Influence of flood control facilities on water level in downstream of river system Sai Gon - Dong Nai

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Abstract. Ho Chi Minh City, Vietnam's largest city, located on the lower reaches of the Sai Gon-Dong Nai (SG-DN) river system, is facing increasingly severe flooding due to changes in river flow and water levels. This article presents the results of a study to assess the impact of hydraulic structures located in the upper reaches on the water level in the lower reaches of the SG-DN River. As part of a study to assess the impact of upstream reservoirs and flood control structures on the water level in the lower reaches of the SG-DN River, hydrological data of the river network were collected. A hydraulic model was developed based on a digital elevation model (DEM) using the software package Mike 11, Mike 21 and Mike Flood. The water level of the Sai Gon River from the upper reaches to the Thu Dau Mot measuring station depends on the Dau Tieng reservoir, and the Tri An reservoir directly affects the water level in the river section from behind the Tri An dam to the Dong Nai section in the Tam An - Long Phuoc area. In the sections of the Sai Gon and Dong Nai rivers, which are less affected by the two overlying reservoirs, it is necessary to develop preventive measures to supply sufficient fresh water to meet the population's and industries' needs. In areas prone to flooding and underflooding due to the operation of anti-flood locks, it is also necessary to reconstruct hydraulic structures (raise the elevations of foundations, expand drainage systems, build reservoirs for collecting flood water, etc.)

1 Introduction

In recent years, in many countries, the consequences of floods have become more and more serious, affecting not only the economy but also causing millions of deaths, and destroying houses and gardens [1-4]. Flood damage is more severe in coastal cities in developing countries where flood control measures are ineffective [1,4,5].

The downstream Sai Gon-Dong Nai area, where Ho Chi Minh City is located, is the largest financial and economic center in Vietnam and can be seen as a typical example of a coastal city in Southeast Asia facing many serious problems related to climate change and

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sea level rise due to its relatively low altitude, rapid rate of urbanization, complex channel system, and lack of tidal control measures. In 2005, Ho Chi Minh City was among the world's top ten cities with the most people affected by flooding [3-6]. And by 2070, experts predict that Ho Chi Minh City will be one of the world's top five.

To solve the problem of flooding in Ho Chi Minh City, flood control engineering structures are currently under construction under the State Irrigation Plan for Flood Prevention and Control in Ho Chi Minh City District under Decree No. 1547 / QD-TTg. The engineering protection structures are mainly designed for flood control during the rainy season and tidal control during the dry season when the maximum tide level exceeds 1.2 m. These flood control structures are designed as sluices with gates that open and close depending on the water level in the river. In addition, the Zau Tieng and Chi An reservoirs upstream of the SG-DN also regulate the flow downstream.

Currently, several authors are studying the runoff regime and sediments in the lower reaches of the SG-DN River [7–10]. These studies have shown that the area is highly sensitive to climate change, sea level rise, and land use. Under the influence of these factors, the regime of flow and sediment changes. In particular, the water level at the measuring stations will increase according to forecast scenarios; the total amount of alluvium and sediments of the entire basin will increase in the coming years.

In addition, studies [11-13] indicate that at a tide height of more than 1.2 m, tidal locks will be closed, which has a significant impact on the water level of the outer territory of flood control structures. Saltwater intrusion creates difficulties for aquaculture, agriculture, and obtaining fresh water for people's daily lives.

These studies are focused only on assessing the impact of climate change, sea level rise, and land use on the flow regime, alluvial regime, water quality, seawater infiltration process, etc., in the SG-DN river basin. It should be noted that no studies have been conducted to assess the impact of upstream flood control structures and reservoirs on the water level in the lower reaches of the SG-DN River.

Therefore, this paper assesses the impact of flood control works and reservoirs on the water level in the lower reaches of the SG-DN River. The study results are of practical importance for assisting urban planning and governing bodies in developing recommendations and flood prevention scenarios to minimize the impact of natural disasters on people's lives and the environment in the lower reaches of the SG-DN River. In addition, it is very important to determine the impact of the two reservoirs upstream of the river to help people on both sides of the river actively use the water to grow rice, and fruit trees and select aquatic species suitable for cultivation.

2 Materials and Methods

In this work, the Mike 11, Mike 21, and Mike Flood programs were used to assess the impact of reservoirs and flood protection facilities on water levels in the lower reaches of the SG-DN River. The main parameters of these structures are presented below.

The study area in this paper is downstream of the Sai Gon-Dong Nai River. This area adjoins the Mekong Delta to the southwest, the East Sea to the south and southeast, and is adjacent to the southern central provinces of Vietnam to the northeast (Figure 1). The area has an intertwined system of rivers and canals, influenced by the tropical monsoon climate and tidal levels in the East Sea.

