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Assessment of Water Quality During 2018-2022 in the Vam Co River Basin, Vietnam

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ABSTRACT

Water pollution in the Vam Co River basin is becoming more complicated due to untreated wastewater being directly discharged into rivers and canals from agricultural, industrial, and domestic activities. To assess the water quality in this area, this study conducted monitoring at ten sampling locations (S1-S10) from 2018 to 2022, calculated the Water Quality Index (WQI) for each parameter, and simulated water quality in 2022 using the 1D- MIKE 11 model developed by DHI with two main modules including HD and AD. The findings showed that most parameters did not surpass the allowable limits per QCVN 08-MT:2015/BTNMT on Vietnam National Technical Regulation on Surface Water Quality. However, organic and microbial pollution led to certain parameters, such as BOD_5, COD, and Coliform, exceeding the limits. The lowest water quality was recorded in Long An province, especially at sampling locations S3, S4, and S6, with the average WQI for nine water quality parameters from February to July 2022 being 58.4, 67.8, and 21.1, respectively. Additionally, the simulation outcomes of the MIKE 11 model salinity, BOD_5, DO, and NH_4 aligned with the real measurements taken. It has been observed that the southern area of the Vam Co River Basin possesses poorer water quality than the northern part, with Long An province located downstream of the Vam Co River basin being the primary source of pollution. The development of this hydraulic model signifies a crucial milestone in comprehending and regulating the effects of pollution in monitoring and managing water management systems, controlling saline intrusion, and ensuring water supply for agricultural production and daily use in the Vam Co River basin.

INTRODUCTION

Water is an essential resource for human life as well as for all industrial and agricultural processes. Over the past few decades, the rapid growth of industrial and agricultural development, along with a surge in population growth, has significantly increased the demand for freshwater (Ramakrishnaiah et al. 2009, Thu Minh et al. 2020, Duc et al. 2021). However, quality water is one of the most sensitive components of the environment (Das & Acharya 2003). Thus, contamination has become more serious over time, mainly due to the growth mentioned above generating domestic waste and residual fertilizer pollution (Girbaciu et al. 2015). Moreover, the varied characteristics of water levels and flows due to climate change also affect water quality (Thanh Giao et al. 2021). Thus, water quality assessments have attracted more attention worldwide (Bilgin 2018, Wu et al. 2018, Li et al. 2020).

Water quality assessments can be done based on their physical, chemical, and biological properties (Loukas 2010). However, in practice, a WQI has been commonly used to summarize the overall water quality of an area in a single term and aid in selecting the appropriate treatment technology to address related issues (Tyagi et al. 2013). Based on the WQI, the assessments can be implemented at the station and regional/basin scale. The latter is more challenging due to the in-situ sampling cost and the limitation of remote sensing technologies for capturing water quality characteristics. Thus, spatial-temporal changes in water quality have been simulated by numerical models, e.g., MIKE 21 (Paliwal & Patra 2011, Tran 2017), WASP (Lai et al. 2011, Yao et al. 2015, Mbuh et al. 2019), MIKE 11 (Cheng & Zhi 2015, Girbaciu et al. 2015, Liang et al. 2015, Thu Minh et al. 2022), SWAT (Abbaspour et al. 2007, Debele et al. 2008, Qiu & Wang 2014, Epelde et al. 2015).

Many efforts have been made to use the models mentioned above to simulate water quality. For instance, Tran (2017) used the MIKE 21 model to simulate the transport of pollutants in the Dinh Vu coastal area, Hai Phong City, Vietnam, with simulation results showing a Nash of 0.96 and 0.93, and the relative and the relatively wrong number of Ecolab parameters are below 20%. Paliwal & Patra (2011) employed MIKE 21 to simulate BOD and DO in the Hoogly estuary, West Bengal, India, providing reasonable predictions. Industrial waste has a minor effect on the Hooghly River. The river mouth has effective dilution, aided by tidal mixing. As a result, BOD levels dropped to under 4 $mg.L^{-1}$, and DO levels were also found to replenish, achieving a level higher than 3 $mg.L^{-1}$.

Similarly, Gordillo et al. (2020) used WASP to simulate steady-state testing and real-life cases at the Ebro River, and Lai et al. (2011) combined IWMM and WASP models to assess the water quality of the Kaoping River. MIKE 11 was used by Cheng & Zhi (2015) and Girbaciu et al. (2015) to identify pollution sources and simulate water quantity and quality, respectively. While Qiu & Wang (2014) applied the SWAT model to assess water quality for the Neshanic River basin, United States, with reasonably simulated hydrological conditions and water quality. Besides that, SWAT is also used by Abbaspour et al. (2007) to simulate all related processes affecting water, sediment, and nutrient availability in the basin. The results show that in river basins with good quality and availability of data and relatively small model uncertainty – SWAT can be used as a flow simulation tool. Debele et al. (2008) combined SWAT and CE-QUAL-W2 to simulate water quantity and quality processes in upland and downstream basins. The study shows that the two models are compatible and can be used to assess and manage water resources in complex basins.

Although previous studies showed significant achievements, there is little agreement on the best model parameters because they heavily rely on the quality/quantity and characteristics of meteorological, hydrological, terrain, and other related factors in a particular area. Thus, there is still a need to research using the model to simulate water quality in case no previous studies have been made or input data has been updated in the area. This topic is undergoing a revolution of considerable interest, especially in the area that has been seriously contaminated.

In this context, the Vam Co River basin, located in the northeast of the Mekong Delta, in Long An and Tay Ninh, Vietnam, is one of the case studies (Fig. 1). The surface water in this region has been contaminated by many different wastewater sources from activities such as agriculture, industry, domestic activities, etc. (Dao & Bui 2016). The main contributor to pollution is the direct discharge of untreated wastewater from various activities into rivers and canals. In addition, due to tides from the East Sea affecting Go Dau and Thanh Hoa, the water supply for daily life and irrigation faces many obstacles, especially in the Tan Tru sub-region. Salinity usually reaches its highest around March-April or May if the rainy season comes slowly. However, research on water quality in the Vam Co River basin has been limited to investigations (Dao & Bui 2016, Huntjens et al. 2013) and statistical analyses (Nguyen 2019). Thus, monitoring water quality regularly for this region is deemed crucial (Ly et al. 2013, Behmel et al. 2016).

This study aims to measure and assess water quality in the Vam Co River basin based on the WQI index. Water quality indicators measured between 2018 and 2022 at ten of the most typical points for monitoring water quality are distributed on the main rivers/canals in the region according to locations with risk of water quality pollution, such as locations of rice cultivation, aquaculture, densely populated areas, locations with strong or small flows. From that, to more accurately assess the water quality changes in the river and canal system. Besides, the MIKE 11 model with two main modules simulates water quality with its stability, reliability, flexibility, and high calculation speed (Turner et al. 2009, Mama et al. 2021). The findings from this study help identify and forecast pollution and guide for sustainably using water resources.

MATERIALS AND METHODS

Study Area

The Vam Co River basin covers a total natural area of 205,077 hectares and is located in the Long An and Tay Ninh provinces. The Vam Co Dong River borders the area to the northeast, the Vam Co Tay River to the southwest, and the Vietnam-Cambodia border to the north (Fig. 1). The average annual temperature ranges from 27-29°C. It increases gradually from the sea to the mainland. Air humidity is positively correlated with rain and inversely correlated with temperature, with an average annual humidity of about 78%. The region experiences two distinct seasons - a rainy season from May to October and a dry season from November to May of the following year, with the Vam Co Dong River area experiencing a longer dry season greater than 15% of the annual rainfall. Freshwater supplies become limited, and water pollution levels increase towards the end of the dry season. At the beginning of the rainy season, rainwater carries surface waste, including alum, into the water source, affecting agriculture and aquaculture's water supply.

Collection of Water Samples

Water samples were collected between 2018 and 2022 at ten stations in the study area, as shown in Fig. 1. Specifically, the field collection of water samples was organized twice a month between February and July in 2018 and 2022 at the locations. As a result, a total of 600 samples were obtained (120 samples/year). The field collection was performed between February and July because the period from February to April represented the dry season, while May to July was rainy. Environmental standard factors of the water samples, such as pH, BOD_5, COD, DO, TSS, NH_4, NO_2, NO_3, PO_4, and Coliform, were analyzed.

Meteorological and Hydrological Data

Rainfall and other meteorological data were collected daily at the stations of Bien Hoa, Can Dang, Dau Tieng, Dong Phu,

