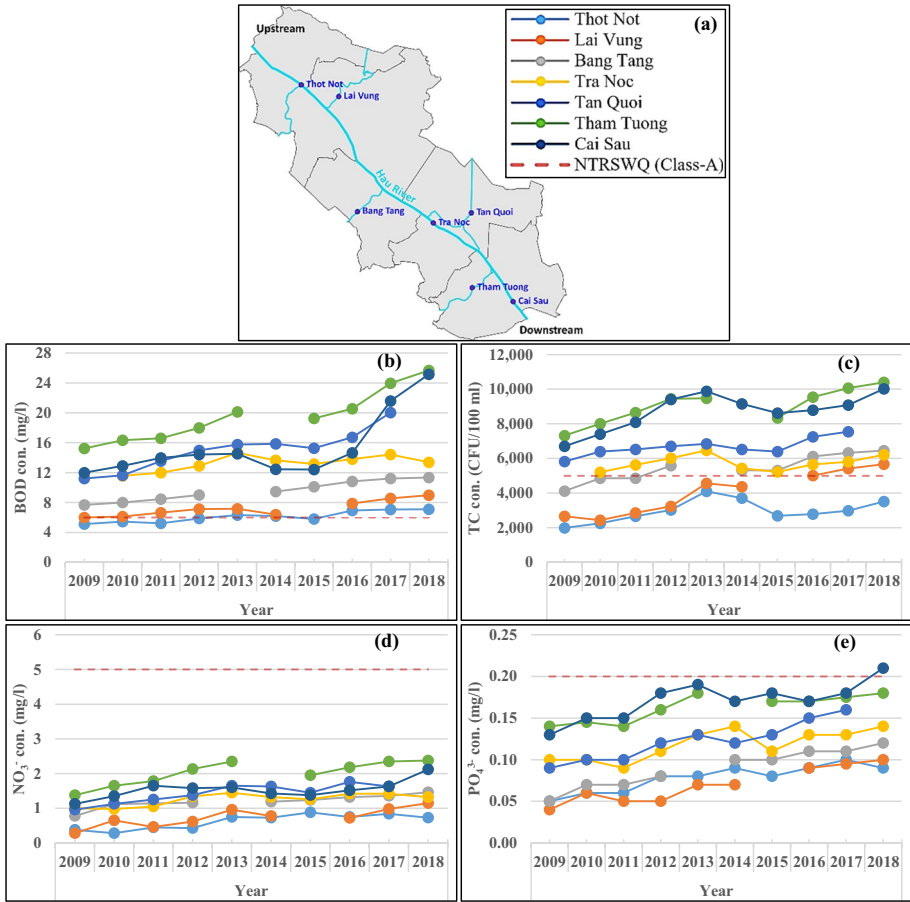


Fig. 2 The BOD (b), TC (c), NO₃⁻ (d), and PO₄³⁻ (e) concentrations at a number of monitoring stations (a) across the study area in the 10-year period of 2009–2018

only five centralized WWTPs are currently being used for industrial wastewater treatment with a total treatment capacity of 70,000 m³ per day, accounting for nearly 64% of the total daily industrial wastewater generated in the study area. Consequently, the remaining domestic and industrial wastewater is discharged directly into the Hau River and its diversion network.

In the current cities’ master plan, therefore, developing policies and strategies to sustain rapid urbanization, significant industrial development, economic activities while maintaining desired water resources for the future are prioritized in these three cities (Long and Cheng 2018; MOPI 2018; DTCPC 2020). One of the current priorities for these cities is to expand advanced centralized WWTPs (CTCPC 2016, 2019a) to cater to all wastewater generated and achieve the ambient water quality of class A prescribed by the Vietnamese national standard (CTCPC 2016).

3 Methodology

3.1 The WEAP model

In this research, the WEAP model was used to simulate rainfall-runoff and water quality variables in different scenarios to assess water quality management and policy alternatives amidst the population growth, industrial extension, and climate change in the Hau River basin. Spatio-temporal river pollution analyses were carried out in the scenario of wastewater increase and then proposed both new rehabilitated WWTPs and RWTPs. The flow-chart for the research methodology is shown in Figure 13 Appendix 1.

3.2 Hydrological/catchment simulation

With support from the geographic information system (GIS) and remote sensing (RS), the study area's schematic maps were generated in the WEAP interface (Fig. 3). Based on the geographical, topographical, geomorphological, hydrological, and climatic features as well as confluence points, then, the study area was required to be divided into nine smaller catchments. These catchments will be one of the main components for the hydrological simulation in the WEAP model (Sieber and Purkey 2015; Kumar 2018).

Due to data availability, the rainfall-runoff method (simplified coefficient method) among five different methods available was applied for the catchment simulation in this research. This method can simulate different components of the hydrologic cycle, including the catchment's potential evapotranspiration (by using crop coefficients), surface runoff, and infiltration of rainfall. In more detail, the available precipitation for the potential evapotranspiration (PrecipAvailableForET) and the catchment's potential evapotranspiration (ETpotential) were calculated by equations based on the real precipitation (Precip), catchment's area (Area), effective precipitation (PrecipEffective), reference evapotranspiration (ETreference), and crop coefficients (K_c) (Eqs. (1) and (2)). The runoff to both groundwater (RunoffToGW) and surface water (RunoffToSurfaceWater) can be calculated with Eqs. (3), (4), and (5) (Sieber and Purkey 2015).

$$\text{PrecipAvailableForET}_{LC} = \text{Precip}_{HU} \times \text{Area}_{LC} \times 10^{-5} \times \text{PrecipEffective}_{LC} \quad (1)$$

$$\text{ETpotential}_{LC} = \text{ETreference}_{HU} \times K_{cLC} \times \text{Area}_{LC} \times 10^{-5} \quad (2)$$

$$\text{Runoff}_{LC} = \text{Max} (0, \text{PrecipAvailableForET}_{LC} - \text{ETpotential}_{LC}) \quad (3)$$

$$\text{RunoffToGW}_{HU} = \sum_{LC} (\text{Runoff}_{LC} \times \text{RunoffToGWFraction}_{LC}) \quad (4)$$

$$\text{RunoffToSurfaceWater}_{HU} = \sum_{LC} (\text{Runoff}_{LC} \times (1 - \text{RunoffToGWFraction}_{LC})) \quad (5)$$

where subscript LC is the land cover and subscript HU is the hydro-unit.

Pollutant transport from a catchment accompanied by rainfall-runoff is enabled by ticking the water quality modeling option. The surface runoff takes the accumulated pollutants from the catchment surfaces during non-rainy days to the water bodies. The formula of the

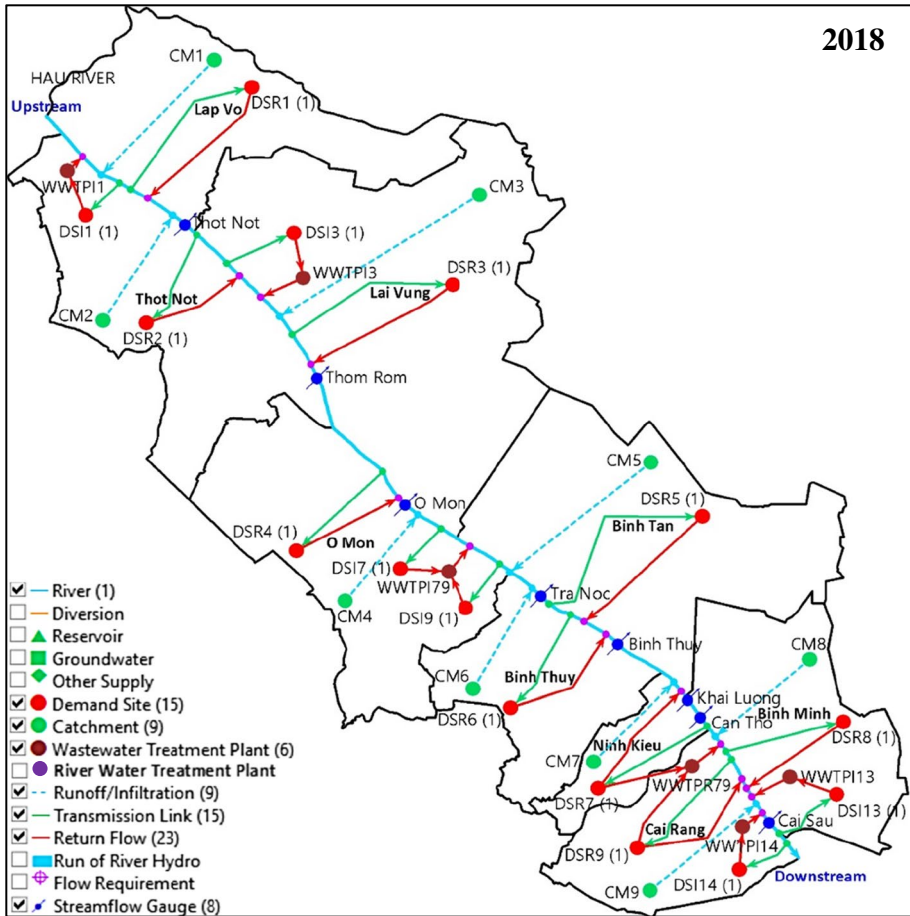


Fig. 3 The current (2018) and future (2030) schematic maps in the WEAP interface showing key components utilized for the Hau River surface water quality modeling

castaway catchment surface pollutants is by multiplying runoff volume and concentration (Sieber and Purkey 2015). All parameters and datasets required for this hydrological/catchment simulation in this research are shown in Table 2.

3.3 Water quality simulation

Developed from the Streeter-Phelps model, the WEAP employs descriptive models of point source pollutant loadings that can simulate the impact of wastewater on receiving waters from demand sites and WWTPs. In terms of simulation of oxygen balance in a river, two processes are identified, which are consumption by decaying organic matter and re-aeration induced by an oxygen deficit. The DO and BOD removal from water is a function of water temperature, settling velocity, and water depth (Eqs. (6), (7), (8), and (9)) (Sieber and Purkey 2015).

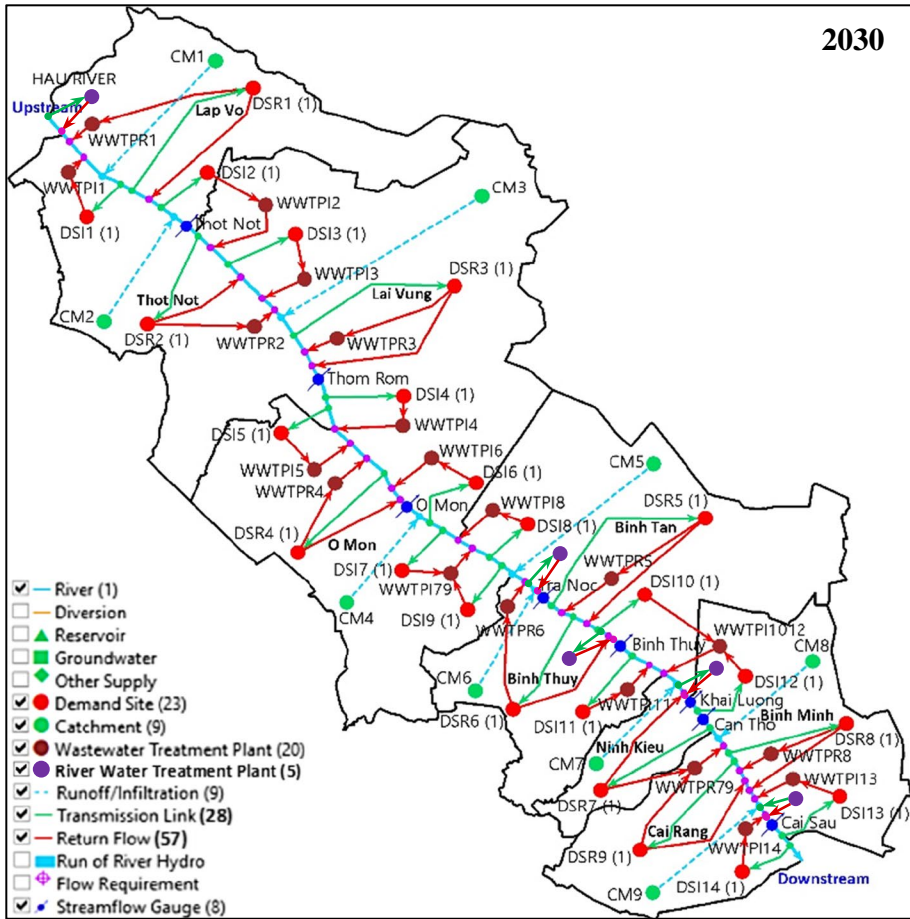


Fig. 3 (continued)

$$BOD_{final} = BOD_{init} \exp \frac{-k_r BOD L}{U} \tag{6}$$

$$\text{where } k_{rBOD} = k_{d20}^{1.047(T-20)} + \frac{v_s}{H} \tag{7}$$

BOD_{init} : the BOD concentration of the pollutant loading (mg/l) at the top of the reach;