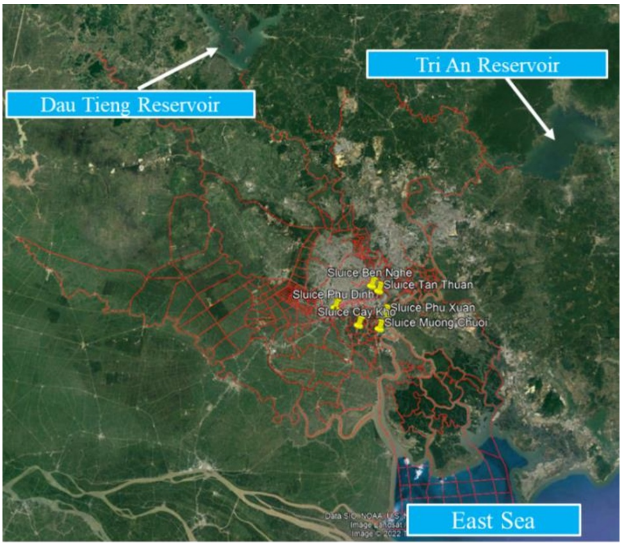


Fig. 1. The downstream of Sai Gon-Dong Nai River.

Located in the upstream reaches of the Sai Gon River, the Dau Tieng Reservoir has been used since 1985 to provide water for agricultural production and everyday life in Tay Ninh, Binh Duong, Long An, and Ho Chi Minh City provinces; to reduce flooding. It is the largest artificial reservoir in Vietnam, with a capacity of 1,580 × 109 m3 with a design flow of 2,800 m3/sec. Construction of the Tri An Reservoir began in 1984 and was completed in early 1987. This artificial lake, located on the Dong Nai River, has a 2765 x 106 m3 capacity, with a design flow of 19580 m3/s. It is a 400 MW Tri An hydropower plant reservoir with an annual power generation capacity of 1.7 billion kWh.

On October 28, 2008, the Prime Minister approved the Irrigation Plan for Flood Prevention and Control in the Ho Chi Minh Area under Ordinance No. 1547/QD-TTg, under which flood control structures will be built in the city. The location of these flood control structures is shown in Figure 2.

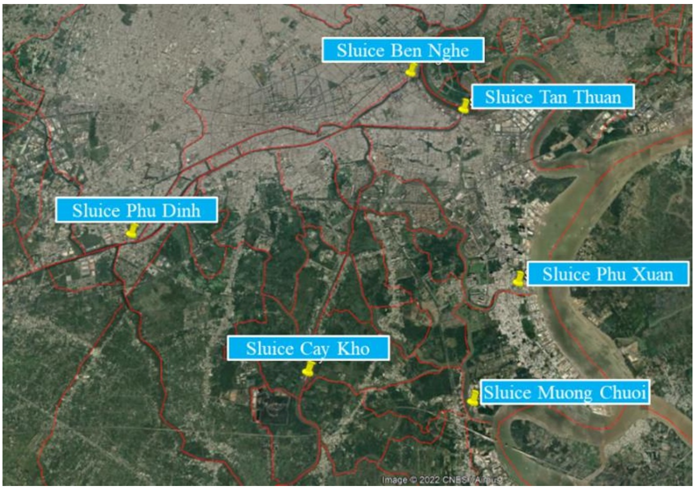


Fig. 2. Location of flood defenses

It was only in mid-May 2016 that these flood control works were started, and as of May 2021, about 90% of the tide locks have been built. The technical parameters of these structures are presented in detail in Table 1.

Table 1. Technical parameters of sluices for tide control.

Sluices	Phu Dinh	Cay Kho	Ben Nghe	Tan Thuan	Phu Xuan	Muong Chuoi
Camera width	40 m	40 m	40 m	40 m	80 m	160 m
Number of cameras	1	2	1	1	2	4
Threshold mark	-5.5 m	-5.5 m	-5.5 m	-5.5 m	-5.0 m	-6.5÷ -10 m
Shutter mark	+3.0 m	+3.0 m	+3.0 m	+3.0 m	+3.0 m	+3.0 m
Marking of the head gateways	+3.5 m	+3.0 m	+3.0 m	+3.5 m	+3.5 m	+3.5 m

Mike 11 is a versatile engineering tool for 1D simulation of hydrodynamic conditions in rivers. Mike 11 HD solves the Saint-Venant equations to determine the hydrodynamic state of river networks. A hydrodynamic (HD) model can model one-dimensional unsteady flow in a network of rivers using a hydrodynamic wave approach. The five main input parameters that need to be specified for the Mike 11(HD) setup are the river network layout, cross sections, boundary conditions, hydrodynamic parameters, and simulation parameters. The river cross-section of the model is shown in Figure 3.