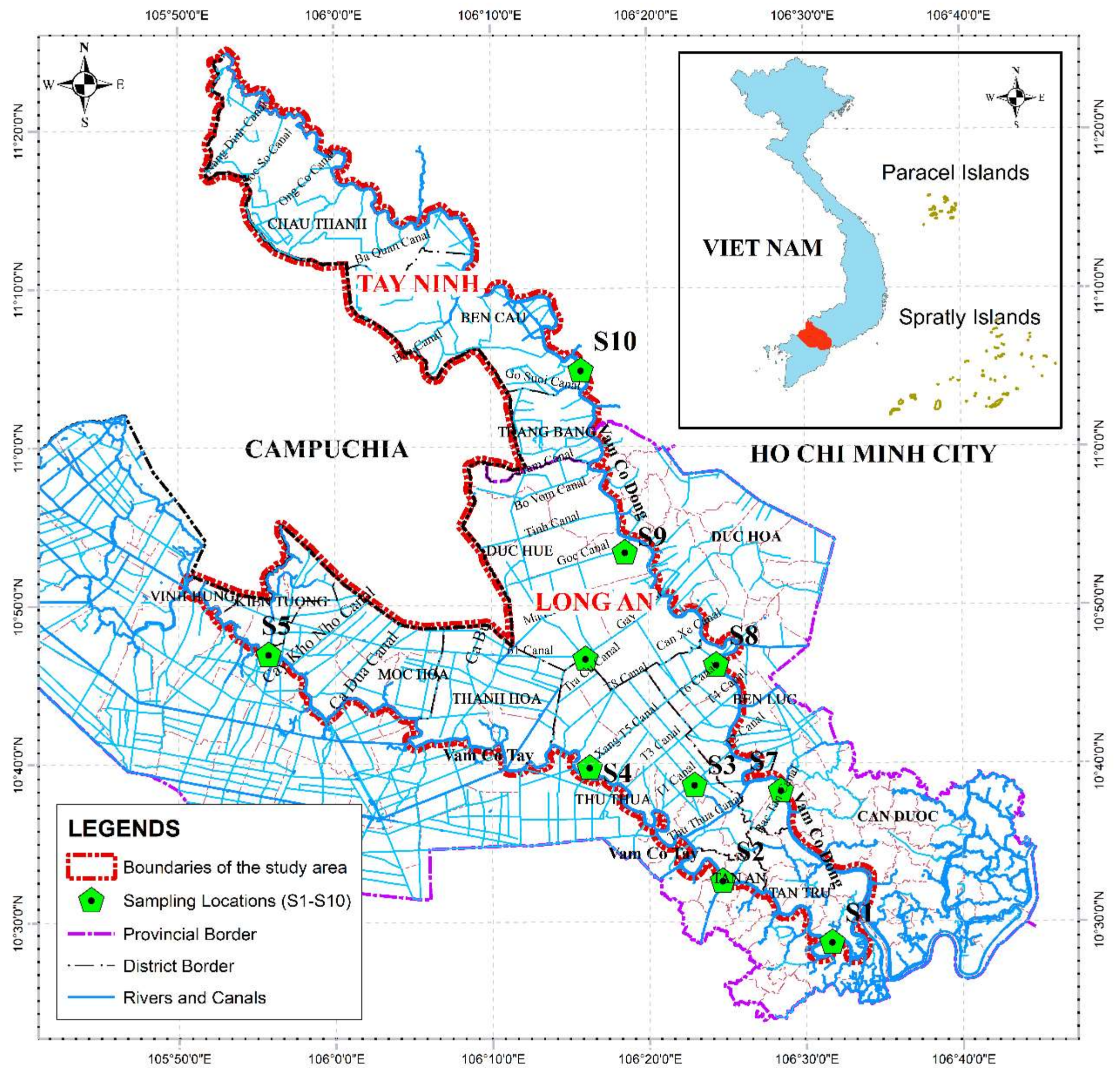

Fig. 1: Study area and sample locations (S1-S10) of the Vam Co River basin.

Go, Dau, Long Thanh, Moc Hoa, Phuoc Hoa, Tan An, Tan Son Nhat, Tay Ninh, Tri An and Vung Tau operated by the Southern Regional Hydrometeorological Center of Vietnam (Fig. 2). Hydrological daily data for 2017 and 2021 (Rainfall, discharge, and flow data) were obtained from the Vung Tau, Bien Hoa, Phu An, Nha Be, Thu Dau Mot, Ben Luc, and Tan An streamflow stations (Fig. 2) due to the Southern Regional Hydro-meteorological Center of Vietnam provides. Water level hourly data for 2017 and 2021 were generated using the global harmonic tidal model of the DHI (2019). In addition, the study also referred to the Tide Forecast Table of the Institute of Coastal and Offshore Engineering (http://www.icoe.org.vn) based on the study of Codiga (2011) and the Center for Oceanography of Vietnam (CFO 2022) annual tide table for model simulation.

Topographic Data

For modeling the topography of rivers, measured channel cross sections of the Saigon, Dong Nai, Can Gio, Long Tau, and Soai Rap Rivers were collected from the Southern Institute of Water Resources Research under the project "Determining high shore edges."

Water Quality Index

Water quality in the Vam Co River basin is related to various sectors such as residential, industrial, agricultural, and aquaculture. The analysis of water quality for the collected water samples was performed based on several standards and regulations of Vietnam, including TCXDVN 33:2006 on Water Supply - Distribution System and Facilities - design standard (MOC 2006), QCVN 40:2011/BTNMT on the National Technical Regulation on Industrial Wastewater (MONRE 2011), QCVN 11:2008/BTNMT (Column B) on National Technical Regulation on the effluent of aquatic products processing industry (MONRE 2008), QCVN 08-MT:2015/BTNMT on Vietnam National Technical Regulation on Surface Water Quality (MONRE 2015) and WHO standards for residential discharge. In addition, a comparison with standards and regulations will help determine if the water meets the respective standards and regulations for safe use and discharge.

WQI is a helpful way to monitor and evaluate water quality (Nguyen & Huynh 2022). According to the MONRE of Vietnam (Nguyen & Huynh 2022), it ranges from 0 to 100. It can be categorized into six levels of water quality, namely Heavily polluted (WQI<10), Very poor (10-25), Poor (26-50), Moderate (51-75), Good (76-90), and Excellent water (91-100) (Table 1).

Besides that, based on the decision No. 1460/QD-TCMT in 2019 issued by the Ministry of Natural Resources and Environment (MONRE), which pertains to the release of technical guidelines on calculating and publication of the Vietnam Water Quality Index (VN_WQI) (MONRE 2019). The VN_WQI is divided into five parameter groups: pH (Group I), pesticide parameters (Group II), heavy metals (Group III), organic and nutrient parameters (Group IV), and microbiological parameters (Group V) (Nguyen & Huynh 2022, Thanh Giao et al. 2021). This study used the WQI to indicate the water used for agricultural production and aquaculture. Therefore, we selected three parameter groups, including pH (Group I): DO, COD, BOD_5, NH_4, PO_4^{3-}, NO_3^-, NO_2^- (Group IV); and Coliform (Group V). The formula of the WQI is expressed as follows:

$$WQI = \frac{WQI_I}{100}\left[\left(\frac{1}{7}\sum_{a=1}^{7} WQI_{IV}\right)^2 \text{ x } WQI_V\right]^{\frac{1}{3}} \quad ...(1)$$

WQI_I, WQI_{IV}, and WQI_V are the calculated results for groups I, IV, and V parameters, respectively.

Calibrating and Validating the MIKE 11 Model

(a) MIKE 11 and the Modules Used

MIKE 11, developed by the Danish Hydraulic Institute (DHI 2017), is a one-dimensional modeling system for simulating flow, sediment transport, and water quality in canals, rivers, irrigation systems, and estuaries (Havnø et al. 1995). MIKE 11 uses finite difference diagrams to calculate unstable

Table 1: Standard rating of water quality as per WQI.

No.	WQI range	Water quality classification	Suitable for use purpose
1.	< 10	Heavily polluted	Contaminated water needs to be remedied and treated
2.	10-25	Very poor	Unsuitable for agricultural and aquaculture
3.	26-50	Poor	Used for navigation and other equivalent purposes
4.	51-75	Moderate	It may be suitable for agricultural and aquaculture purposes with certain precautions or treatments.
5.	76-90	Good	Suitable for agriculture and aquaculture with certain precautions or treatments
6.	91-100	Excellent	Used good for agriculture and aquaculture

flows. It can also describe subcritical and supercritical flow conditions through a numerical scheme that adapts to local flow conditions (in time and space) (Girbaciu et al. 2015). This study employed the hydrodynamic module (HD) and advection-dispersion module (AD) to solve water contamination problems.

(b) Defining the River Network and Boundaries

The river network shown in Fig. 2 comprises the Saigon River, Be River, Vam Co Dong River, and Vam Co Tay River. The hydraulic scheme of the river network included 255 river branches with a total length of 2,341,639m and 1,076 cross-sections.

The upstream boundary conditions of the river networks for the HD module were determined by using the discharge data at Tri An, Dau Tieng, Phuoc Hoa, and Can Dang stations. Regarding the downstream boundary, four water level boundaries are arranged at the sea outlet and the water level boundary at Moc Hoa. The selection is based on the geographic condition of the study area. It is part of the Saigon-Dong Nai basin and is an almost closed basin with the main entrance to the sea at Soai Rap and some other small estuaries affected by the flow of the Mekong Delta. The data is the tidal level of Vung Tau station, which will be calibrated according to the correlation between Vung Tau and Soai Rap. The salinity concentration data collected from the survey documents were used for the salinity margin at the upstream boundary.

For the AD module, the upstream boundary conditions were set the same as in the HD module. To assign the downstream boundary of the AD model, the water quality data of Soai Rap River (outside the sea) was used, including the quality of discharge water in industrial parks, export processing zones, factories, and domestic wastewater included in the model to simulate. The concentration of waste discharged into rivers and canals is calculated to