BOD_{final} : the BOD concentration of the pollutant loading (mg/l) at the end of reach;

T : the water temperature (in degrees Celsius); H : the depth of the water (m); and L : the reach length (m);

U : the water velocity in the reach; and v_s : the settling velocity (m/s);

$k_r = 0.4$; $k_d = 0.4$, and $k_a = 0.95$: the re-aeration, decomposition, and reaction rates, respectively (1/time);

Table 2 The summary of required parameters and dataset as well as their sources and usage for the case study

No.	Dataset	Brief description	Scale	Type	Source	Usage					
						Model setup	Hydrological simulation	Water quality simulation	Calibration	Validation	Scenario building
1	Climate	Temperature	Monthly	Secondary	DOHM	✓	✓	-	-	-	-
		Evaporation				✓	-	-	-	-	-
2	Hydrology and LULC	Precipitation, effective rainfall	Monthly	Secondary	DOHM	✓	✓	✓	✓	-	✓
		River streamflow				✓	✓	-	✓	-	-
		River cross-section and length	Yearly	Secondary	DOHM, DONRE and DOC	✓	✓	-	-	-	-
		Catchment area and slope				✓	✓	-	-	-	-
3	Population, industry and water use-related issues	LULC	Yearly	Secondary	Statistical Office and UNDESA	✓	-	✓	-	-	✓
		runoff/infiltration ratio				✓	-	-	✓	-	-
		Population growth	5-yearly	Secondary	Statistical Office and DOC	✓	-	✓	-	-	✓
		Industrial growth				✓	-	-	-	-	-
4	Water quality	Water consumption	Daily	Primary and secondary	DONRE and DOC	✓	-	✓	-	-	✓
		Wastewater discharge				✓	-	-	-	-	-
		Surface water quality	Quarterly	Secondary	DONRE	✓	-	-	-	✓	-
		Riverhead water quality				✓	-	✓	✓	-	-
5	WWTPs	Point sources of pollution	-	Secondary	DONRE and DOC	✓	-	✓	-	-	✓
		Number and location				✓	-	✓	-	-	✓
		Capacity	Daily	Secondary	DONRE and DOC	✓	-	✓	-	-	✓
		Technology and efficiency				✓	-	✓	-	-	✓
6	Drainage network	Location	-	Secondary	DONRE and DOC	✓	-	✓	-	-	✓
		Connection rate				✓	-	✓	-	-	✓

k_{d20} : The decomposition rate at a reference temperature of 20 °C.

Oxygen concentration in the water is a function of water temperature, DO, and BOD:

$$\text{Oxygen saturation or OS} = 14.54 - (0.39T) + (0.01T^2) \quad (8)$$

$$O_{\text{final}} = \text{OS} - \left(\frac{k_d}{k_a - k_r} \right) \left(\exp^{-\frac{k_r L/U}{} } - \exp^{-\frac{k_a L/U}{} } \right) \text{BOD}_{\text{init}} - [(\text{OS} - O_{\text{init}}) \exp^{-\frac{k_r L/U}{} }] \quad (9)$$

where O_{init} is the oxygen concentration (mg/l) at the top of the reach and O_{final} is the oxygen concentration (mg/l) at the end of the reach.

Even though these different parameters should be examined and measured in the individual research, most water quality parameters have been estimated from the secondary database due to the lack of time and funds (Bowie et al. 1985).

3.4 Data requirement

To simulate the current status and predict the future for river water quality in the WEAP model, various input data were collected and its summary is shown in Table 2. The point pollution sources' locations and concentrations, past spatio-temporal water quality, WWTPs' and RWTPs' locations and capacities, past and projected population, water consumption, and current drainage networks were considered required datasets for the water quality simulation. The historical and future climate (rainfall, evaporation, temperatures, etc.), hydrological data (river flow-stage-width relationships, river length, surface water inflows, etc.), LULC, and catchments' areas and locations were utilized for hydrological simulation. Besides, the cities' documents (reports, master plans, etc.) were also collected for the scenario building and evaluation.

To model water quality with WEAP, schematic diagrams (the virtual representation of the contributory elements of the water pollution in the study area) for both the current stage (the year 2018) and the target year (the year 2030) are prepared as shown in Fig. 3. As mentioned earlier, the Hau River basin was also divided into nine smaller catchments (CMs) areas with inter-basin transfers. Water demand sites (red dots) for residential (DSRs) and industrial (DSIs) zones mainly give a schematic representation of current and future water consumption in the study area. Based on the study areas' population and industrial distribution, their areas and locations were identified in the catchments along the Hau River. Locations of existing and planned WWTPs were also identified based on the cities' reports and master plans, while proposed RWTPs' sites were located based on the simulated results of river water quality conditions from the model using the scenario with measures (WM100). Located along the Hau River, gauges (dark blue nodes) represent water quality and streamflow monitoring stations. For more details, water quality data were monthly measured at Thot Not, Thom Rom, O Mon, Tra Noc, Binh Thuy, Khai Luong, and Cai Sau stations, while streamflow data were monthly recorded at three stations, namely Thot Not, Tra Noc, and Can Tho.

Historical climatic data, including daily temperature, rainfall, and evaporation for the 40 years from 1979 to 2018, were collected from the Department of Hydro-Meteorology of the cities (DONRE 2019). Instead of using rainfall from 2018, the 10-year average rainfall in the period of 2009–2018 from this study area was considered the current

rainfall for setting up the model to reduce the bias influence of climate variability on simulated outcomes. For climate change impact on water quality analysis, the future prediction of precipitation was done using different Global Climate Models (GCMs), and Representative Concentration Pathway (RCP) output was used after downscaling and bias correction. Changes in average monthly precipitation were calculated as an indicator of climate change on river water quality. Statistical downscaling and trend analysis (a less demanding computation technique to reduce biases in the precipitation frequency and intensity) (Goyal and Ojha 2011) were employed to get monthly climate variables. A historical rainfall analysis with monthly precipitation data of 25 years (1989–2013) was integrated. In the proposal of climate change mitigation strategies, understanding and examining the potential impacts of climate change are vital. Based on the above-mentioned historical rainfall analysis of 25 years, in this research, an assessment of the possible climate change (mainly rainfall change) in the study area over the period 2020–2044 was carried out by using MRICGCM3 and MIROC5 as GCMs with RCP4.5 and RCP8.5 emission scenarios.

Similarly, LULC and hydrological data used in this research were also collected from the cities' Department of Hydro-Meteorology (DOHM), Department of Construction (DOC), and Department of Natural Resources and Environment (DONRE). As mentioned above, Thot Not, Tra Noc, and Can Tho are streamflow monitoring stations in the study area (Fig. 1). In which, monthly streamflow data have been measured in Thot Not and Tra Noc since 2013, while Can Tho station was established for monitoring since 2001 (DONRE 2019; MRC 2020). In this research, the collected data were applied for the calibration and validation processes by comparing them with the simulated values from the WEAP hydrology module simulation. In detail, average monthly streamflow values for the period of 2013–2018 at upstream stations, namely, Thot Not and Tra Noc, were used for calibration, while validation was separately done at Can Tho station located at the downstream area because of observed data availability for a longer period. Parameters utilized for the calibration process are effective precipitation and runoff/infiltration ratio, and the steps used to achieve the best fit are shown in Table 3.

In this research, the Hau River water quality was assessed and simulated under the impact of wastewater discharged from industrial and domestic activities of cities' nine districts along the Hau River banks. Thus, these districts' population and industrial data in the period of 2013–2018 were collected from the cities' Statistical Offices (VNCSO 2018; CTCSSO 2019). The DSRs mainly give a schematic representation of domestic

Table 3 Summary of parameters and steps used for streamflow and water quality calibration processes

Parameters	Initial values	Best-fit values	Steps
Streamflow calibration			
Effective precipitation (%)	100	98	±0.5
Runoff/infiltration ratio (%)	50/50	40/60	±5/5
Water quality calibration			
Riverhead's BOD (mg/l)	8	5	±0.5
Riverhead's TC (CFU/100 ml)	500	650	±25
Riverhead's NO ₃ ⁻ (mg/l)	1	0.5	±0.1
Riverhead's PO ₄ ³⁻ (mg/l)	0.07	0.055	±0.005

water consumption (130, 150, and 180 L/capita/day in the periods of 2013–2015 (DONRE 2015; DOC 2019), 2016–2025 (Trung et al. 2019b), and 2026–2030 (MOC 2011; CTCPC 2019b), respectively) and wastewater pollution loads (domestic discharge) per capita (DOC 2019). In order to evaluate the impact of population growth on the future river water quality, the future population distribution at these DSRs was also calculated by ratio method using the United Nations Department of Economic and Affairs (UNDESA) projected growth rate (UN DESA 2019). In terms of industry, the water consumption and demand of current and future DSIs were calculated and assumed based on the cities' reports and master plans (CTCPC 2019b; WASSC 2013, 2020).

For river water quality data, BOD, TC, NO_3^- , and PO_4^{3-} concentrations, which were monitored on a monthly basis for the period of 2013–2018 by the Can Tho Centre of Natural Resources and Environment, were used (DONRE 2020). This observed data of river water quality were seasonally compared with the simulated ones with the aim of calibrating and validating the WEAP water quality modeling component. In the calibration process, the seasonal values of BOD, TC, NO_3^- , and PO_4^{3-} concentrations in the wet (May to November) and dry (December to April) periods for the year 2013–2018 at four upstream stations, namely, Thot Not, Thom Rom, O Mon, and Tra Noc, were used for calibration, while concentrations at Binh Thuy, Khai Luong, and Cai Sau stations located in lower areas were utilized for validation. Table 3 shows the Hau Riverhead water quality parameters adjusted for the calibration process.

In the study area, the numbers of centralized WWTPs and RWTPs as wastewater and river water handling infrastructures considered for current and future scenarios were 6 (DOC 2019) and 25 (Master Plans), respectively (Fig. 3). In the scenarios with mitigation measures, the sewerage connection rates for households, industrial factories, and the Hau River were assumed as equals to the percentages of total wastewater and river water being transported to centralized WWTPs and RWTPs. In other words, clogging and leakage of sewerage pipelines were neglected. In this research, the sewerage pipeline systems for households and industrial factories were the only input sources of domestic and industrial wastewater into the Hau River and its tributaries, while the system used to collect polluted river water for treating was also applied for transporting river water only. In terms of technology, current WWTPs adopted in the model was of up-flow anaerobic sludge blanket reactor coupled with trickling filter (UASB-TF) type (Chernicharo and Nascimento 2001; JICA 2010) (with the filtering velocity: only 0.1–0.5 m/h) in wastewater treatment, and their average treatment efficiency for BOD, TC, NO_3^- , and PO_4^{3-} levels are calculated as 86.47%, 89.63%, 50.79%, and only 31.59% respectively (DOC 2019). However, the key aim of the cities' master plans is to achieve class A of surface water quality ($\text{BOD} \leq 6$ mg/l, $\text{TC} \leq 5,000$ CFU/100 ml, $\text{NO}_3^- \leq 5$ mg/l, and $\text{PO}_4^{3-} \leq 0.2$ mg/l) (MONRE 2015) prescribed by Vietnamese national standard with all possible mitigation measures in the future (DOC 2019). Therefore, more advanced treatment technology—the up-flow anaerobic sludge blanket reactor coupled with sequencing batch reactor (UASB-SBR) type (Khan et al. 2013; Kumar 2018)—will be adopted for both new WWTPs and RWTPs in the future scenarios of 2030 (CTCPC 2016). Consequently, the average treatment efficiency of these new treatment plants for 2030 will be 97.26%, 99.72%, 75.55%, and 76.65% for the BOD, TC, NO_3^- , and PO_4^{3-} levels, respectively (DOC 2019). (For details, Table 6 of Appendix 2 indicates the characteristics of the existing and planned WWTPs as well as proposed RWTPs along the Hau River in the study area.)

As mentioned earlier, the compulsory processes of the water quality simulation are the calibration and validation processes performed with river discharge and water quality

parameters. Once satisfied statistically, numerical simulation using different future scenarios called business-as-usual (BAU) scenario and scenarios with mitigation measures (WM75, WM100, and WM_Opt. with WWTPs and RWTPs) will be applied.

Assumptions made.

The following assumptions are made for this study.