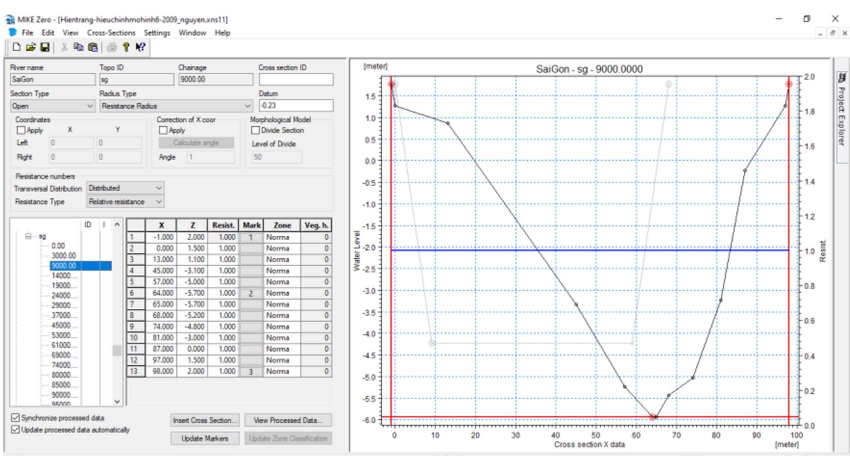


Fig. 3. River cross-section of the Mike 11 model

The two-dimensional Mike 21 solves the complete, time-dependent, non-linear equations of continuity and conservation of momentum [14, 15]. Mike 21 resolves the solution using an implicit second-order accuracy finite difference scheme. The input parameter of the Mike 21 model is a digital elevation model derived from LiDAR-DEM for the study area, which was processed to produce bathymetry as input to Mike 21. The resolution of the input bathymetry was 30 m x 30 m, and the assumed time step was 30 seconds for various models. On fig. 4 shows the bathymetry used in the study area.

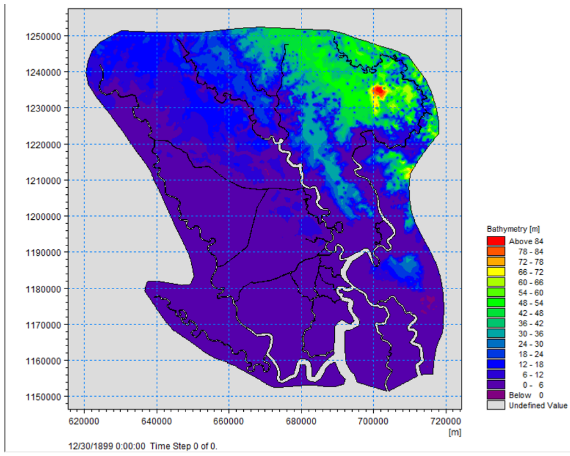


Fig. 4. Bathymetry used in studied area.

The Mike 11 river network was connected to the Mike 21 bathymetry using the lateral link option available in Mike Flood [16, 17]. The degree of flooding and floodplain depth for excess water is calculated using Mike 21. Other parameters for left and right bank laterals, such as momentum factor, weir factor, and allowable depth factor, are kept at default values. The simulation period for Mike 11 and Mike 21 was kept the same, and the model time step was adjusted to a low value of 30 seconds so that the Courant number (CR) is less than or equal to 1 to achieve a stable Mike Flood simulation run without errors. The Mike Flood installation with the river (Mike 11) and both side links (Mike 21) is shown in Fig. 5.