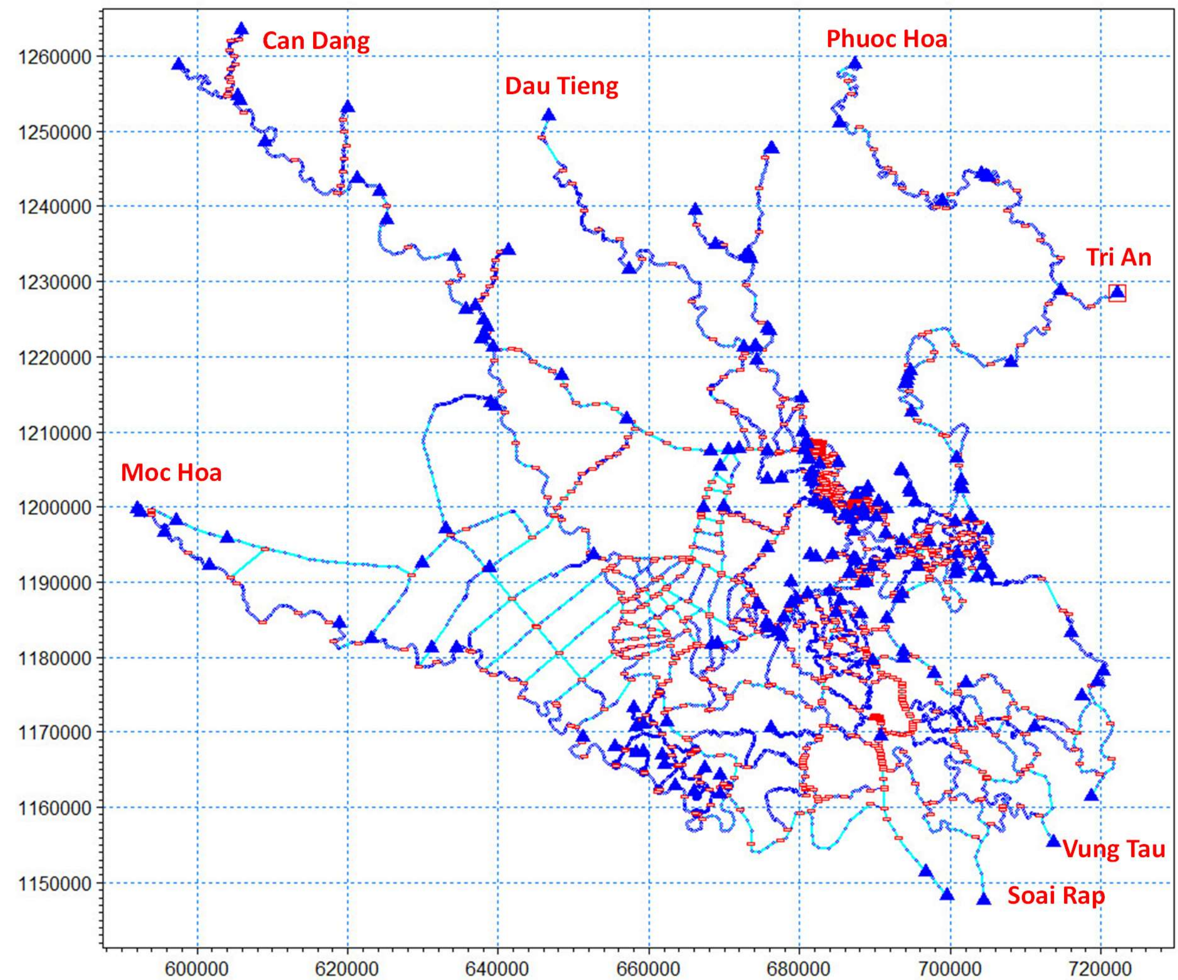

Fig. 2: River network of Vam Co River basin in MIKE 11 with cross-section (red dots) and water level (blue dots).

simulate water quality. After being calculated, the water quality indicators are the sectors' loads converted to the concentration of substances (mg.L^{-1}). Wastewater input data based on various sectors, namely, industrial, agricultural, and domestic zones, were computed by considering drainage areas of the river and canal sections.

(c) Calibration, Validation, and Evaluation of the MIKE 11 Model

The MIKE 11 with the HD and AD modules underwent calibration and validation using salinity and water level data from monitoring stations at Cau Noi, Ben Luc, Tan An, Phu An, and Nha Be in 2017 and 2021. Various parameters, such as Manning's roughness coefficient (n) for the HD module and the diffusion load factor for the AD module, were adjusted to improve model accuracy. The values of the MIKE 11 model parameters were modified based on the trial-and-error method.

After calibrating and validating the model, water quality during the dry season 2022 was simulated and compared with actual measurements. The WQI was calculated using ten representative sampling locations (S1-S10) within the study area, and the results were displayed as a spatial distribution map to visualize the water quality status. The simulated data was evaluated by comparing it with the measured data, using various statistical measures such as the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), Root mean square error (RMSE), and Mean absolute error (MAE). In R^2 and NSE, values range from 0 to 1, where higher values closer to 1 indicate a stronger correlation between the simulated and measured data (Krause et al. 2005; McCuen et al. 2006). The RMSE and MAE values have a range from 0 to ∞, and lower values indicate better performance of the simulated model (Moriasi et al. 2012, 2007).

The formula used to calculate the indicators is as follows:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i-\overline{O})(P_i-\overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\overline{P})^2}}\right)^2 \quad ...(2)$$

$$NSE = 1-\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \quad ...(3)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i-P_i)^2} \quad ...(4)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|O_i-P_i \quad ...(5)$$

Where O_i is the observed data at the time i, P_i is the simulated data at the time i, $\overline{O}$ is the mean value of the observed data and $\overline{P}$ is the mean value of the simulated data.

RESULTS

Calibration and Validation MIKE 11 Model

The HD module of the MIKE 11 model was calibrated by comparing its simulation results with measured water level data obtained at Tan An and Ben Luc hydrological stations during the dry season 2017. Fig. 3 shows the comparisons between the observed and simulated water levels at the hydrological stations. The simulated water levels closely resembled the measured water levels, showing similar magnitudes and tidal amplitudes. The evaluation metrics, including R^2 = 0.990, NSE = 0.990, RMSE = 0.002, and MAE = 0.002, indicate a high level of agreement between the simulated and measured values, falling within the optimal range of distribution (Table 2). To further confirm the effectiveness of the HD module, the validation procedures were performed with the observed water level data gathered in 2021. The results in Fig. 4 demonstrate a close agreement between the simulated and observed water levels, indicating falling within the optimal distribution range. At the Phu An station, the evaluation indices of R^2 = 0.812, RMSE = 0.811, NSE = 0.353, and MAE = 0.261 were obtained, while at the Nha Be station, the indices were R^2 = 0.863, RMSE = 0.863, NSE = 0.308, and MAE = 0.236 (Table 2). According to the calibration and validation results, the HD module of the MIKE 11 model was acceptable, and its model parameters can be utilized to simulate the pollutant propagation processes in the Vam Co River basin.

Calibrating the AD module is more challenging than the HD model due to saltwater intrusion in the Vam Co River basin, affected by factors like seasonal winds and salt control structures. The dense stream network makes it hard to determine suitable Advection-Dispersion coefficients for each section and channel leading to the basin, and the lack of continuous salinity data is also a concerning issue for

Table 2: Statistical evaluation of model performance on water level simulations.

Station	R^2	NSE	RMSE	MAE
I	Calibration			
Ben Luc	0.990	0.990	0.002	0.002
Tan An	0.990	0.990	0.002	0.002
II	Validation			
Nha Be	0.863	0.863	0.308	0.236
Phu An	0.812	0.811	0.353	0.261

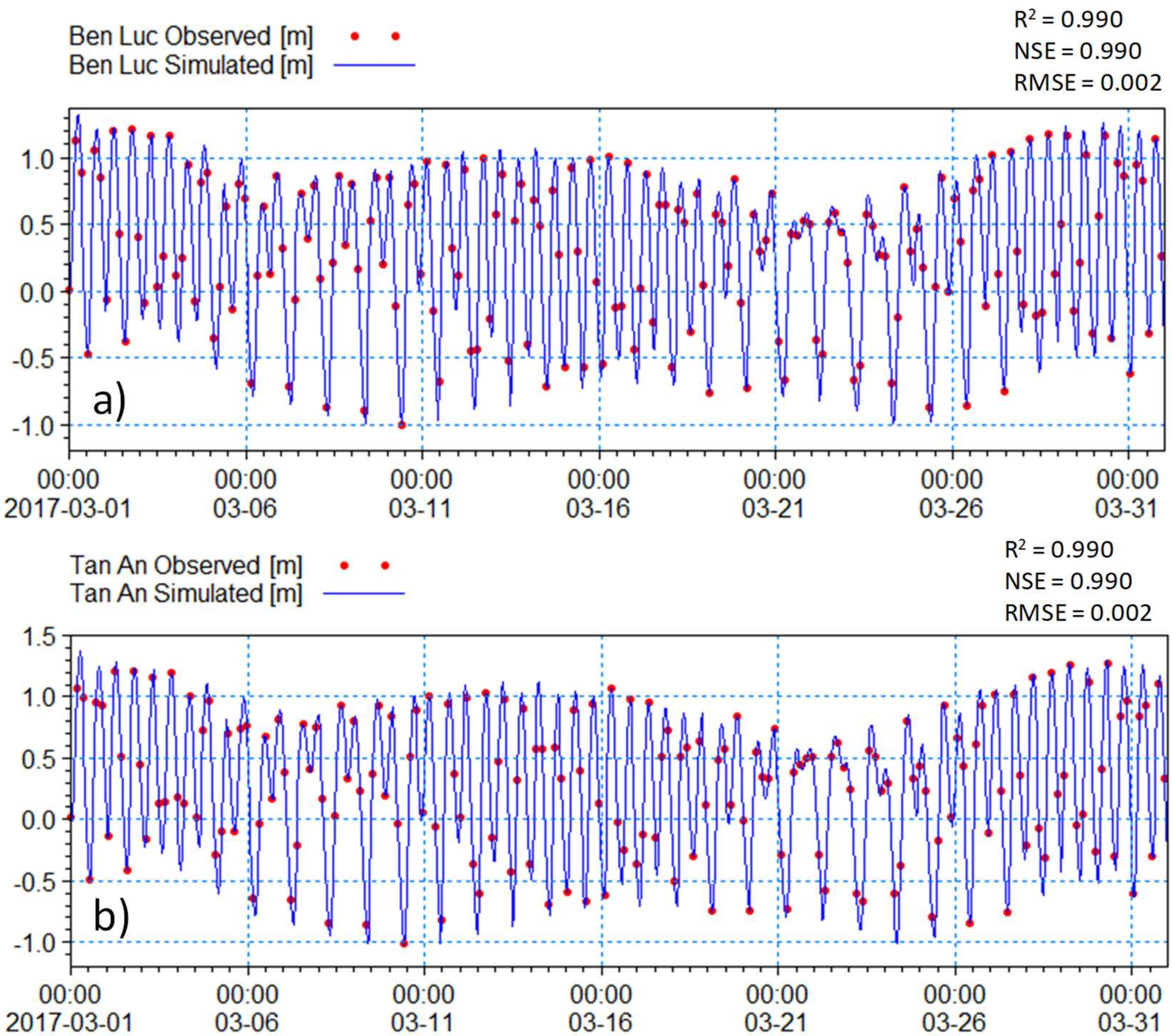

Fig. 3: Calibrated water level (a) at Ben Luc station and (b) at Tan An station.

model calibration and validation. Nonetheless, the simulated saltwater intrusion model is reasonably precise. MIKE 11 AD model was calibrated with measured salinity data between January and April 2017 at Cau Noi and Ben Luc stations. The calibration results of salinity daily at the Cau Noi and Ben Luc stations are shown in Fig. 5. The calibration results show a good agreement with the measured salinity data in terms of magnitude and tidal variation over time. The model validation results in February 2021 and March 2021 at Cau Noi and Ben Luc stations, respectively, are shown in Fig. 6. According to the comparison results between calculated and measured data, the MIKE 11 AD model was able to produce good simulations of the salinity concentration at Ben Luc and Cau Noi stations during the dry season of 2021. Therefore, the MIKE 11 model can be used to predict water quality during the dry season 2022.