- (i) No consideration about non-point pollution sources because of the unavailability of the dataset. However, if the data are available, the WEAP model can handle simulation of non-point source pollutants like pollutants from agricultural runoff. For example, if we would like to consider the simulation of pollutants coming from agricultural runoff, we need to know the area of agricultural fields, chemical composition and amount of fertilizers used, amount of irrigation water used, etc., then we have an empirical formula to calculate the pollutant generated from runoff. Specifically, according to USEPA (2001), Sieber and Purkey (2015), and Kipyego and Ouma (2018), the non-point sources' load contribution from each land use type at catchment level is estimated using the simple and export coefficient methods based on the data availability and applicability on a watershed. In these methods, the following equation is used for the estimation of constituents such as total suspended solids (TSS), BOD, NO_x (nitrate and nitrite), ammonia, and fecal coliforms.

$$L_p = \sum_p (L_{pU} \times A_U) \quad (10)$$

where L_p is the pollutant load (kg/year); L_{pU} is the pollutant export coefficient for each land use (kg/hectare/year); and A_U is the area by certain land use (hectare).

- (ii) No consideration about the seasonal fluctuations of water consumption and wastewater discharge. Because the differences in water consumption and wastewater discharge between the wet and dry seasons are insignificant (WASSC 2020);
- (iii) No consideration about the mixing of stormwater with domestic wastewater in the sewerage pipelines. This is because, since 2017, domestic wastewater drainage pipelines have been operating independently (DOC 2019).

4 Results and discussion

4.1 Future pattern of precipitation

To study the climate change impact on water quality, the change of rainfall pattern in the future was forecast using the GCMs (MRICGCM3 and MIROC5) and RCPs (RCP4.5 and RCP8.5). Comparison of average monthly rainfall for current, i.e., 10-year average, and future, i.e., 2030, years is shown in the line chart in Fig. 4. Although it is evident that the differences between annual average rainfall for both the current and future simulated values are small, this study further investigates the impact of seasonal variation in rainfall patterns on water quality.

4.2 Population and industrial growth

In this study area, population growth and intensive industrialization were considered to have a potential threat to river water quality in the future. The current population of the

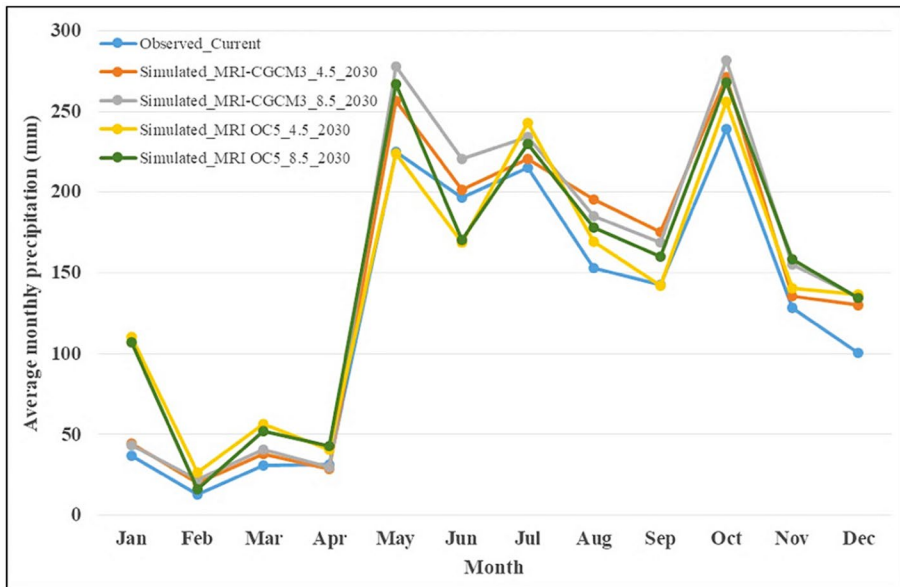


Fig. 4 The current and future monthly precipitation at the Can Tho station

study area in 2018 (base year) collected from the cities' statistical offices was 1,337,931 people (VNCSO 2018; VLCSO 2018). Based on the projected growth rates in the UN DESA's report (UN DESA 2019), the ratio method was used for the study area's future population prediction (see Table 7 of Appendix 2 for projected population growth rates of the study area from 2018 to 2030). The current (2018) and future (2030) populations of each district/catchment as well as the total population of the study area are calculated and shown in Table 1. It is predicted that the estimated population in the target year 2030 (1,974,767 people) will be 47.6% higher than that in the base year 2018 (1,337,931 people). Remarkably, this increasing population has resulted in much higher water demand for domestic activities in the study area's residential areas in the future, from 73.25 million m^3 in 2018 to 130.33 million m^3 in 2030. Regarding industrial development in the future, based on the cities' reports and master plans, the used data are the number of new planned industrial parks; their locations and areas; and water demand (MOC 2009; DONRE 2015; VLCPC 2018). Eight new planned industrial zones considered in the study area are High-Tech Can Tho, O Mon, Bac O Mon, Song Hau 2, Song Hau 3, HighTech Lai Vung, Dong Binh, and Binh Tan. The total area and daily water consumption of these planned industrial zones were 3,090 ha and 299.3 million m^3 , respectively (MOC 2011; MOPI 2018; DTCPC 2015, 2020). Figure 14 of Appendix 1 indicates the study area's comparative water demands of residents and industry between 2018 and 2030. In the absence of precise information, the amount of wastewater being generated from both domestic and industrial sites for the WEAP modeling was calculated based on the actual demand. For example, in the case of the domestic sector, wastewater generated was roughly 80% of the total water being consumed (DOC 2019), whereas for the industrial sector it was 75% (JICA 2017; CTCCP 2019b; WASSC 2020).

4.3 Water quality simulation

4.3.1 Model performance evaluation

For streamflow and water quality calibration processes, effective precipitation, runoff/infiltration ratio, and the Hau Riverhead water quality parameters (with their best-fit values

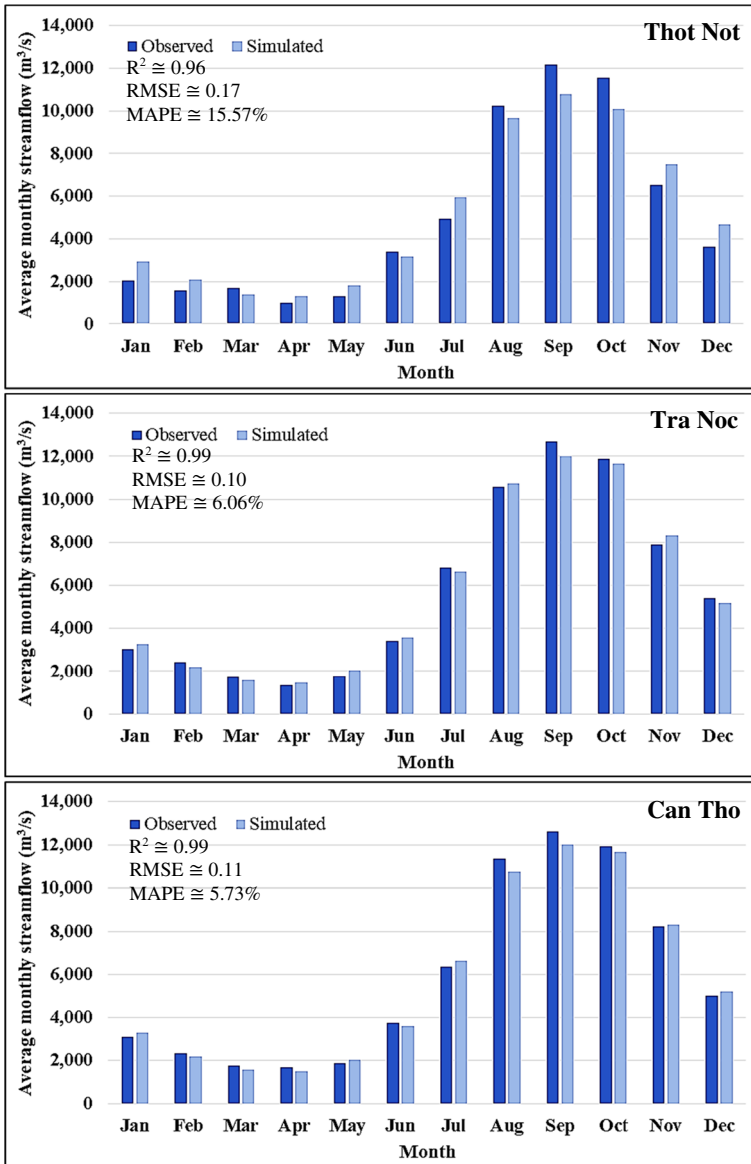


Fig. 5 The comparative values of average monthly observed and simulated streamflow for the year 2013–2018 for calibration (Thot Not and Tra Noc stations) and validation (Can Tho station) processes in the Hau River

shown in Table 3) were adjusted using the trial-and-error method. These processes aim to obtain simulated results having a high association with observed values. The association level is represented by correlation coefficients R -squared (R^2), root mean square error (RMSE), and mean absolute percentage error (MAPE). The calibration and validation results of hydrological components through comparative results between the average monthly observed and simulated streamflow for the year 2013–2018 at three hydraulic stations (namely Thot Not, Tra Noc, and Can Tho) in the Hau River are shown in Fig. 5. Basically, both simulated streamflow and observed streamflow for Thot Not, Tra Noc, and Can Tho stations have shown high associations supported by $R^2 \cong 0.96$, $RMSE \cong 0.17$, and $MAPE \cong 15.57\%$; $R^2 \cong 0.99$, $RMSE \cong 0.10$, and $MAPE \cong 6.06\%$; and $R^2 \cong 0.99$, $RMSE \cong 0.11$, and $MAPE \cong 5.73\%$, respectively.

Results for calibration and validation processes in case of water quality parameters, i.e., BOD, TC, NO_3^- , and PO_4^{3-} , were shown through the comparison between average seasonally observed and simulated concentrations for the year 2013–2018 at seven stations, namely Thot Not, Thom Rom, O Mon, Tra Noc (selected for calibration), Binh Thuy, Khai Luong, and Cai Sau (used for validation). As Figs. 6, 7, 8 and 9 show, significant associations are also found between observed and simulated average seasonally BOD, TC, NO_3^- , and PO_4^{3-} levels in both the wet and dry periods at selected stations. These matches were expressed through the fluctuations of $R^2 \cong 0.76$ – 0.99 , $RMSE \cong 0.02$ – 0.16 , and $MAPE \cong 2.48$ – 16.61% for the comparison of these four parameters. Thus, the calibration and validation results for both streamflow and water quality parameters of the Hau River had demonstrated high reliability and suitability of the model performance for both hydrological and water quality modeling.

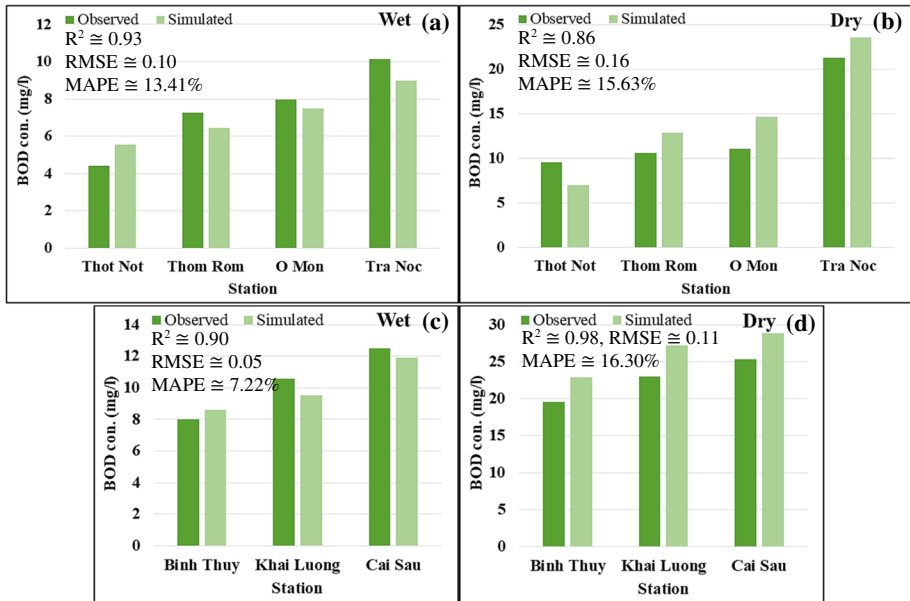


Fig. 6 The comparative values of average seasonally observed and simulated BOD levels in the period of 2013–2018 utilized in the calibration (a, b) and validation (c, d) processes