Evaluation of Water Quality Monitoring in 2018-2022

The analysis results of water quality from 2018 to 2022 are presented in Fig. 7, with ten water quality indicators at the ten sampling locations. In Fig. 7, the results are compared to the permissible limit values of the indicators (QCVN 08-MT: 2015 / BTNMT column A1). Almost all locations had values of pH within the acceptable range ranging from 5.5 to 7.5. Excepting location S6, pH values were lower than the other sampling locations, indicating heavy iron pollution in the area, which has persisted for many years. BOD_5 values were higher than the allowable limit at all locations and fluctuated between 3-8 $mg.L^{-1}$. COD values showed a similar trend to BOD_5 measurements. Their values exceeded the permissible limit. Dissolved oxygen (DO) levels were lower than required, fluctuating between 2-3

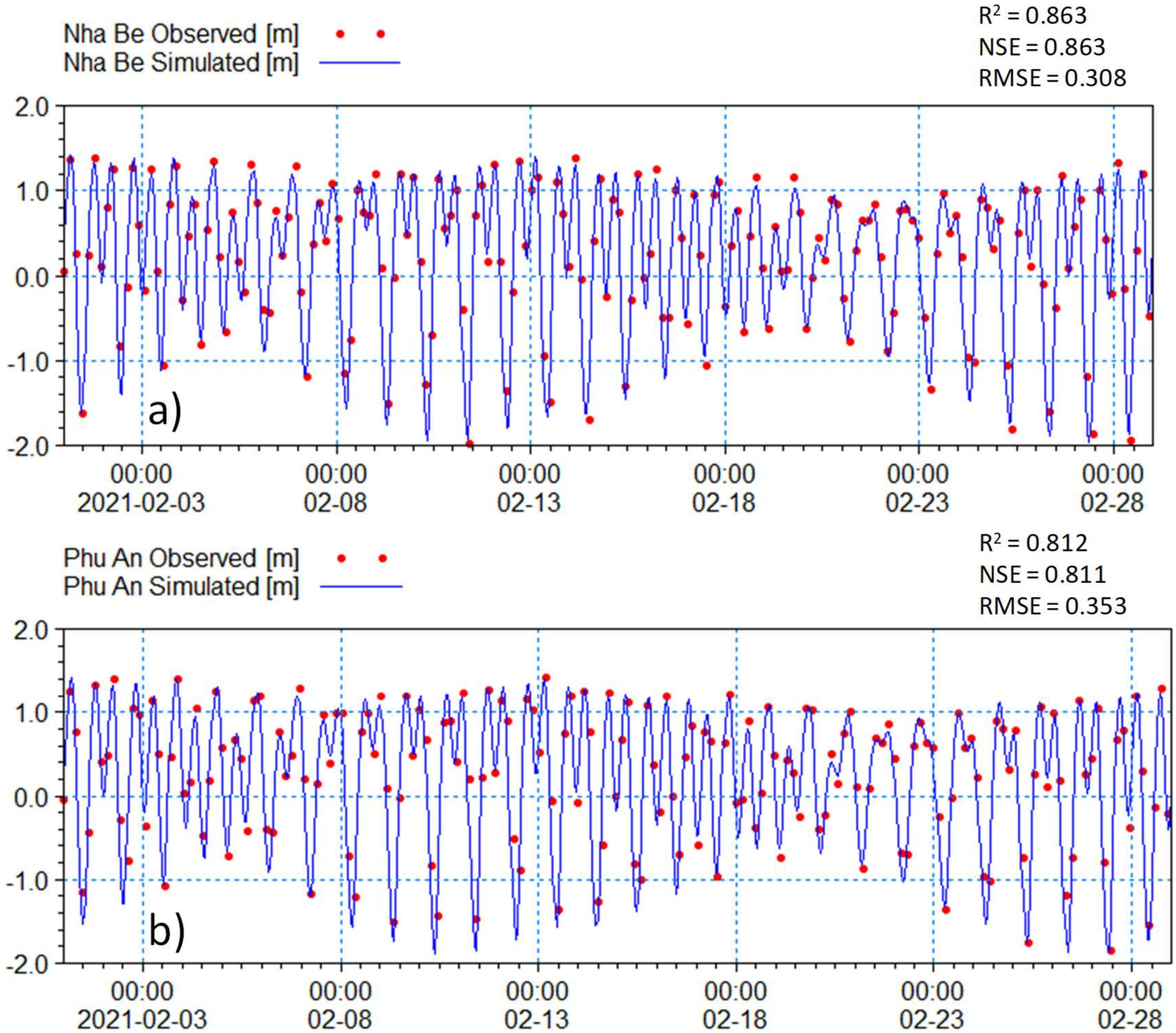

Fig. 4: Validated water level (a) at Nha Be station and (b) at Phu An station.

mg.L^{-1}, which can be attributed to low water exchange capacity during the dry season. TSS values showed significant variation between the minimum and maximum values but were lower than the allowable limit. Measured values of NH_4, NO_2, and PO_4 concentrations were lower than the permissible limit. However, the values of the Coliform concentrations were higher than the allowable limit. This indicated that the water at the study locations was unsuitable for aquaculture and crops. At location S7, the observed values of Coliform concentration greatly fluctuated, indicating long-term contamination by microorganisms in the area.

For salinity during the study period, the monitoring results in 2022, the highest salinity values at Cau Noi, Ben Luc, and Tan An stations were 14.3, 3.2, and 1.7 g.L^{-1}, respectively. Their values were lower than the highest salinity in 2016, 2020, and 2021. The main reason is that 2016 and 2020 were two years of record drought in the Mekong Delta, Vietnam. In 2016, the highest salinity at 3 stations was 20.3, 12.8, and 11.8 g.L^{-1}, respectively, and in 2020, 21.6, 15.7, and 11.7 g.L^{-1}. For 2022, managers and people have been more proactive in preventing salinity due to the experience of 2 years of historical salinity drought. However, salinity in 2022 is still high, and the highest is at Cau Noi station, with a sanity value of 14.3 g.L^{-1} (Fig. 8).

Evaluating the Sampling Sites and Frequencies of the Water Quality Monitoring

Table 3 presents an assessment of water quality based on the Water Quality Index (WQI) for 9 parameters (pH, BOD_5,

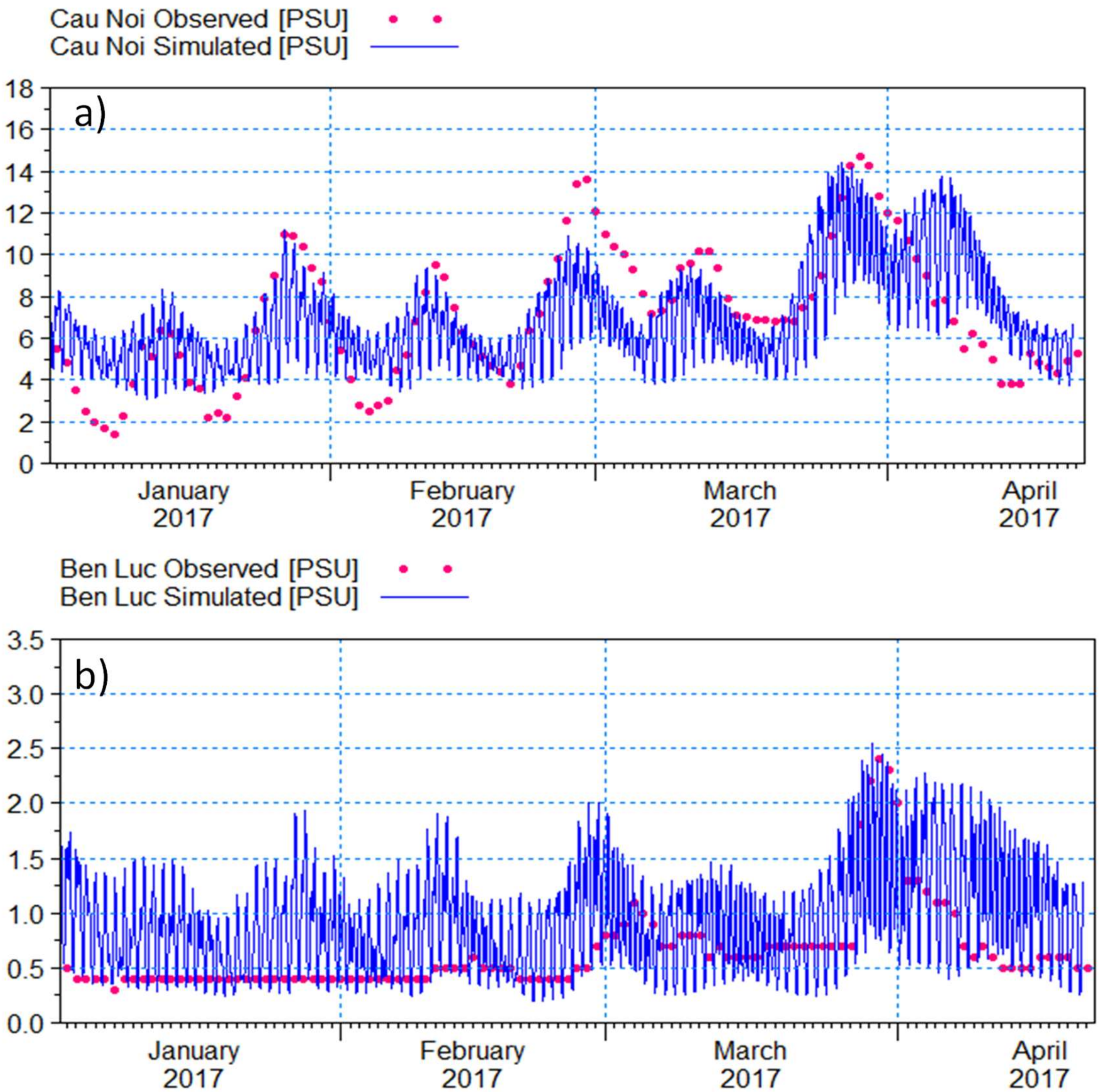

Fig. 5: Calibration results of salinity (a) at Cau Noi station and (b) at Ben Luc station.

COD, DO, TSS, NH_4, NO_2, NO_3, and PO_4) obtained from 12 sampling events conducted twice a month for 6 months from February to July 2022 at ten locations, with a total of 120 samples collected. The purpose of this assessment is to evaluate the water quality for production purposes and to monitor the production progress of the local area. At location S6, the WQI values were 25.0 for pH and NO_3, which has a significant impact on the total score of the WQI at this location. Additionally, the WQI values of DO at all monitoring sites range from 36.8 to 66.2 and significantly influence the total score of the WQI at all monitoring points.

According to the analysis of the WQI, it can be concluded that the water quality in the Vam Co River Basin is suitable for irrigation or other activities. Although some locations have pollution issues during the late dry and early rainy seasons, the water quality is suitable for irrigation purposes in other periods.

The water quality at location S6 was Very poor, indicated by red. The two locations (S3 and S4) had moderate water quality, and the remaining seven locations had good water quality, indicated by green. The map depicting the spatial distribution of WQI values in Fig.

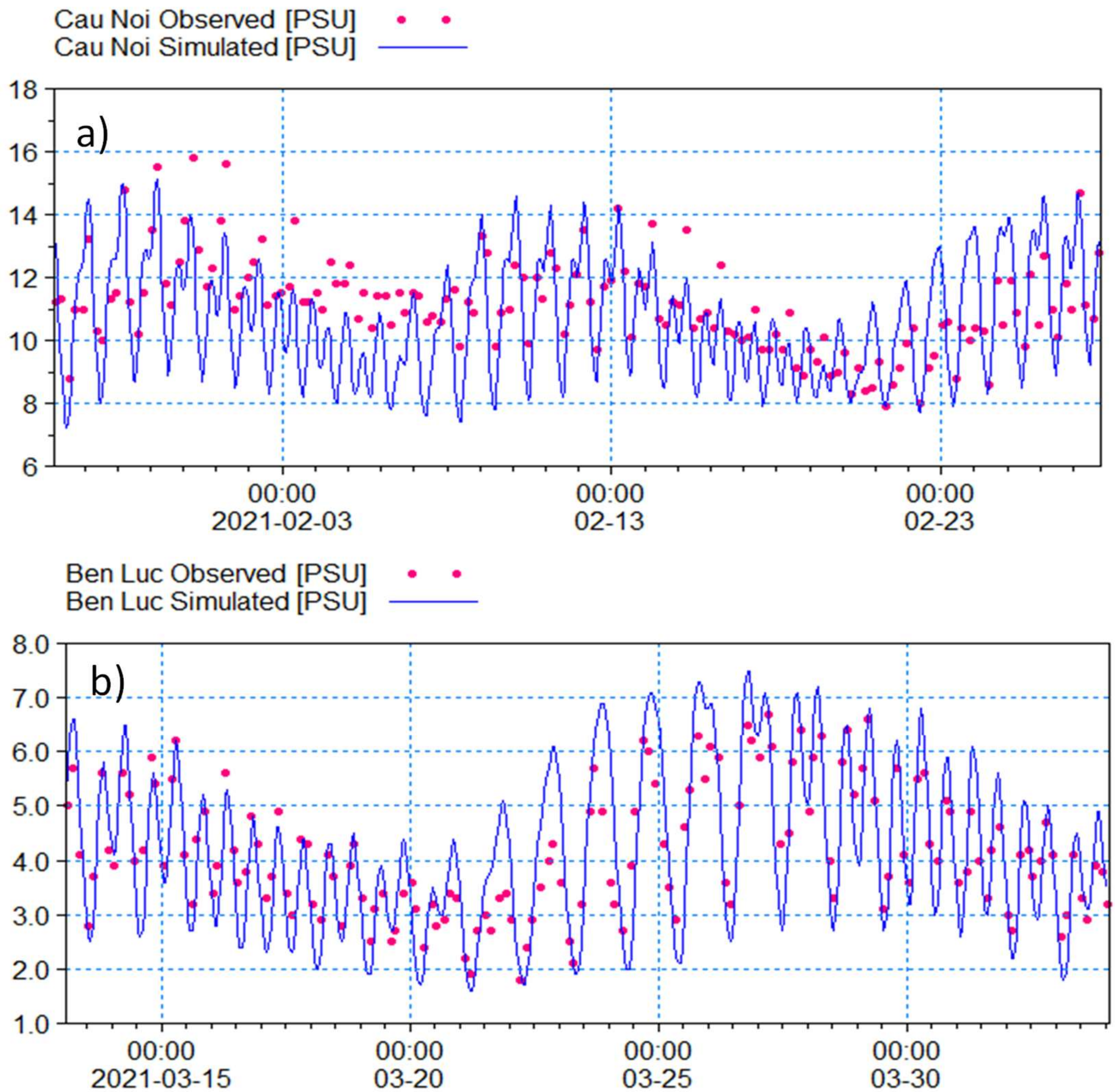

Fig. 6: Salinity validation results at (a) Cau Noi station and (b) Ben Luc station.

9 shows that Long An had the lowest water quality in 2022.

Evaluation of Simulated Water Quality

The study area is mainly affected by seawater intrusions from the East Sea. Thus, the salinity concentration has strongly impacted water quality in the Vam Co River Basin. Fig. 10a shows the comparison between simulated and measured values of water quality indicators, namely, salinity, BOD_5, DO, and NH_4, at the sampling locations during the dry season of 2022. The simulated values of salinity fit well with the measured values with R^2 = 0.961, NSE = 0.956, RMSE = 0.023, and MAE = 0.017 (Table 4).

Fig. 10b and 10c show the comparisons between simulated and observed values of BOD_5 and DO, respectively. The simulated and observed values of BOD_5 have a good agreement with R^2 = 0.919, NSE = 0.911, RMSE = 0.266, and MAE = 0.170. Moreover, the simulated values of DO

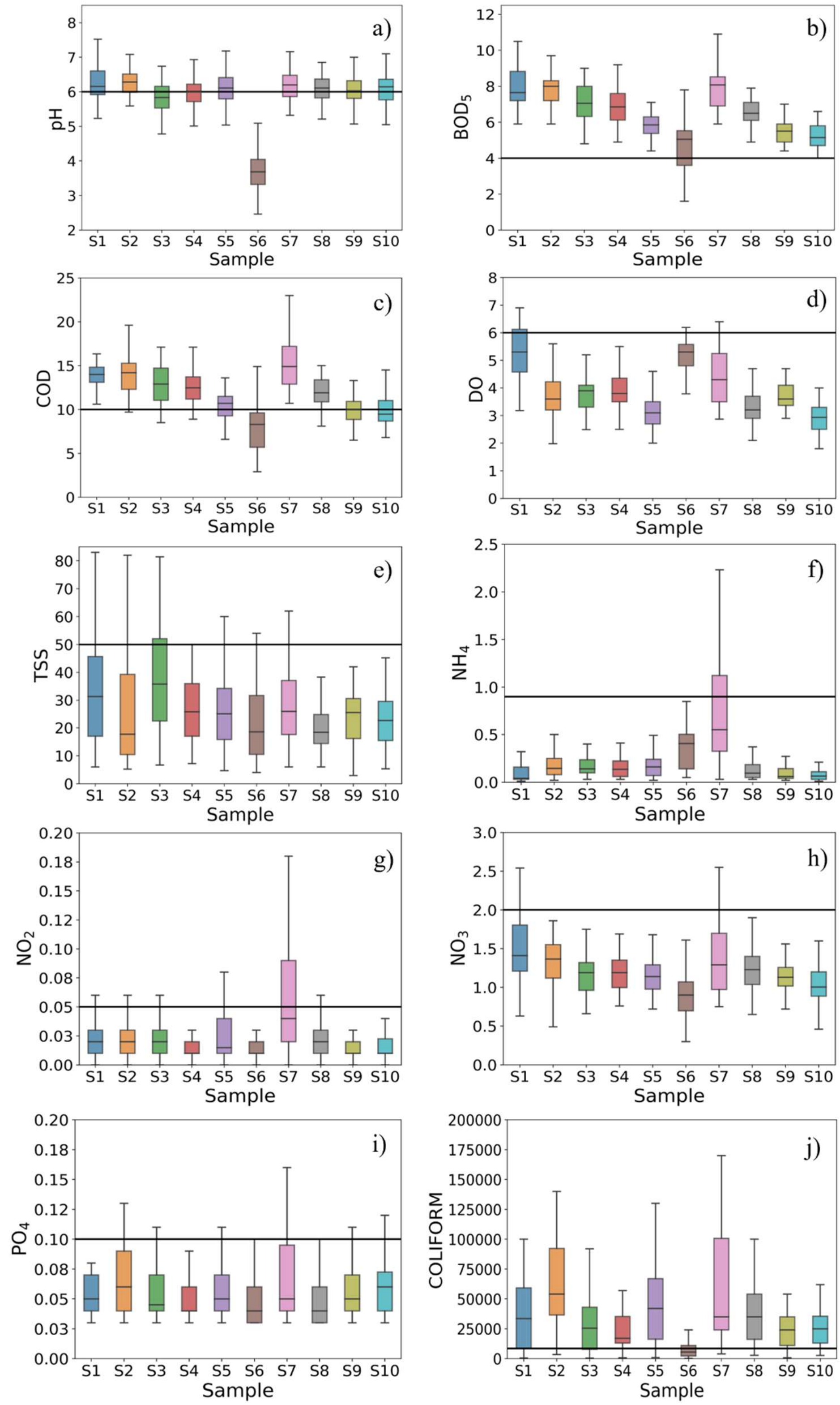

Fig. 7: Average water quality parameters were measured at ten sampling locations from February to July each year for 2018 to 2022.