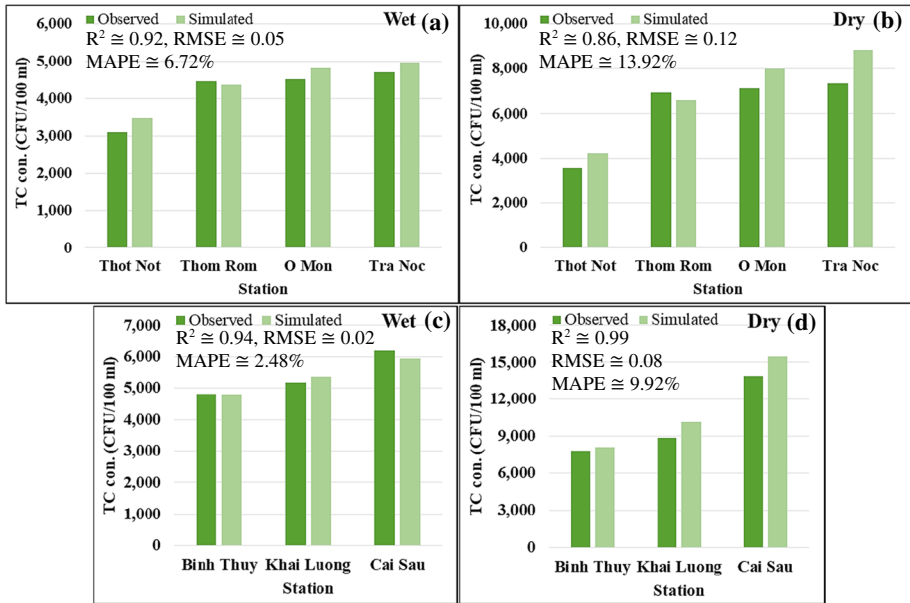


Fig. 7 The comparative values of average seasonally observed and simulated TC levels in the period of 2013–2018 utilized in the calibration (a, b) and validation (c, d) processes

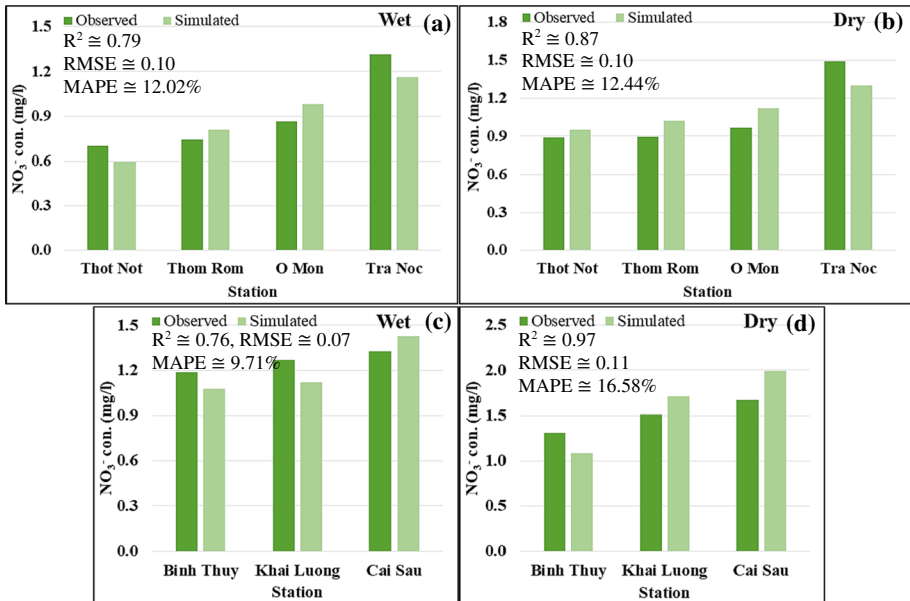


Fig. 8 The comparative values of average seasonally observed and simulated NO_3^- levels in the period of 2013–2018 used in the calibration (a, b) and validation (c, d) processes

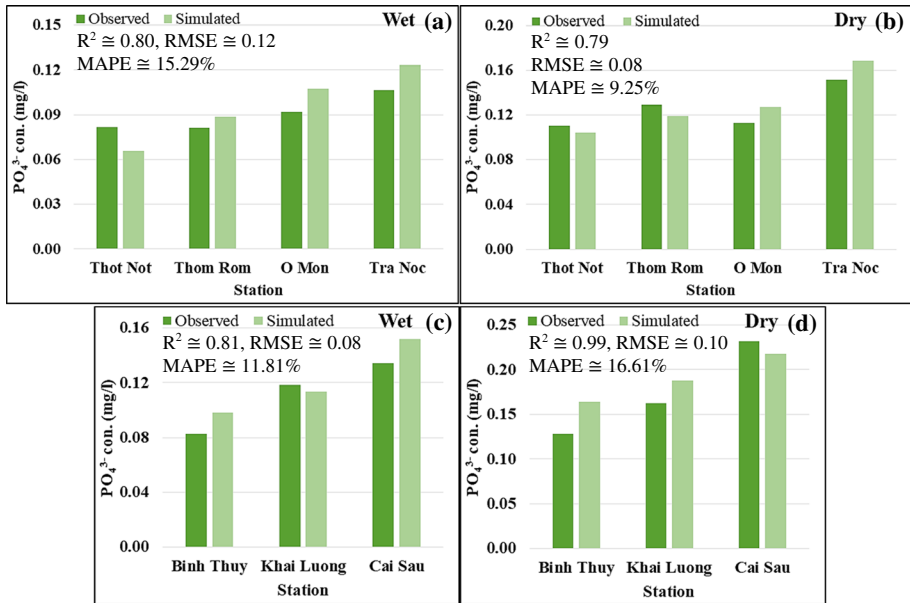


Fig. 9 The comparative values of average seasonally observed and simulated PO_4^{3-} levels in the period of 2013–2018 used in the calibration (a, b) and validation (c, d) processes

4.3.2 Predicting future water quality using scenario analyses

Scenario analysis was done to predict possible future water quality status in both the wet and dry seasons and evaluate the effectiveness of the proposed countermeasures in water pollution mitigation. In this study, the future changes in BOD, TC, NO_3^- , and PO_4^{3-} concentrations were simulated and analyzed under four different future scenarios. While the scenario with BAU employs key drivers to water quality influence such as population growth, industrial development, and climate change (mainly rainfall changes); countermeasures, i.e., wastewater treatment policy change (WWTPs' and RWTPs' application) will be included in other scenarios. Noticeably, the study area's government has often faced a number of difficulties related to the financial limitation, technology changes, and policy barriers that lead to the delayed completion of WRM projects in recent years (listed in Table 8 of Appendix 2 as examples). Therefore, future scenarios with mitigation measures had been built based on the study area's more realistic conditions in recent years. Currently, to solve the current and future Hau River water pollution, the study areas' government is planning to build from 11 to 14 new centralized WWTPs with the national budget and the Japanese Official Development Assistance (ODA) loan. The major target of this investment is to collect and treat 75 to 100% of the total domestic and industrial wastewater discharged from the study areas' point pollution sources by 2030 (CTCPC 2016). Based on the cities' current condition and future strategies, therefore, two future mitigation measures (with centralized WWTPs applied for treating 100% (WM100) and only 75% (WM75) of total wastewater, respectively) were assumed and analyzed. In addition, to achieve the ambient water quality of class A prescribed by the Vietnamese national standard (CTCPC 2016) in case the WM100 scenario is unable to bring about the expected effectiveness, an optimistic scenario (WM_Opt.) has been also

built. This additional scenario possesses similar components as the WM100 scenario but with the addition of five RWTPs for treating surface water at seriously polluted locations along the Hau River in 2030 (Fig. 3). As previously mentioned, sites of planned WWTPs were identified based on the cities' reports and master plans, while proposed RWTPs' sites were located based on the pollution status of the Hau River water quality, which was simulated from the model.

One thing to note is that according to CTCPC (2019b) and MOC (2020), in the study area, the total average costs investing for a water treatment plant (treatment capacity: 30,000 m³ per day) with the technology of UASB-TF and UASB-SBR are nearly 22.69 and 24.25 million USD, respectively. All scenarios used in the study as well as their key characteristics, components, and estimated costs are briefly indicated in Table 4.

In the four considered scenarios, the BOD, TC, NO₃⁻, and PO₄³⁻ concentrations of the Hau River surface water were simulated on a seasonal basis for the year 2030. After establishing proposed scenarios, the Hau River water quality simulations were modeled, and obtained results are shown in the bar charts and maps in Fig. 10. In addition, these simulated results are also illustrated at the spatial scale in Figs. 11 and 12. The differences in simulated parameters' concentrations caused by rainfall changes from the GCMs with RCP4.5 and RCP8.5 emission scenarios are shown by small bars on the top of bar charts. It can be noticed that the impacts of rainfall changes on BOD, TC, NO₃⁻, and PO₄³⁻ concentrations of the Hau River water in both wet and dry seasons were negligible. This might be explained by the insignificant difference between the increased volume of rainfall in the future (as shown in Fig. 4) and the Hau River streamflow.

In the current year, as can be seen from Fig. 10, simulated BOD, TC, NO₃⁻, and PO₄³⁻ concentrations from most monitoring stations, except for some ones in the Hau River downstream areas, in the wet season were not too high, fluctuating from 5.36 to 11.42 mg/l, from 3,391 to 6,127 CFU/100 ml, from 0.57 to 0.93 mg/l, and only from 0.06 to 0.09 mg/l respectively. Compared to class A of the NTRSWQ, the Hau River surface water quality in the wet season of 2018 was relatively polluted in terms of BOD and TC at Binh Thuy, Khai Luong, and Cai Sau stations despite this river's large discharge during the rainy period (Fig. 10a and c). Noticeably, regarding NO₃⁻ and PO₄³⁻, these parameters' current levels were much lower compared to the permissible ones of class A (Fig. 10e and g). For the BAU scenario, consequently, the BOD and TC pollution has increasingly become more serious in 2030 under the impacts of intensive population and industry growths, and rainfall change without any appropriate mitigating measure applied, while NO₃⁻ and PO₄³⁻ concentrations are still within the desired limits of class A1. In this scenario, it can be seen that the BOD and TC levels in the wet season at four downstream stations of the Hau River basin have sharply increased and are much higher compared to class A, ranging from 7.95 to 14.48 mg/l and from 6,470 to 9,973 CFU/100 ml, respectively (Figs. 10a and c and 11a). Because of the key drivers (population growth, industrial development, and climatic changes), the average levels of BOD, TC, NO₃⁻, and PO₄³⁻ in the wet season will be increased by 16.01%, 40.85%, 30.49%, and 20.22%, respectively by 2030 compared to 2018 (Table 5).

In the dry season, the Hau River water pollution has intensively become more serious in both the current (2018) and the coming years (2030). Simulated BOD, TC, and PO₄³⁻ levels at most stations, especially for the ones downstream, in 2018 were much higher compared to class A of the NTRSWQ, fluctuating from 6.22 to 64.34 mg/l, from 4,024 to 14,306 CFU/100 ml, and 0.08 to 0.45 mg/l, respectively (Figs. 10b, d, and h). Noticeably, simulated BOD, TC, and PO₄³⁻ levels at four downstream stations in 2030 for the

Table 4 The summary of key components of four different scenarios used for the future water quality simulation

Future scenarios	Population growth	Industrial growth	Climate change	WWTPs' and RWTP's application/treatment capacity	Estimated cost (million USD)
Business-as-usual (BAU)				(6 WWTPs: 100,000 m ³ /day)	-
With measure_75% (WM75)				(15 WWTPs: 1,117,500 m ³ /day)	822.48
With measure_100% (WM100)				(20 WWTPs: 1,490,000 m ³ /day)	1,123.58
With optimistic measure (WM_Opt.)				(20 WWTPs: 1,490,000 m ³ /day; 5 RWTPs: 775,000 m ³ /day)	1,750.04