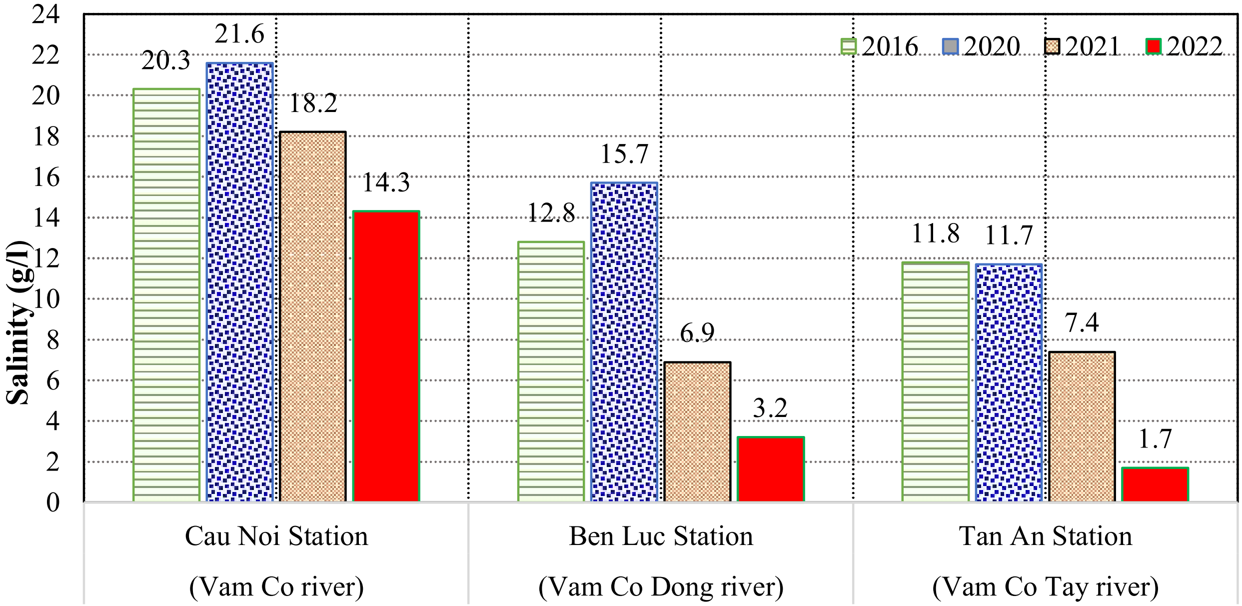

Fig. 8: The highest salinity in the dry season of 2016, 2020, 2021, and 2022

Table 3: The average WQI for each parameter from February to July 2022.

Locations	WQI *(pH)*	WQI *(BOD_5)*	WQI *(COD)*	WQI *(DO)*	WQI *(TSS)*	WQI *(NH_4)*	WQI *(NO_2)*	*WQI* *(NO_3)*	WQI *(PO_4)*	WQI
S1	98.3	71.3	83.3	66.2	82.8	90.6	64.3	100.0	77.1	78.4
S2	96.9	70.6	82.2	43.7	100.0	78.3	80.1	77.5	79.9	81.6
S3	77.7	72.6	85.6	46.9	80.2	81.0	72.5	77.5	83.2	58.4
S4	85.9	75.3	84.7	44.5	86.7	79.3	82.7	77.5	80.9	67.8
S5	94.4	80.4	94.4	37.9	96.9	84.6	71.6	100.0	92.7	82.9
S6	25.0	89.5	100.0	65.4	90.4	55.0	41.6	25.0	90.0	21.1
S7	98.6	70.6	80.6	59.4	88.2	55.0	87.8	32.5	67.6	75.3
S8	97.9	77.0	90.6	41.6	84.5	85.9	88.1	92.5	84.6	78.0
S9	97.2	83.7	97.9	44.5	93.5	88.4	78.1	100.0	89.8	84.1
S10	99.4	81.3	92.3	36.8	81.2	92.0	80.9	100.0	86.6	78.6

also fit well with observed values of DO with $R^2 = 0.995$, NSE = 0.995, RMSE = 0.054, and MAE = 0.029 (Table 4). The values of DO concentrations fluctuated because streamflow at different locations was varied.

Fig. 10d shows the comparison between the simulated and observed values of NH_4 at the different sampling locations in the Vam Co River Basin. The results show that the simulated values were significantly fitted to the observed values with $R^2 = 0.977$, NSE = 0.973, RMSE = 0.022, and MAE = 0.015 (Table 4). As can be seen in the figure, the simulated values of NH_4 were lower than the measured ones. However, the overall results of the water quality modeling were acceptable. It can be said that the statistical indicators R^2, NSE, RMSE, and MAE are all within a good range, indicating a high degree of consistency and accuracy between the simulated data and the observed data.

Fig. 11 shows a spatial distribution of WQI of 2022 in the study area. The map clearly shows strong variations in the WQI values, indicating that the southern part of the Vam Co River basin has lower water quality than the northern part. According to WQI, the water quality in Thu Thua district (S3 and S4) was at a Moderate level. The water quality at

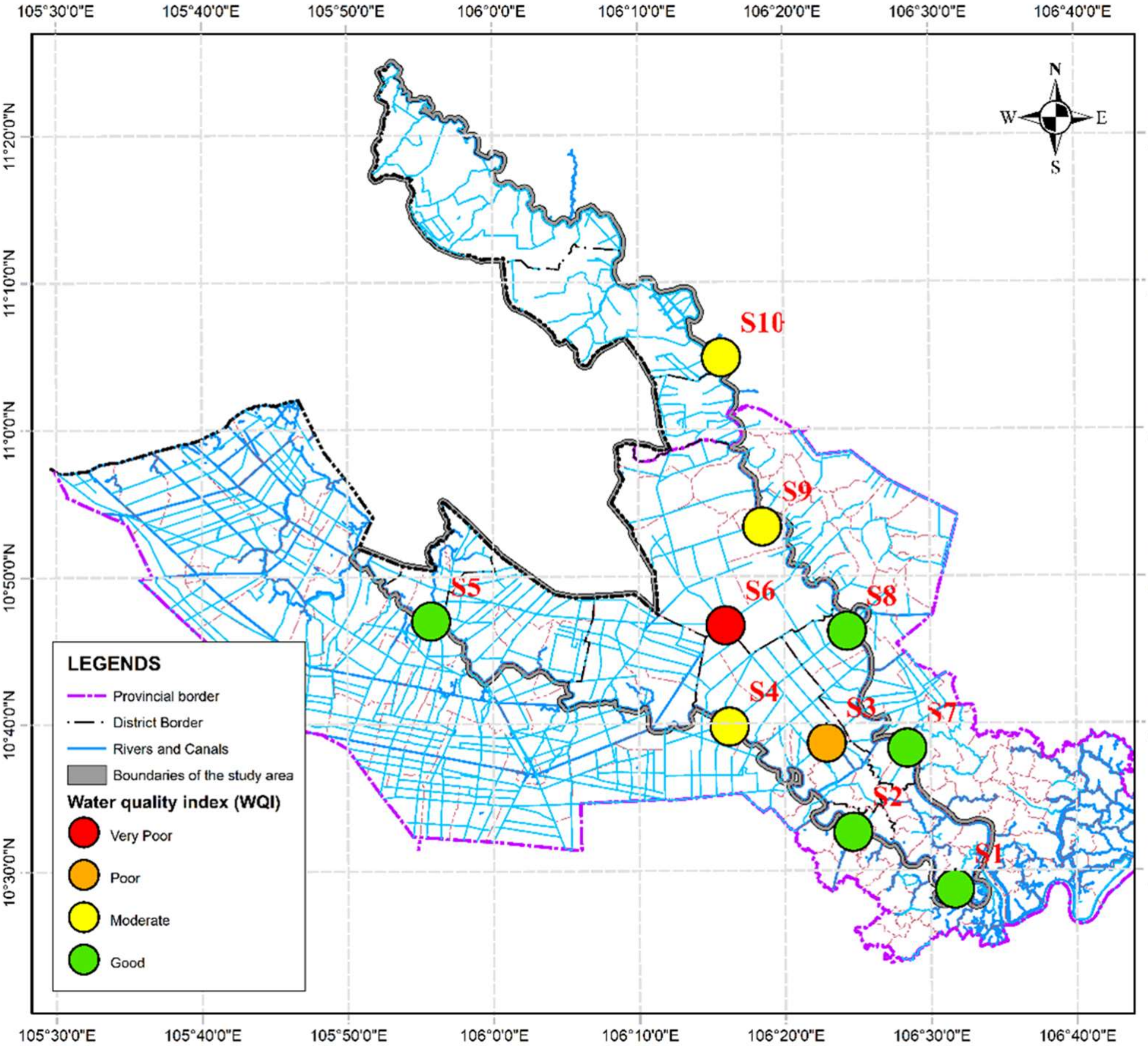

Fig. 9: Average WQI at ten sampling locations from February to July 2022.

the Moc Hoa (S5) was determined as Poor based on the WQI value, and the water quality at the Duc Hue (S6) districts of Long An province was Very poor. This is because economic and social activities in the area are intense. In addition, this area receives a significant amount of wastewater from industrial, agricultural, aquaculture, and domestic activities.

DISCUSSION

Overall, the water quality analysis conducted between 2018 and 2022 on nine indicators shows that most of them are within limits allowed by QCVN 08-MT:2015/BTNMT, indicating stable and satisfactory water quality. However, COD, BOD_5, and Coliform still exceed the allowed limits due

Table 4: Statistical evaluation of model performance on water quality simulation 2022.