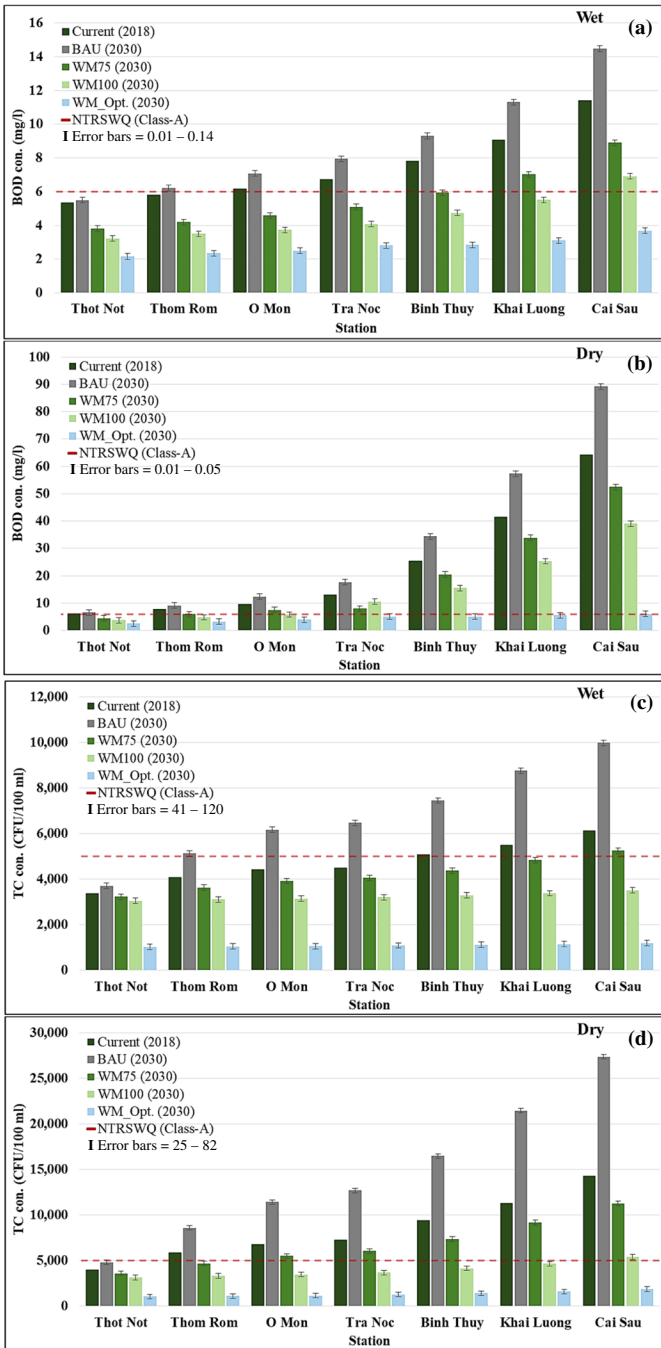


Fig. 10 The average seasonally comparative results of simulated BOD (a, b), TC (c, d), NO_3^- (e, f), and PO_4^{3-} (g, h) levels for the current status and future scenarios. The error bars show differences in simulated levels caused by rainfall changes from the GCMs with RCP4.5 and RCP8.5 emission scenarios

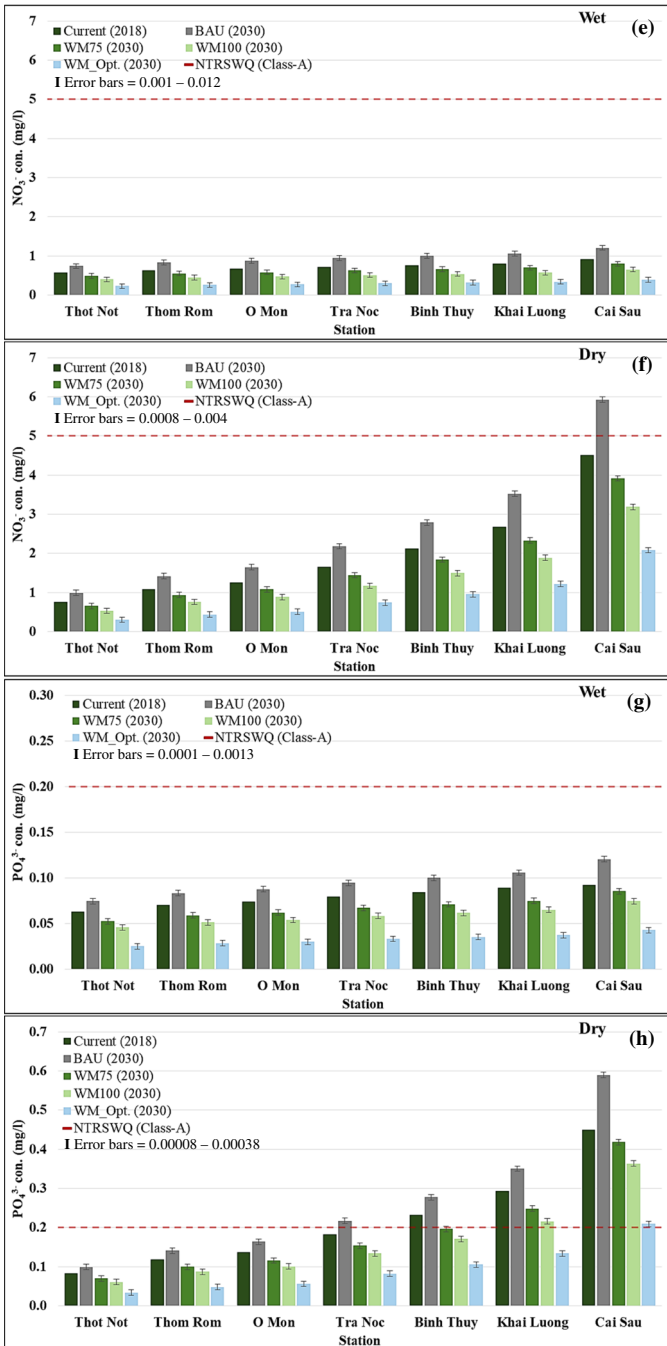


Fig. 10 (continued)

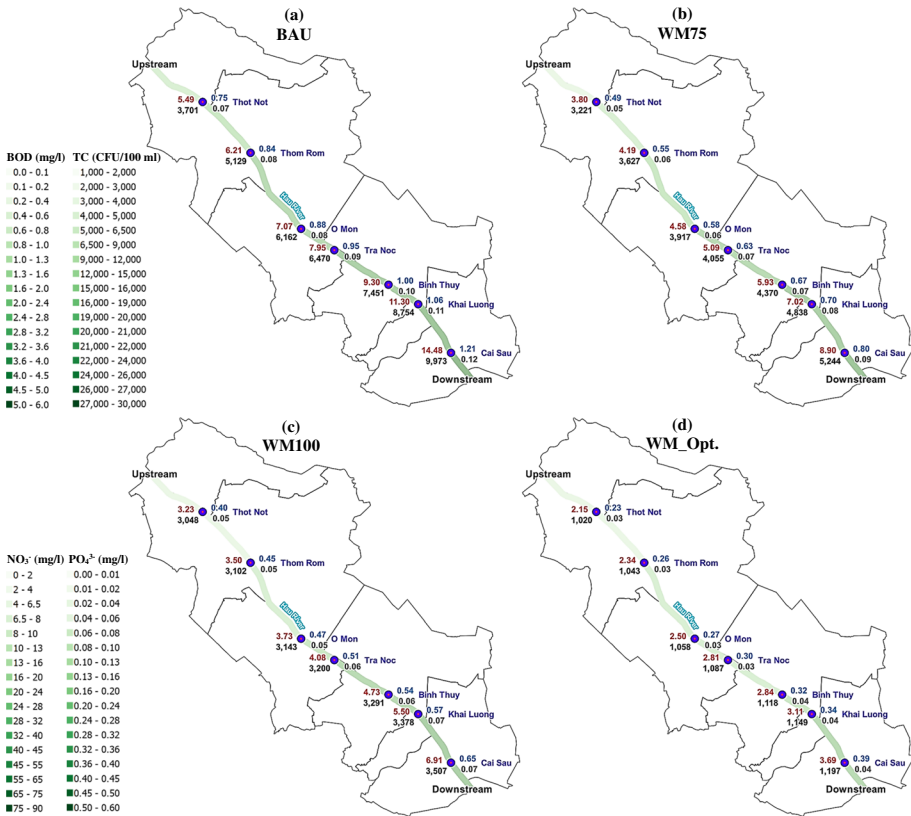


Fig. 11 The seasonally spatial variations of BOD (red numbers), TC (black), NO₃⁻ (blue), and PO₄³⁻ (gray) levels simulated in scenarios in the wet season

BAU scenario will further deteriorate in comparison with these levels in the current year, ranging from 17.64 to 89.21 mg/l, from 12,700 to 27,345 CFU/100 ml, and from 0.22 to 0.59 mg/l, respectively (Fig. 12a). These significantly high levels are mostly due to untreated wastewater discharged from future domestic and industrial activities as well as low discharge and severe droughts in the Hau River during the dry period. Regarding NO₃⁻ level in the BAU scenario, only the nitrogenous pollution at Cai Sau station should be noted and solved in the future (Fig. 10f). Table 5 also shows the average increased percentages of future BOD, TC, NO₃⁻, and PO₄³⁻ levels in the dry season as compared to these levels in 2018. From simulated results, it can be clear that these parameters' current and future concentrations at all monitoring stations along the Hau River in the dry season are much higher than those in the wet one. For the year 2030, without any measures applied, indeed, the average BOD, TC, NO₃⁻, and PO₄³⁻ levels in the dry season are from two to threefold as much as those in the wet one. Remarkably, the highest difference in TC level can be seen at Cai Sau station, at 9,973 CFU/100 ml in the wet season as opposed to 27,345 CFU/100 ml in a dry one (Figs. 11a and 12a). For BOD, this difference has amounted to more than sixfold, at 14.48 mg/l as compared to 89.21 mg/l (Figs. 11a and 12a). In terms of NO₃⁻ and PO₄³⁻ levels, the highest differences are also noted at the lowest monitoring station, at 1.21 mg/l as compared to

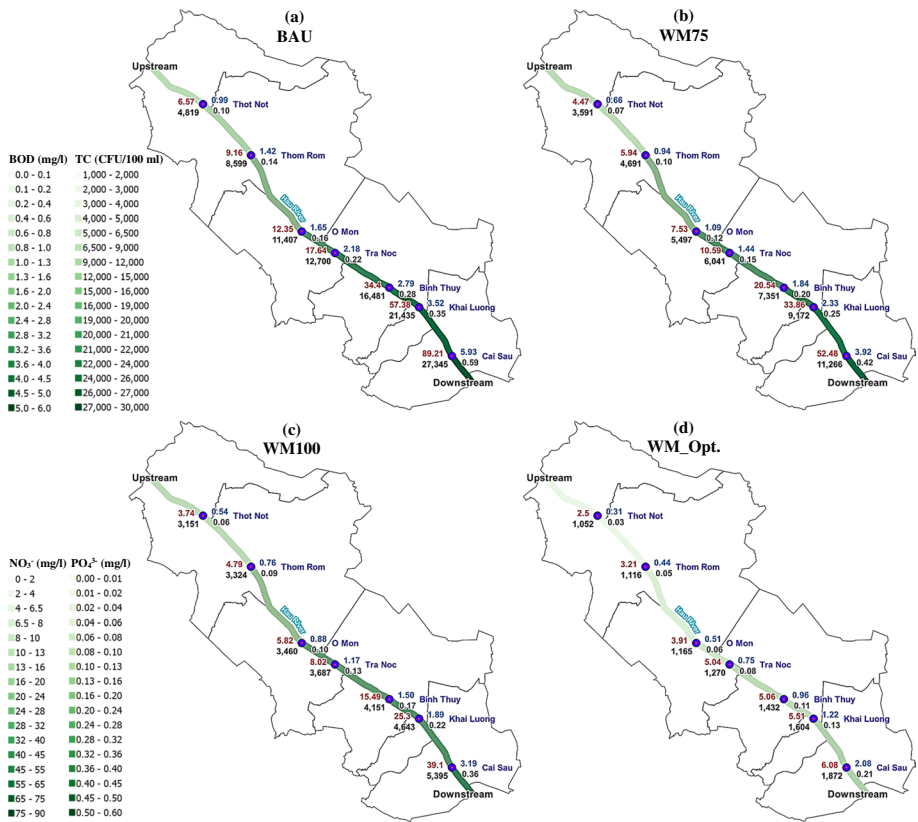


Fig. 12 The seasonally spatial variations of BOD (red numbers), TC (black), NO₃⁻ (blue), and PO₄³⁻ (gray) levels simulated in scenarios in the dry season

Table 5 The average increases and key components' contribution rates on seasonal BOD, TC, NO₃⁻, and PO₄³⁻ concentrations of the Hau River water in the BAU scenario

Parameters	Average increase with BAU scenario (2018–2030) (%)		Rate of contribution (%)					
	Wet	Dry	Population growth	Industrial growth	Rainfall change			
	Wet	Dry	Wet	Dry	Wet	Dry		
BOD	16.01	27.80	1.08	1.10	98.81	98.74	0.11	0.16
TC	40.85	65.94	55.74	55.51	43.44	43.66	0.82	0.83
NO ₃ ⁻	30.49	31.05	34.86	34.30	59.24	60.73	5.23	5.62
PO ₄ ³⁻	20.22	20.64	33.98	33.66	59.15	59.77	6.48	6.98

5.93 mg/l and 0.12 mg/l as opposed to 0.59 mg/l respectively (Figs. 11a and 12a). Key factors responsible for the differences in river water pollution levels between the wet and dry seasons in the study area are seasonal changes in rainfall and especially the Hau River discharge.

With the aim of generating more detailed and practical use of this result to support the cities' policymakers and master plans, the seasonal impact of each considered driver on the Hau River water quality was separated and assessed individually and the result was shown in Table 5. There is an insignificant difference in contribution rates between the two seasons. For BOD concentration, industrial growth has accounted for the highest percentage of contribution, fluctuating from 98.74 to 98.81%, whereas the opposite is true of rainfall change and population growths (only 0.11–0.16% and 1.08–1.10%, respectively). This is due to the fact that the typical average BOD concentration of industrial wastewater was nearly 13-fold higher than that of residential wastewater, at 1,000 mg/l as opposed to 80 mg/l for the latter (JICA 2017; CTCPC 2019b; DOC 2019). Moreover, the increased volume of industrial wastewater of the study area in 2030 considered in this model will be very large in comparison to that of domestic wastewater (Figure 14 of Appendix 1). Regarding the increased TC level in 2030, the industrial expansion and population growth have shared similarly high rates of contribution to TC pollution in both the wet and dry seasons, ranging from 43.44 to 43.66% and 55.51 to 55.74%, respectively. This similarity can be explained by the converse TC level in domestic and industrial sewages. Specifically, although the volume of the forecast wastewater from domestic activities in 2030 is only about one-fifth of the industrial wastewater (57.08 million m³ versus 299.03 million m³), the average recorded TC level of the former is much higher than that of the latter (8.8 million CFU/100 ml versus 1 million CFU/100 ml) (Phung et al. 2015; Nga et al. 2018; DOC 2019). Noticeably, the contribution through the change in future rainfall trend and volume is also relatively small (only 0.82–0.83%). This result is consistent with the statement mentioned earlier in the future rainfall forecast.

In terms of NO₃⁻ and PO₄³⁻ increases, the contribution rates of industrial development in both the wet and dry seasons fluctuate around 60%, while around 34% are contributed by population growth. These were due to that although typical average NO₃⁻ and PO₄³⁻ levels of domestic wastewater in the study area were higher than those of industrial wastewater (at NO₃⁻: 19 mg/l and PO₄³⁻: 1.5 mg/l as opposed to NO₃⁻: 5 mg/l and PO₄³⁻: 0.4 mg/l for the latter (JICA 2017; CTCPC 2019b; DOC 2019)), the volume of the predicted wastewater from residential activities is much lower compared to the industrial waste. One thing to note is that the precipitation changes in the future have accounted for worth-noting percentages of contribution on the increases in both NO₃⁻ and PO₄³⁻ levels, fluctuating from more than 5% to nearly 7%. This can be explained that urban runoffs and especially agricultural runoffs with quite high input of inorganic nitrogenous and phosphorus fertilizers and manures (Kumar et al. 2010, 2019; Minh et al. 2020) in the study area are also considered remarkable contributors of NO₃⁻ and PO₄³⁻ concentrations to the Hau River.

Under the negative impacts from inevitable drivers (population and industrial growths) and pressure (climate change) on the Hau River water quality in the future, the WEAP model was used to evaluate the effectiveness of potentially structural measures in the study area. In three scenarios with measures, building WWTPs (with the total treatment

capacities of nearly 1.118 and 1.49 million m³ per day) and RWTPs (0.775 million m³ per day) with advanced treatment technology UASB-SBR for treating 75% and 100% wastewater discharged from residential and industrial zones as well as the polluted Hau River water in the future was considered. These water treatment plants' effectiveness is simulated, assessed, and also illustrated in Figs. 10, 11, and 12.

In both scenarios with mitigation measures (WM75 and WM100), as shown from these figures, the application of WWTPs led to the considerable decline in the average BOD, TC, NO₃⁻, and PO₄³⁻ levels in the wet season of 2030, by 35.28% (for WM75)/47.68% (WM100), 35.65% (MW75)/48.39% (WM100), 33.80% (MW75)/46.09% (WM100), and 29.10% (MW75)/38.03% (WM100) respectively compared to those in the BAU scenario. Noticeably, the simulated values of four these parameters' levels in the wet season at all stations will meet the desired water quality of class A (BOD ≤ 6 mg/l, TC ≤ 5,000 CFU/100 ml, NO₃⁻ ≤ 5 mg/l, and PO₄³⁻ ≤ 0.2 mg/l) (MONRE 2015) of the NTRSWQ except for BOD levels at Cai Sau station. The average BOD concentrations at this station for WM75 and WM100 were only 8.90 and 6.91 mg/ml, which were just over that in class A (Figs. 10a and 11b and c). Regarding water quality in the dry season, however, the simulated concentrations of both BOD, TC, and PO₄³⁻ for both scenarios WM75 and WM100 indicated that the application of WWTPs has given high effectiveness for river water quality improvement at the upstream stations only. At the remaining stations in lower areas, including Tra Noc, Binh Thuy, Khai Luong, and Cai Sau; TC, PO₄³⁻, and especially BOD levels were still much higher compared to class A, ranging from 6,041 to 11,266 CFU/100 ml, from 0.13 to 0.42 mg/l, and from 8.02 to 52.48 mg/l, respectively (Figs. 10d, 10f, 10b, 12b, and 12c). In the WM100, however, TC levels in the dry season at most stations along the Hau River were quite low and meet the desired level of class A (Fig. 10d). It is also noteworthy that the study area's NO₃⁻ pollution in the dry season is not a concerning matter in 2030.

Based on simulated outcomes, it can be seen that the BOD, TC, NO₃⁻, and PO₄³⁻ pollution of the Hau River water in the study area was significantly improved in the wet season by adopting WWTPs with advanced technology treatment of UASB-SBR. In the dry season, however, the pollution of BOD and PO₄³⁻ had not been completely resolved in this river downstream areas (Fig. 10b and h). The key reasons responsible for this issue are that (i) the residual concentrations of pollutants after wastewater treatment in the upstream area will be enhanced in the downstream regions by accumulative effects, (ii) being located at the downstream regions of the study area, the most populous and industrialized districts, namely O Mon, Binh Thuy, Ninh Kieu, Cai Rang, and Binh Minh, hence release a higher amount of wastewater, and (iii) the Hau River streamflow is very low in the dry months. Therefore, in the optimistic scenario (WM_Opt.), the application of RWTPs with the optimal and possible lowest treatment capacity has been proposed with the aim of thoroughly solving the water quality pollution of the entire Hau River in general and its downstream areas in particular. As shown in Figs. 10 and 11, thanks to the application of five RWTPs (with a total treatment capacity of 775,000 m³ per day) at key locations along the Hau River, the BOD and PO₄³⁻ levels at downstream stations have significantly decreased. Indeed, the BOD and PO₄³⁻ levels at Tra Noc, Binh Thuy, Khai Luong, and Cai Sau stations in the dry season have only ranged from 5.04 to 6.08 mg/l and from 0.08 to 0.21 mg/l, respectively (Figs. 10b, 10h, and 12d). It is also noteworthy that the water quality improvement in the dry season is much higher than that in the wet season. This is because the difference between the total treatment capacity of proposed plants and the Hau River discharge in the dry season is much lower compared to that in the wet period.

4.4 Merits and demerits of proposed measures

Although the application of WWTPs has proven its effectiveness on river water pollution mitigation, it cannot be considered as a standalone solution for improving water quality to reach a desirable value of BOD and PO_4^{3-} under class A without an additional support of RWTPs. Reason for selection and application of RWTPs within the WM_Opt. scenario proposed for achieving the desired SWQ of the city are appended below. First of all, based on the simulated results from W100, it was found that even if 100% of future wastewater was collected and treated, the Hau River water with the BOD and PO_4^{3-} pollution in the dry season could not be thoroughly resolved in downstream areas. Also, treatment efficiency of the applied WWTPs under W100 scenarios was equipped with most cutting-edge one technology. So, there is no scope of either increasing the capacity of WWTPs or their treatment efficiency. Apart of rapid industrial urbanization, the issues remain here is the accumulation of pollutants in river downstream area, especially in the dry months, which is a concerning driver leading to this river water quality degradation. An Giang, an upstream city (Fig. 1), is also one of the prominent agro-industrial cities in Vietnam; hence, the quality of river water flowing from this city to the study area can also be considered under the wastewater management and treatment plans. Moreover, according to the current and future master plans, the cities' governments are investing in environmental projects to improve the future river water quality by mainly using structural measures, especially applying more advanced wastewater treatment plants. The national budget and international grants are the main financial sources of these projects. With the aforementioned facts, considering the existing gap to achieve the desired 2030 water quality with WM100, RWTPs at serious water pollution locations along the Hau River were considered to apply in WM_Opt.

However, implementation of proposed structural measures might have some negative issues as well like financial burden for building supporting structures like pipelines, land appropriation in urbanized centers, and disturbances to the local ecosystems. For example, the estimated costs for investing and building water treatment plants in proposed scenarios were relatively high, ranging from 822.48 to 1,750.04 million USD. Therefore, the local authorities should not consider the application of these plants as the sole solution for the study area. Hence, proposing a hybrid solution, where along with building these WWTPs, other options especially green infrastructures or nature-based solutions, viz. constructed wetlands, rain gardens, vegetated swales and median strips, bioswales, porous pavement, and enhancement of riparian buffers and floodplains should be considered for managing industrial wastewater, which can be more environmentally sustainable and cost-effective. Nevertheless, doing technical, economical, and socio-ecological evaluation of these green infrastructures is beyond the scope of this study. Because as mentioned before, this study aims to (i) assess the operational efficiency of water treatment plants proposed in current master plans of the cities to enhance the future Hau River water and thereby (ii) support policymakers in reviewing these plans as well as proposing more environmentally resilience approaches. Therefore, there would be the research gap with the application of these green measures for future studies.

In addition, based on the estimated contribution rates to the water pollution, industrial growth was attributed as the biggest driver of the future Hau River water pollution compared to the other inevitable drivers, i.e., population growth and climate change. Thus, stricter but technically feasible policies and regulations

should be issued to restrict both effluent concentration and volume of wastewater discharged from industrial plants into river bodies. These policies and regulations can focus on main requirements ranging from promoting decentralized WWTPs, adopting industrial symbiosis and sustainability-oriented hybrid solutions, and applying onsite green technologies (e.g., absorbent gardens, green rooftops, roadside plantings, storm water tree trenches) for wastewater treatment and sustainable resource management. Furthermore, concepts of circular economy, sustainable cleaner production, and Industry 4.0 standards should also be considered by the study area's government in the future. Indeed, circular economy practices are being considered one of the most important factors for increasing sustainability performance in manufacturing, followed by the practices of cleaner production and Industry 4.0. Supply chain traceability and information, reuse and recycling infrastructure, natural and clean environment, etc. are globally being the potential practices identified for manufacturing organizations in particular and cities, in general, aiming to enhance sustainability. However, before prioritizing and practicing these concepts at the local level, a robust scientific understanding about their economic and environmental benefits must be there.

5 Conclusions and recommendations

This study presents an overall picture of the current and future water quality in the wet and dry seasons of the Hau River using the scenario-based analysis to identify key drivers responsible for water pollution and to aware the local policymakers. It is evident that BOD, TC, and PO_4^{3-} concentrations in 2018 are high in the river water, especially in the dry period, as compared to the desired level in class A of NTRSWQ. Under the BAU scenario with the anticipated population growth, rapid industrialization, and rainfall change, the river water quality will be further deteriorated, especially in the dry season and in downstream areas. Noticeably, industrial development is considered the main driver compared to the other ones, i.e., population growth and climate change. In the scenario with measures, the implementation of WWTPs in the residential and industrial areas can potentially deal with the water pollution problem in the wet season in the Hau River by 2030. However, water quality, especially BOD and PO_4^{3-} pollution, will still be a matter of concern when looking into the downstream water quality in the dry period. In order to combat this issue, the additional combination of RWTPs for treating river water at a number of key locations of pollution was successfully applied. However, given the relatively high investment costs for the application of water treatment plants, the cities' governments should consider and propose more other solutions to the future water pollution in the Hau River. Besides, the monitoring and assessing programs on non-point pollution sources in the study area should be also developed with the aim of achieving a more comprehensive assessment of future river water pollution.