Parameter	R^2	NSE	RMSE	MAE
Salinity	0.961	0.956	0.023	0.017
BOD_5	0.919	0.911	0.266	0.170
DO	0.995	0.995	0.054	0.029
NH_4	0.977	0.973	0.022	0.015

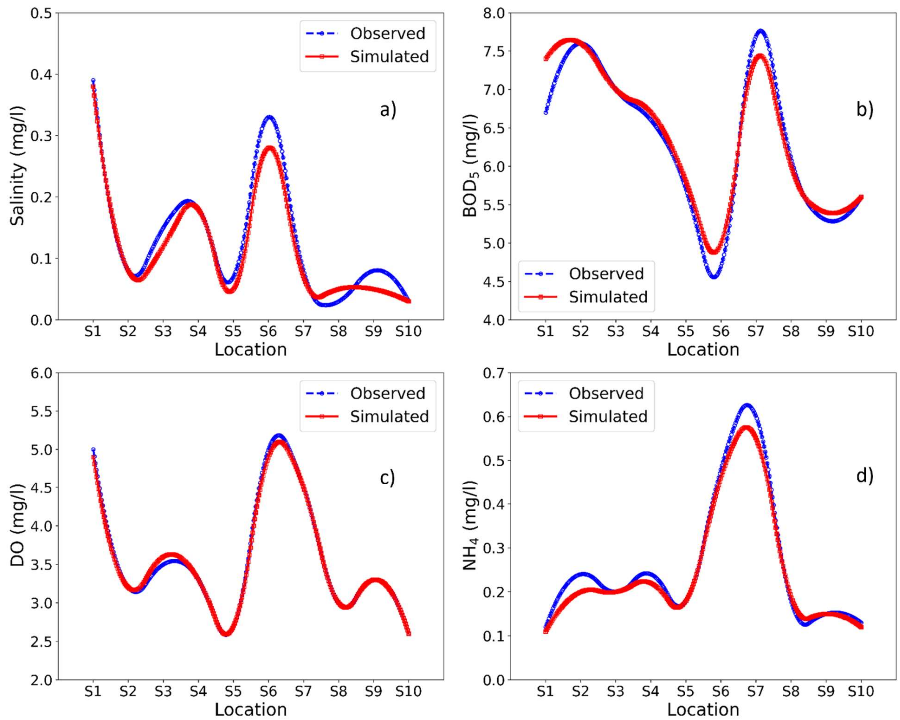

Fig. 10: Comparison of measured and forecasted water quality indicators (mg.L^{-1}).

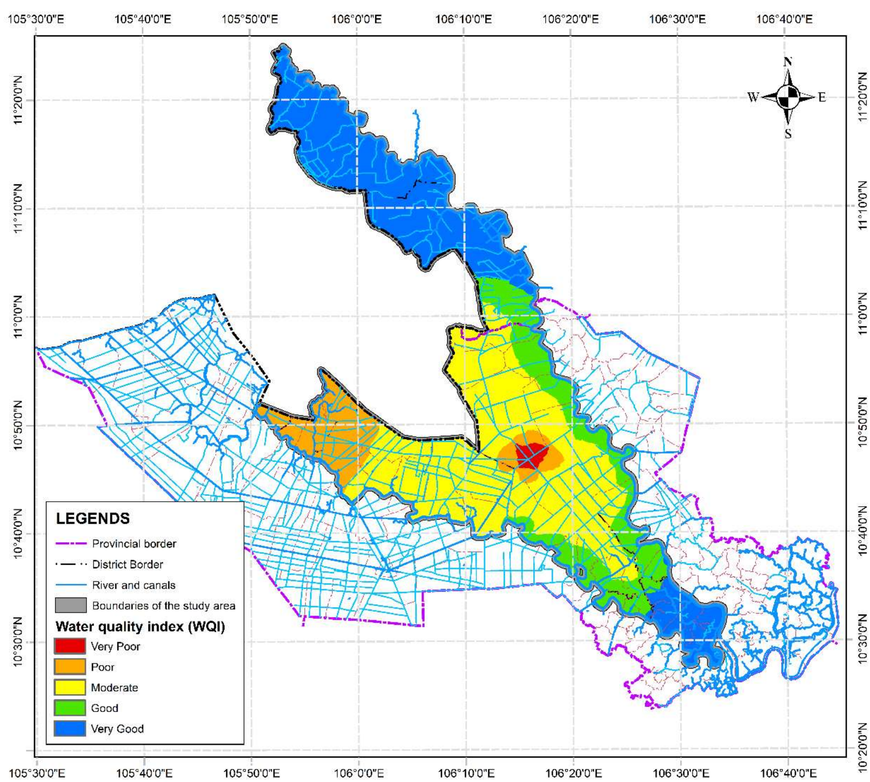

Fig. 11: Spatial distribution map of average WQI in 2022.

to mild organic and microbial contamination. This finding is corroborated by a study conducted by Nguyen and Huynh (2022), which yielded similar results. Table 3 shows that the water source in the irrigation system of the Vam Co River Basin is generally good for irrigation or other purposes. However, pollution still occurs in some locations, particularly in the late dry season and early rainy season. Earlier research conducted in the Mekong Delta also indicated that the water was contaminated with organic pollutants and exhibited fluctuations based on the season (Giao & Minh 2021, Ly et al. 2013, Nguyen 2020). Additionally, 2016 and 2020 were two years of record drought in the Mekong Delta, Vietnam (Loc et al. 2021, Park et al. 2022), so people have experienced and taken proactive preventive measures. Therefore, the salinity situation in 2022 was lower than in previous years.

The study also shows that the simulated results of water quality in 2022 are relatively good, with insignificant differences between predicted and measured salinity values. However, the predicted results were slightly lower than the measured results at some locations due to unpredictable weather conditions. The model is stable and produces results relatively close to reality based on seasonal weather conditions, simulating a similar trend to saltwater intrusion in the study area. For indicators such as BOD_5, DO, and NH_4, the simulated results differ from the actual measured values due to varying environmental factors in space and time, particularly at location S6, where there is a construction site. Abrupt fluctuations between measurement times were observed in DO and NH_4 values, possibly due to wastewater, dead vegetation, decomposed straw after rice harvest, mud on the bank, excess food settling on channels and rivers, and waste discharged at actual station locations. According to the research conducted by Viet and Kieu (2020), it has been evident since 2018 that the Vam Co Dong River, which passes through the Ben Luc District in Long An Province, has become incapable of sustaining acceptable levels of BOD_5 and DO. This is primarily attributed to the substantial discharge of untreated wastewater stemming from various sources such as industrial, agricultural, residential, and service activities. Besides that, the NH_4 value showed sudden changes due to production habits and excessive use of pesticides and chemical fertilizers, and this has also been demonstrated in the study of Dang et al. (2019).

However, many factors can affect the results, especially if the data sources are inaccurate or incomplete (Moges et al. 2021). Monitoring water quality every two weeks is insufficient to fully assess the fluctuations in water quality according to hydrological changes, leading to inaccurate predictions and inconsistency with reality (Asadollah et al. 2021, Rode & Suhr 2007). Pollution sources often occur locally, in areas with little flow due to drainage systems and the characteristics of the canal network and terrain. Investigating wastewater discharge into water sources still has many limitations due to difficulties accessing waste discharge units into the irrigation system, incomplete information, and scattered data from various sources.

CONCLUSION

This study aims to evaluate the water quality status in the Vam Co River Basin by conducting sampling at ten stations during 2018-2021 and utilizing the WQI and the MIKE 11 model. At the station scale, the results of the sampling from 2018-2022 indicate that while the area has been desalinated, saltwater intrusion is still prevalent during the dry season. Besides that, indicators analysis is within acceptable limits, but some, such as BOD5, COD, and Coliform, still exceed allowable limits. The WQI calculation for 2022 shows that pollution status ranges from Very poor to Moderate, concentrated mainly in Thu Thua (S3, S4), Moc Hoa (S5), and Duc Hue (S6) districts of Long An province due to active industry, agriculture, and high population density.

At the basin scale, the MIKE 11 model's simulated water quality results are relatively accurate, with little difference between the predicted and actual results. The southern part of the Vam Co River Basin has lower water quality than the northern part, with pollution mainly concentrated in Long An province. Establishing this hydraulic model is a significant step towards understanding and managing the impacts of pollution in the Vam Co River basin.

This study not only enriches the awareness of water quality in the Vam Co River Basin from 2018 to 2022 but highlights the feasibility of using the MIKE 11 model to simulate water quality and provides useful information for monitoring and forecasting water quality, controlling saltwater intrusion, and ensuring water supply for agriculture and people's livelihoods. With further refinement and improvement, this model has the potential to play a critical role in ensuring the long-term sustainability of the local environment and the communities that depend on it.

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DATA AVAILABILITY STATEMENT

The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author at a reasonable request.

REFERENCES

Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J. and Srinivasan, R. 2007. Modeling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. J. Hydrol., 333: 413–430.

Asadollah, S.B.H.S., Sharafati, A., Motta, D. and Yaseen, Z.M. 2021. River water quality index prediction and uncertainty analysis: A comparative study of machine learning models. J. Environ. Chem. Eng., 9: 104599.

Behmel, S., Damour, M., Ludwig, R. and Rodriguez, M.J. 2016. Water quality monitoring strategies—A review and future perspectives. Sci. Total Environ., 571: 1312–1329.

Bilgin, A. 2018. Evaluation of surface water quality using Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) method and discriminant analysis method: a case study Coruh River Basin. Environ. Monit. Assess., 190: 1-11.

CFO. 2022. Tide Table in 2022. Publishing House Natural Resources - Environment and Maps of Vietnam, Hanoi, Viet Nam.

Cheng, H. and Zhi, Z. 2015. Identification of the most efficient methods for improving water quality in rapidly urbanized areas using the Mike 11 modeling system. In the 2015 Seventh International Conference on Measuring Technology and Mechatronics Automation, June 13-14, 2015, Nanchang, China, IEEE, Manhattan, NY, US, pp. 545-548.

Codiga, D.L. 2011. Unified tidal analysis and prediction using the UTide Matlab functions. https://www.mathworks.com/matlabcentral/fileexchange/46523-utide-unified-tidal-analysis-and-prediction-functions

Dang, T.Q., Van, S.P., Dang, T.D. and Anh, D.T. 2019. Predicting water quality responses under climate change using coupled one-and two-dimensional models for Dong Nai River Basin. In Conference: 15th International Asian Urbanization Conference (AUC) At. Vietnamese-German University (VGU), November 27-30, 2019, Ho Chi Minh City, Vietnam, Springer, NY.