Appendix 1

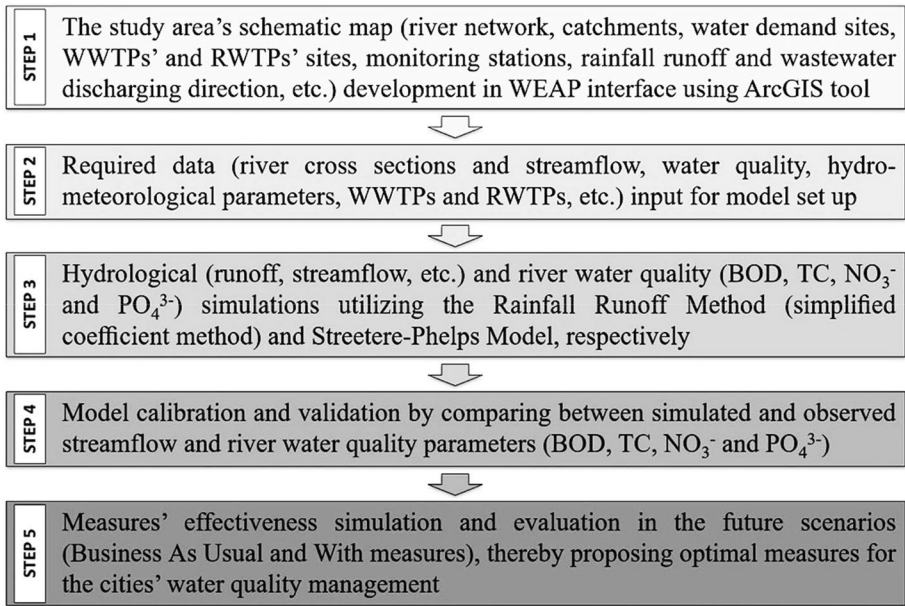


Fig. 13 Flowchart for the research methodology

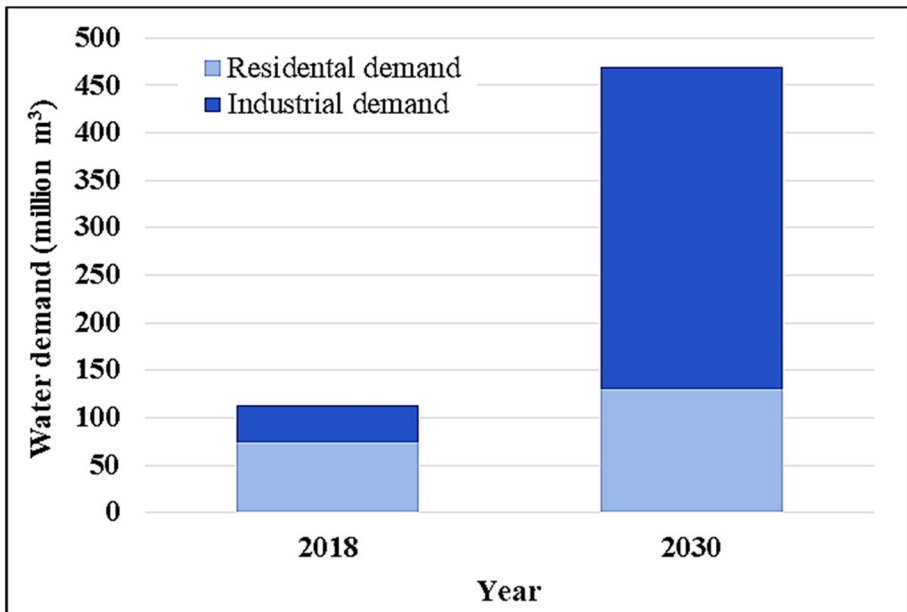


Fig. 14 The study area's comparative water demands of residents and industry between 2018 and 2030

Appendix 2

Table 6 The treatment characteristics of existing and new WWTPs and RWTPs located in the study area

WWTPs	Location (district)	Capacity (thousand m ³ /day)		Efficiency (%) / discharged concentration (BOD, NO ₃ ⁻ , and PO ₄ ³⁻ ; mg/l; TC CFU/100 ml)							
		2018 (current standard)	2030 (designed standard)	BOD	TC	NO ₃ ⁻	PO ₄ ³⁻	BOD	TC	NO ₃ ⁻	PO ₄ ³⁻
Domestic WWTPs											
Can Tho	Ninh Kieu	30	110	87.83/9.74	89.75/902,422	51.58/9.2	30.67/1.04	97.5/≤2	99.74/≤22,500	75.65/≤5	76.8/≤0.35
Thot Not	Thot Not	-	50	-	-	-	-	97.5/≤2	99.74/≤22,500	75.65/≤5	76.8/≤0.35
O Mon	O Mon	-	40	-	-	-	-	97.5/≤2	99.74/≤22,500	75.65/≤5	76.8/≤0.35
Binh Thuy	Binh Thuy	-	35	-	-	-	-	97.5/≤2	99.74/≤22,500	75.65/≤5	76.8/≤0.35
Lap Vo	Lap Vo	-	40	-	-	-	-	97.5/≤2	99.74/≤22,500	75.65/≤5	76.8/≤0.35
Lai Vung	Lai Vung	-	40	-	-	-	-	97.5/≤2	99.74/≤22,500	75.65/≤5	76.8/≤0.35
Binh Tan	Binh Tan	-	25	-	-	-	-	97.5/≤2	99.74/≤22,500	75.65/≤5	76.8/≤0.35
Binh Minh	Binh Minh	-	20	-	-	-	-	97.5/≤2	99.74/≤22,500	75.65/≤5	76.8/≤0.35
Total		30 (1 plant)	360 (8 plants)								
Industrial WWTPs											
Thot Not Industry	Thot Not	10	150	85.1/149	89.5/104,980	50/2.5	32.5/0.27	97.01/≤30	99.7/≤3,000	75.45/≤1.25	75.3/≤0.1
Tra Noc	O Mon	30	80	85.1/149	89.5/104,980	50/2.5	32.5/0.27	97.01/≤30	99.7/≤3,000	75.45/≤1.25	75.3/≤0.1
Bac O Mon	O Mon	-	70	-	-	-	-	97.01/≤30	99.7/≤3,000	75.45/≤1.25	75.3/≤0.1
Hung Phu	Cai Rang	10	90	85.1/149	89.5/104,980	50/2.5	32.5/0.27	97.01/≤30	99.7/≤3,000	75.45/≤1.25	75.3/≤0.1
HighTech Can Tho	Ninh Kieu	-	110	-	-	-	-	97.01/≤30	99.7/≤3,000	75.45/≤1.25	75.3/≤0.1

Table 6 (continued)

WWTPs	Location (district)	Capacity (thousand m ³ /day)		Efficiency (%) / discharged concentration (BOD, NO ₃ ⁻ , and PO ₄ ³⁻ : mg/l; TC CFU/100 ml)							
		2018 (current standard)	2030 (designed standard)	BOD	TC	NO ₃ ⁻	PO ₄ ³⁻	BOD	TC	NO ₃ ⁻	PO ₄ ³⁻
Song Hau 1	Lai Vung	10	130	85.1/149	89.5/104,980	50/2.5	32.5/0.27	97.01/≤30	99.71/≤3,000	75.45/≤1.25	75.3/≤0.1
Song Hau 2, 3, and HighTech	Lai Vung	-	70, 110, and 80	-	-	-	-	97.01/≤30	99.71/≤3,000	75.45/≤1.25	75.3/≤0.1
Binh Minh Industry	Binh Minh	10	60	85.1/149	89.5/104,980	50/2.5	32.5/0.27	97.01/≤30	99.71/≤3,000	75.45/≤1.25	75.3/≤0.1
Dong Binh	Binh Minh	-	100	-	-	-	-	97.01/≤30	99.71/≤3,000	75.45/≤1.25	75.3/≤0.1
Binh Tan	Binh Tan	-	80	-	-	-	-	97.01/≤30	99.71/≤3,000	75.45/≤1.25	75.3/≤0.1
Total		70 (5 plants)	1,130 (12 plants)								
RWTPs											
Hau River-head	Lap Vo	-	155	-	-	-	-	97.26/≤0.5	99.72/≤50	75.55/≤0.4	75.65/≤0.05
Binh Tan	Binh Tan	-	155	-	-	-	-	97.26/≤0.5	99.72/≤50	75.55/≤0.4	75.65/≤0.05
Binh Thuy	Binh Thuy	-	155	-	-	-	-	97.26/≤0.5	99.72/≤50	75.55/≤0.4	75.65/≤0.05
Binh Minh	Binh Minh	-	155	-	-	-	-	97.26/≤0.5	99.72/≤50	75.55/≤0.4	75.65/≤0.05
Cai Sau	Binh Minh	-	155	-	-	-	-	97.26/≤0.5	99.72/≤50	75.55/≤0.4	75.65/≤0.05
Total		0 (0 plant)	775 (5 plants)								

Table 7 The UN DESA's projected population growth rate of the study area from 2018 to 2030

Cities	Population growth rate (%)		
	2018–2020	2021–2025	2026–2030
Can Tho	6.24	4.32	2.67
Dong Thap and Vinh Long	2.24	2.14	2.29

Table 8 The implementation progress of WRM projects in the study area in recent years

Project	Quantity	Capacity (m ³ /day)/technology	Cost (million USD)	Planned year	Targeted year	Finished year	Delayed gap	Main reasons
Domestic WWTP	1	30/UASB-TF	21.03	2003	2006	2017	11 years	Financial shortage, changes in technology, policy barriers, etc
Industrial WWTPs	5	70/UASB-TF	56.79	2008	2010	2016	6 years	

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References

- Avtar R, Aggarwal R, Kharrazi A, Kumar P, Kurniawan TA (2020) Utilizing geospatial information to implement SDGs and monitor their Progress. *Environ Monit Assess* 192(1):1–35
- Blanco-Gutiérrez I, Varela-Ortega C, Purkey DR (2013) Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: a hydro-economic modeling approach. *J Environ Manag* 128:144–160. <https://doi.org/10.1016/j.jenvman.2013.04.037>
- Bowie G, Mills W, Porcella D, Campbell C, Chan P, Pagenkopf J, Rupp G, Johnson K, Gherini S (1985) Rates, Constants, and kinetics formulations in surface water quality modeling (Second Edition). US EPA, Athens, Georgia EPA 600/3–85/040
- Chernicharo CAL, Nascimento MCP (2001) Feasibility of a pilot-scale UASB/trickling filter system for domestic sewage treatment. *Water Sci Technol* 44(4):221–228
- CTCPC (Can Tho City's People Committee) (2014) The completion of the 2nd phase urban upgrading project in Can Tho City. *Can Tho News*. <https://baocantho.com.vn/som-hoan-thanh-du-an-nang-cap-do-thi-tp-can-tho-giai-doan-2-a65413.html>. Accessed 10 Jan 2021
- CTCPC (Can Tho City's People Committee) (2016) The approval of water drainage planning project in Can Tho City up to 2030, with a vision to 2050 (Vietnamese). Can Tho City, Vietnam, pp 1–12. <https://thuvienphapluat.vn/van-ban/xay-dung-do-thi/quyet-dinh-3672-qd-ubnd-quy-hoach-thoat-nuoc-thanh-pho-can-tho-2030-2050-nam-2016-335826.aspx>. Accessed 14 Mar 2020
- CTCPC (Can Tho City's People Committee) (2019a) Resilient Can Tho: Can Tho resilience strategy until 2030. The Rockefeller Foundation project, Can Tho City, Vietnam, pp 1–111
- CTCPC (Can Tho City's People Committee) (2019b) The environmental protection in the Can Tho City for the year 2018 (Vietnamese). Can Tho City, Vietnam, pp 1–20
- CTCPC website (Can Tho City's People Committee) (2020) General information of Can Tho City, Vietnam. Can Tho City's governmental portal (Vietnamese). Can Tho City, Vietnam. <https://www.cantho.gov.vn/wps/portal/>. Accessed 13 Mar 2020