Dao, T.S. and Bui, T.N.P. 2016. Phytoplankton from Vam Co River in Southern Vietnam. Environ. Manag. Sustain. Dev., 5: 113-125.

Das, J. and Acharya, B.C. 2003. Hydrology and assessment of lotic water quality in Cuttack City, India. Water. Air. Soil Pollut., 150: 163-175.

Debele, B., Srinivasan, R. and Parlange, J.Y. 2008. Coupling upland watershed and downstream waterbody hydrodynamic and water quality models (SWAT and CE-QUAL-W2) for better water resources management in complex river basins. Environ. Model. Assess., 13: 135–153. https://doi.org/10.1007/s10666-006-9075-1

DHI. 2019. MIKE 21 - Tidal Analysis and Prediction Module, DHI, Denmark.

DHI. 2017. MIKE 11: A modeling system for Rivers and Channels. User Guide. DHI, Denmark

Duc, N.H., Avtar, R., Kumar, P. and Lan, P.P. 2021. Scenario-based numerical simulation to predict future water quality for developing robust water management plan: a case study from the Hau River, Vietnam. Mitig. Adapt. Strateg. Glob. Change, 26: 1-38.

Epelde, A.M., Cerro, I., Sánchez-Pérez, J.M., Sauvage, S., Srinivasan, R. and Antigüedad, I. 2015. Application of the SWAT model to assess the impact of changes in agricultural management practices on water quality. Hydrol. Sci. J., 60: 825-843.

Giao, N.T., Minh, V.Q. 2021. Evaluating surface water quality and water monitoring variables in Tien River, Vietnamese Mekong Delta. J. Teknol., 83: 29-36.

Girbaciu, A., Girbaciu, C., Petcovici, E. and Dodocioiu, A.M. 2015. Water quality modeling using Mike 11. Rev. Chim., 66: 1206-1211.

Gordillo, G., Morales-Hernández, M. and García-Navarro, P. 2020. Finite volume model for the simulation of 1D unsteady river flow and water quality based on the WASP. J. Hydroinform., 22: 327-345.

Havnø, K., Madsen, M.N. and Dørge, J. 1995. MIKE -11a generalized river modelling package. Comput. Model. Watershed Hydrol., 11: 733–782.

Huntjens, P., Kool, J., Lasage, R., Sprengers, C., Ottow, B. and Kerssens, P. 2013. Preferred Climate Change Adaptation Strategy for the Lower Vam Co River Basin, Viet Nam. Water Governance Center, Vietnam.

Krause, P., Boyle, D.P. and Bäse, F. 2005. Comparison of different efficiency criteria for hydrological model assessment. Adv. Geosci., 5: 89-97.

Lai, Y.C., Yang, C.P., Hsieh, C.Y., Wu, C.Y. and Kao, C.M. 2011. Evaluation of non-point source pollution and river water quality using a multimedia two-model system. J. Hydrol., 409: 583–595.

Li, X., Li, Y. and Li, G. 2020. A scientometric review of the research on the impacts of climate change on water quality during 1998–2018. Environ. Sci. Pollut. Res., 27: 14322-14341.

Liang, R., Schruff, T., Jia, X., Schüttrumpf, H. and Frings, R.M. 2015. Validation of a stochastic digital packing algorithm for porosity prediction in fluvial gravel deposits. Sediment. Geol., 329: 18-27.

Loc, H.H., Van Binh, D., Park, E., Shrestha, S., Dung, T.D., Son, V.H., Truc, N.H.T., Mai, N.P. and Seijger, C. 2021. Intensifying saline water intrusion and drought in the Mekong Delta: From physical evidence to policy outlooks. Sci. Total Environ., 757: 143919.

Loukas, A. 2010. Surface water quantity and quality assessment in Pinios River, Thessaly, Greece. Desalination, 250: 266-273.

Ly, K., Larsen, H. and Duyen, N. 2013. Lower Mekong Regional Water Quality Monitoring Report. Mekong River Commission, Vientiane, p. 205.

Mama, A.C., Bodo, W.K.A., Ghepdeu, G.F.Y., Ajonina, G.N. and Ndam, J.R.N. 2021. Understanding the seasonal and spatial variation of water quality parameters in mangrove estuary of the Nyong River using multivariate analysis (Cameroon Southern Atlantic Coast). Open J. Mar. Sci., 11: 103-128.

Mbuh, M.J., Mbih, R. and Wendi, C. 2019. Water quality modeling and sensitivity analysis using the Water Quality Analysis Simulation Program (WASP) in the Shenandoah River watershed. Phys. Geogr., 40: 127-148.

McCuen, R.H., Knight, Z. and Cutter, A.G. 2006. Evaluation of the Nash–Sutcliffe efficiency index. J. Hydrol. Eng., 11: 597-602.

MOC. 2006. TCXDVN 33:2006-Water Supply - Distribution System and Facilities Design Standard. Ministry of Construction, Hanoi, Vietnam.

Moges, E., Demissie, Y., Larsen, L., Yassin, F. 2021. Sources of hydrological model uncertainties and advances in their analysis. Water., 13: 28.

MONRE. 2019. Decision No. 1460/QD-TCMT-Technical Guidance on Calculation and Publication of Vietnam Water Quality Index (VN_WQI). Ministry of Natural Resources and Environment, Hanoi, Vietnam.

MONRE. 2015. Studying the impact of Mekong hydropower on the Mekong Delta (Project by HDR and DHI). Ministry of Natural Resources and Environment, Hanoi, Vietnam.

MONRE. 2011. National Technical Regulation on Industrial Wastewater. Minister of Natural Resources and Environment, Hanoi, Vietnam.

MONRE. 2008. National Technical Regulation on the Effluent of Aquatic Products Processing Industry. Ministry of Natural Resources and Environment, Hanoi, Vietnam.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE, 50: 885-900.

Moriasi, D.N., Wilson, B.N., Douglas-Mankin, K.R., Arnold, J.G. and Gowda, PH 2012. Hydrologic and water quality models: Use, calibration, and validation. Trans. ASABE., 55: 1241-1247.

Nguyen, C.N. 2019. Applying Geostatistics to Predict Dissolvent Oxygen (DO) in Water on the Rivers in Ho Chi Minh City. In Context-Aware Systems and Applications, and Nature of Computation and Communication: 8th EAI International Conference, ICCASA 2019, 5th EAI International Conference, ICTCC 2019, My Tho City, Vietnam, November 28-29, 2019, Proceedings. Springer, NY, pp. 247-257.

Nguyen, G.T. 2020. Evaluating current water quality monitoring system on Hau River, Mekong Delta, Vietnam using multivariate statistical techniques. Appl. Environ. Res., 42: 14-25.

Nguyen, T.G. and Huynh, T.H.N. 2022. Assessment of surface water quality and monitoring in southern Vietnam using multicriteria statistical approaches. Sustain. Environ. Res., 32: 1-12.

Paliwal, R. and Patra, R.R. 2011. Applicability of MIKE 21 to assess temporal and spatial variation in water quality of an estuary under the impact of effluent from an industrial estate. Water Sci. Technol., 63: 1932-1943.

Park, E., Loc, H.H., Van Binh, D. and Kantoush, S. 2022. The worst 2020 saline water intrusion disaster of the past century in the Mekong Delta: Impacts, causes, and management implications. Ambio, 51: 691-699.

Qiu, Z. and Wang, L. 2014. Hydrological and water quality assessment in a suburban watershed with mixed land uses using the SWAT model. J. Hydrol. Eng., 19: 816-827.

Ramakrishnaiah, C.R., Sadashivaiah, C. and Ranganna, G. 2009. Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India. E-J. Chem., 6: 523-530.

Rode, M. and Suhr, U. 2007. Uncertainties in selected river water quality data. Hydrol. Earth Syst. Sci., 11: 863-874.

Thanh Giao, N., Kim Anh, P. and Thi Hong Nhien, H. 2021. Spatiotemporal analysis of surface water quality in Dong Thap province, Vietnam using water quality index and statistical approaches. Water., 13: 336.

Thu Minh, H.V., Avtar, R., Kumar, P., Le, K.N., Kurasaki, M. and Ty, T.V. 2020. Impact of rice intensification and urbanization on surface water quality in An Giang using a statistical approach. Water, 12: 1710.

Thu Minh, H.V., Tri, V.P.D., Ut, V.N., Avtar, R., Kumar, P., Dang, T.T.T., Hoa, A.V., Ty, T.V. and Downes, N.K. 2022. A model-based approach for improving surface water quality management in aquaculture using MIKE 11: A case of the Long Xuyen Quadrangle, Mekong Delta, Vietnam. Water, 14: 412.

Tran, T.H. 2017. Application of MIKE 21 FM modeling to simulate the water quality at the coastal area Đinh Vu. VNUHCM J. Nat. Sci., 1: 282-292 (Vietnam).

Turner, S., Pangare, G. and Mather, R.J. 2009. Water governance: A situational analysis of Cambodia, Lao PDR and Viet Nam. Mekong Reg. Water Dial. Publ., 2: 47.

Tyagi, S., Sharma, B., Singh, P., Dobhal, R. 2013. Water quality assessment in terms of water quality index. Am. J. Water Resour., 1: 34-38.

Viet, L.B. and Kieu, P.T.M. 2020. Assessment of pollutant load on Vam Co Dong river in Ben Luc district, Long An province. Sci. J. Dong Nai Univ. 18: 145.

Wu, Z., Wang, X., Chen, Y., Cai, Y. and Deng, J. 2018. Assessing river water quality using water quality index in Lake Taihu Basin, China. Sci. Total Environ., 612: 914-922.

Yao, H., Qian, X., Yin, H., Gao, H. and Wang, Y. 2015. Regional risk assessment for point source pollution based on a water quality model of the Taipu River, China. Risk Anal., 35: 265-277.