- CTCSO (Can Tho Central Statistics Office) (2019) Statistical Summary Yearbook 2018 of Can Tho City (Vietnamese). Can Tho City, Vietnam, pp 1–553
- Dell’Angelo J, Rulli MC, D’Odorico P (2018) The global water grabbing syndrome. *Ecol Econ* 143:276–285. <https://doi.org/10.1016/j.ecolecon.2017.06.033>
- DOC (Department of Construction) (2019) Raising treated wastewater quality of the Can Tho domestic wastewater treatment plant: From Class-B to Class-A of the Vietnamese clean water standard: 40–2011/BTNMT (Vietnamese). Can Tho City, Vietnam, pp 1–56
- DONRE (Department of Natural Resources and Environment) (2015) Report on water supply policy analyzing and cooperation in water supply implementation for urban and peri-urban in Can Tho City (Vietnamese). Can Tho City, Vietnam, pp 1–34
- DONRE (Department of Natural Resources and Environment) (2020) Annual report on water quality monitoring in the 2010 – 2020 period in Can Tho City (Vietnamese). Can Tho City, Vietnam, pp 1–77
- DONRE website (Department of Natural Resources and Environment) (2019) Hydro-meteorology and climate change. <http://cantho.gov.vn/wps/portal/sotnmt/>. Accessed 14 Dec 2019
- Downing TE (2012) Views of the frontiers in climate change adaptation economics. *Wires Clim Change* 3(2):161–170. <https://doi.org/10.1002/wcc.157>
- DTCPC (Dong Thap City’s People Committee) (2015) Decision 907/QĐ-UBND.HC on the development and planning for industrial zones in Dong Thap City up to 2020, with a vision to 2030 (Vietnamese). Dong Thap City’s People Committee, Dong Thap City, Vietnam
- DTCPC (Dong Thap City’s People Committee) (2020) Plan 34/KH-UBND on key mission and solution for the implementation of socio-economic master plans in the 2020–2030 period in Dong Thap City (Vietnamese). Dong Thap City’s People Committee, Dong Thap City, Vietnam
- FAO AQUASTAT website (2016) Food and Agriculture Organization of the United Nations. <http://www.fao.org/land-water/databases-and-software/aquastat/en/>. Accessed 9 Mar 2020
- Frija A, Dhehibi B, Chebil A, Villholth KG (2015) Performance evaluation of groundwater management instruments: the case of irrigation sector in Tunisia. *Groundw Sustain Dev* 1(1–2):23–32. <https://doi.org/10.1016/j.gsd.2015.12.001>
- Goyal MK, Ojha CSP (2011) Evaluation of linear regression methods as downscaling tools in temperature projections over the Pichola Lake Basin in India. *Hydrol Process* 25(9):1453–1465. <https://doi.org/10.1002/hyp.7911>
- Grohmann A (2009) How urban areas can contribute towards easing the world-wide water crisis. *Beitrag der urbanen räume zur linderung der weltweiten wasserkrise. Notwendigkeiten und spielräume* 150(7–8):576–586
- Heinemann AB, Hoogenboom G, de Faria RT (2002) Determination of spatial water requirements at county and regional levels using crop models and GIS: an example for the State of Parana, Brazil. *Agric Water Manag* 52(3):177–196
- Henriques S (2011) Too little, too hard to find: Addressing the global water crisis. *Int Atom Energy Agency Bull* 53(1):3–5
- Hoekstra AY, Buurman J, Ginkel KCH (2018) Urban water security: a review. *Environ Res Lett* 13(5):053002. <https://doi.org/10.1088/1748-9326/aaba52>
- Ingol-Blanco E, McKinney DC (2013) Development of a Hydrological Model for the Rio Conchos Basin. *J Hydrol Eng* 18(3):340–351. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000607](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000607)
- JICA (Japan International Cooperation Agency) (2017) The estimation and calculation of water quality parameters (BOD, COD, SS and Total Coliform) of wastewater discharging sources in Vietnam (Vietnamese). Hanoi, Vietnam, pp 103–119
- JICA (Japan International Cooperation Agency) (2010) Technology for industrial wastewater treatment (Vietnamese). Technical Report, Vietnam, pp 1–112
- Kannel PR, Lee S, Lee YS, Kanel SR, Pelletier GJ (2007) Application of automated QUAL2Kw for water quality modeling and management in the Bagmati River, Nepal. *Ecological Modelling* 202(3–4):503–517. <https://doi.org/10.1016/j.ecolmodel.2006.12.033>
- Khan AA, Gaur RZ, Diamantis V, Lew B, Mehrotra I, Kazmi AA (2013) Continuous fill intermittent decant type sequencing batch reactor application to upgrade the UASB treated sewage. *Bioprocess Biosyst Eng* 36:627–634. <https://doi.org/10.1007/s00449-012-0831-0>
- Kipyego S, Ouma Y (2018) Analysis of nonpoint source pollution loading on water quality in an urban-rural river catchment using GIS-PLOAD model: case study of Sosiani River. *Civ Environ Res* 10(10):70–84
- Konings V (2012) Can Tho, how to grow? Flood proof expansion in rapidly urbanizing delta cities in the Mekong delta: The case of Can Tho, Dissertation, Faculty of Architecture, Graduation Studio Delta Interventions, the Netherlands

- Kumar P (2018) Simulation of Gomti River (Lucknow City, India) future water quality under different mitigation strategies. *Heliyon* 4(12):e01074. <https://doi.org/10.1016/j.heliyon.2018.e01074>
- Kumar P (2019) Numerical quantification of current status quo and future prediction of water quality in eight Asian Megacities: challenges and opportunities for sustainable water management. *Environ Monit Assess* 191:319
- Kumar P, Kumar M, Ramanathan AL, Tsujimura M (2010) Tracing the factors responsible for arsenic enrichment in groundwater of the middle Gangetic Plain India: a source identification perspective. *Environ Geochem Health* 32(2):129–1467. <https://doi.org/10.1007/s10653-009-9270-5>
- Kumar P, Dasgupta R, Johnson B, Saraswat C, Basu M, Kefi M, Mishra B (2019) Effect of land use changes on water quality in an ephemeral coastal plain: Khambhat City Gujarat India. *Water* 11(4):724. <https://doi.org/10.3390/w11040724>
- Long NV, Cheng Y (2018) Urban landscape design adaption to flood risk: a case study in Can Tho City. *Vietnam Environment and Urbanization ASIA* 9(2):138–157. <https://doi.org/10.1177/0975425318783587>
- Minh HVT, Ram V, Kumar P, Kieu LN, Kurasaki M, Ty TV (2020) Impact of rice intensification and urbanization on surface water quality in An Giang using a statistical approach. *Water* 12(6). <https://doi.org/10.3390/w12061710>
- Miranda D, Ostoich M (2018) Assessment of pressure sources and water body resilience: an integrated approach for action planning in a polluted river basin. *Int J Environ Res Public Health* 15(2):390. <https://doi.org/10.3390/ijerph15020390>
- Mishra BK, Regmi RK, Masago Y, Fukushi K, Kumar P, Saraswat C (2017) Assessment of Bagmati River pollution in Kathmandu Valley: scenario-based modeling and analysis for sustainable urban development. *Sustain Water Qual Ecol* 9–10:67–77. <https://doi.org/10.1016/j.swaqe.2017.06.001>
- MOC (Ministry of Construction) (2009) Decision 1581/QĐ-TTg on approving the construction planning of the Mekong River Delta region to 2020 and a vision to 2050 (Vietnamese). Ministry of Construction, Hanoi, Vietnam
- MOC (Ministry of Construction) (2011) Report on the general planning for Can Tho City up to 2030 (Vietnamese). Can Tho City, Vietnam, pp 1–280
- MOC (Ministry of Construction) (2020) Solving the problem of drainage and wastewater treatment in urban areas of Can Tho City (Vietnamese). Vietnam. <http://moc.gov.vn/vn/tin-tuc/1184/64497/can-tho--giai-quyet-van-de-thoat-nuoc--nuoc-thai-sinh-hoat-do-thi-.aspx>. Accessed 17 May 2021
- Moglia M, Perez P, Burn S (2008) Water troubles in a Pacific atoll town. *Water Policy* 10(6):613–637. <https://doi.org/10.2166/wp.2008.004>
- Moglia M, Neumann LE, Alexander KS, Nguyen MN, Sharma AK, Cook S, Trung NH, Tuan DDA (2012) Application of the water needs index: Can Tho City, Mekong Delta, Vietnam. *J Hydrol* 468–469:203–212
- MONRE (Ministry of Natural Resources and Environment) (2015) National Technical Regulation on Surface Water Quality: QCVN 08-MT: 2015/BTNMT (Vietnamese). Hanoi, Vietnam, pp 1–13
- MOPI (Ministry of Planning and Investment) (2018) Decision 1824/QĐ-TTg on approving the master plan for socio-economic development of Vinh Long province up to 2020, with a vision to 2030 (Vietnamese). Ministry of Planning and Investment, Hanoi, Vietnam
- MOPI (Ministry of Planning and Investment) (2020) Local economy and land characteristics of 63 cities in Vietnam (Vietnamese). Hanoi, Vietnam. <http://www.mpi.gov.vn/Pages/tinhthanh.aspx>. Accessed 26 Mar 2020
- MRC (Mekong River Committee) 2020 MRC Data and information services: monitoring services. <https://portal.mrcmekong.org/home>. Accessed 10 Jan 2020
- Mukate S, Panaskar D, Wagh V, Muley A, Jangam C, Pawar R (2018) Impact of anthropogenic inputs on water quality in Chincholi industrial area of Solapur, Maharashtra, India. *Groundw Sustain Dev* 7:359–371. <https://doi.org/10.1016/j.gsd.2017.11.001>
- Neumann L, Nguyen M, Moglia M, Cook S, Lipkin F (2011) Urban water systems in Can Tho, Vietnam: understanding the current context for climate change adaption. *AusAID-CSIRO Res Dev Alliance* 12:1–72. <https://doi.org/10.4225/08/584EE8F2E3474>
- Nga BT, Giao NT, Nu PV (2018) The impacts of Tra Noc industrial park on water bodies nearby Can Tho City. *Sci Mag Can Tho Univ* 9:194–201
- Nguyen MN, Cook S, Moglia M, Neumann L, Wang X, Trung NH (2016) Climate adaptation through sustainable urban water development in Can Tho City, Vietnam. *CSIRO Land Water* 14(1):1–8. <https://doi.org/10.13140/RG.2.1.4122.3924>
- ODAPMU (ODA Project Management Unit) (2016) Construction investment project management unit using official development assistance capital, Can Tho City: Big Projects for Re-Creating New Vitality

- of Can Tho City. <http://odapmu.cantho.gov.vn/en/Cac-du-an-lon-tao-suc-song-moi-cho-do-thi-Can-Tho>. Accessed 10 Jan 2021
- Phung D, Huang C, Rutherford S, Dwirahmadi F, Chu C, Wang X, Nguyen M, Nguyen NH, Do CM, Nguyen TH, Dinh TAD (2015) Temporal and spatial assessment of river surface water quality using multivariate statistical techniques: a study in Can Tho City, a Mekong Delta area, Vietnam. *Environ Monit Assess* 187(5):1–13. <https://doi.org/10.1007/s10661-015-4474-x>
- Quan NH, Huynh N, Peter VDS, Assela P, Phi H, Hieu DN, Salingay MLB (2013) Water pollution and health risk caused by urban flooding in Can Tho City: lessons learned from the field campaigns 2013. *Proceedings of the 19th IAHR-APD Congress*, pp 1–6
- Shrestha S, Kazama F (2007) Assessment of surface water quality using multivariate statistical techniques: a case study of the Fuji river basin, Japan. *Environ Model Softw* 22(4):464–475. <https://doi.org/10.1016/j.envsoft.2006.02.001>
- Sieber J, Purkey D (2015) *Water evaluation and planning (WEAP). User Guide*. Stockholm Environment Institute (SEI), U.S. Center, Boston
- Simeonov V, Tsakovski S, Lavric T, Simeonova P, Puxbaum H (2004) Multivariate statistical assessment of air quality: a case study. *Microchim Acta* 148(3):293–298. <https://doi.org/10.1007/s00604-004-0279-2>
- Slaughter AR, Mantel SK, Hughes DA (2014) Investigating possible climate change and development effects on water quality within an arid catchment in South Africa: a comparison of two models. *Proceedings of the 7th International Congress on Environmental Modelling and Software*, June 15–19, 2014, San Diego, California, USA, pp 978–988. ISBN: 97888-9035-744-2
- Trung NH, Duc NH, Loc NT, Tuan DDA (2019a) Addressing urban water scarcity in Can Tho City amidst climate uncertainty and urbanization. In: Krittasudthaheewa C, Navy H, Tinh BD, Voladet S (eds) *Development and Climate Change in the Mekong Region*, 1st edn. Stockholm Environment Institute (SEI) Asia Centre, Thailand, pp 287–321
- Trung NH, Duc NH, Loc NT, Tuan DDA, Thinh LV, Lavane K (2019b) Urban water management under uncertainty: a system dynamic approach. In: Stewart MA, Coclanis PA (eds) *Water and power. Advances in Global Change Research*. Springer, Cham, pp 319–336
- UN DESA (Department of Economic and Social Affairs) (2019) *World urbanization prospects: the 2018 revision* Population Division, the United Nations, New York, pp 1–104
- UNDP (United Nations Development Programme) (2006) *Human Development Report 2006 - Beyond scarcity: power, poverty and the global water crisis*. United Nations, New York, pp 1–224
- USEPA (the United States Environmental Protection Agency) (2001) *PLOAD: an ArcView GIS Tool to Calculate Nonpoint Sources of Pollution in Watershed and Stormwater Projects- version 3.0*. Washington, DC
- VLCP (Vinh Long City's People Committee) (2018) *The development plan for 14 industrial zones from the present to 2030 in Vinh Long City, Vietnam (Vietnamese)*. Vinh Long City, Vietnam, pp 1–18
- VLCSO (Vinh Long Central Statistics Office) (2018) *Statistical Summary Yearbook 2018 of Vinh Long City (Vietnamese)*. Vinh Long City, Vietnam, pp 1–122
- VNCSO (Vietnamese Central Statistics Office). (2018). *Statistical Summary Yearbook 2018 of Vietnam (Vietnamese)*. Hanoi, Vietnam, pp 1–452
- Wakida FT, Lerner DN (2005) Non-agricultural sources of groundwater nitrate: a review and case study. *Water Res* 39(1):3–16. <https://doi.org/10.1016/j.watres.2004.07.026>
- WASSC (Water Supply-Sewerage Joint Stock Company) (2013) *Preparatory study on Can Tho city water supply improvement project: final report (summary)*. Japan International Cooperation Agency (Jica), pp 1–86
- WASSC (Water Supply-Sewerage Joint Stock Company) (2020) *Annual Reports (Vietnamese)*. <https://ctn-cantho.com.vn/Bao-cao-dinh-ky/>. Accessed 02 Jan 20

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