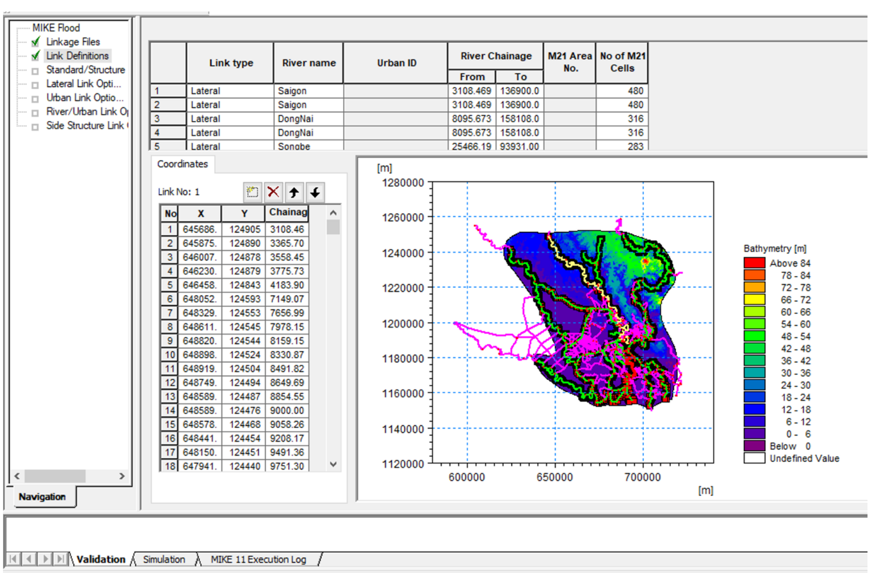


Fig. 5. Connection diagram of Mike 11 and Mike 21 in Mike Flood

This study aims to assess the impact of reservoirs and flood control structures on the water level in the downstream Sai Gon-Dong Nai river system; therefore, calculation scenarios have been developed for years with typical flow characteristics based on discharges from upstream reservoirs. On fig. 6 shows that for 24 years (1988-2012), there is a pattern between the magnitude of the discharge of water bodies in years. According to this rule, the flow of water from the lakes in many years will be quite large; in subsequent years, the value of this flow will decrease significantly. In years of high flow, there is a sharp increase in runoff for 1 year; similarly, in years with low flow from the reservoir, there is a sharp decrease in runoff for 1 year.

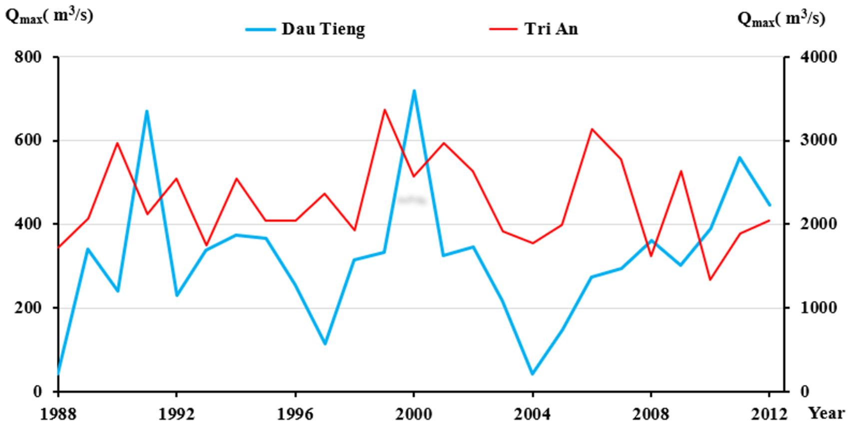


Fig.6. Volume of water consumption came in reservoirs in period 1991-2011

Based on the above analysis, calculation scenarios are constructed for flood years (2000), low water years (2004), and average discharge years (1998). These scenarios are presented in Table 2.

Table 2. Numerical simulation scenarios

Scenarios	Description of the boundary condition
Scenario 1 (Sce.1)	Upstream: Discharge of 1998 Downstream: Tidal level at the Vung Tau measuring station of 1998
Scenario 2 (Sce.2)	Upstream: Discharge of 2000 Downstream: Tidal level at the Vung Tau measuring station of 2000
Scenario 3 (Sce.3)	Upstream: Discharge of 2004 Downstream: Tidal level at the Vung Tau measuring station of 2004
Scenario 4 (Sce.4)	Upstream: Q_{max} at P=0.1% Downstream: Tidal level at the Vung Tau measuring station (H_{max}=1.48m)

In addition, the scenarios are also constructed with the highest discharge (Q_{max}) entering the Dau Tieng and Tri An reservoirs with a frequency of P = 0.1% (that is, it occurs once every 1000 years). Many different probability distribution functions have been proposed to analyze the frequency of extreme variables in hydrology (flow, water level, precipitation, etc.), and these functions are often listed as a family of distribution functions.

These include the family of normal distributions, the family of extreme distributions, the Gamma family, the Beta family, the Pareto family, the Hyphen family, and many others [18,19]. Examples: the Gumbel function in Europe and Japan, the GEV function in Australia, the GEV, GNO, and Log-Pearson 3 function in Canada, the Log-Pearson and Pearson 3 function in the USA, and the GLO function in the UK [18]. Traditional design flood characteristics in Vietnam are calculated from the PE3 or GEV probability distribution curve [20,21,22]. Therefore, the Qmax values (P = 0.1%) are calculated by the GEV frequency distribution function.

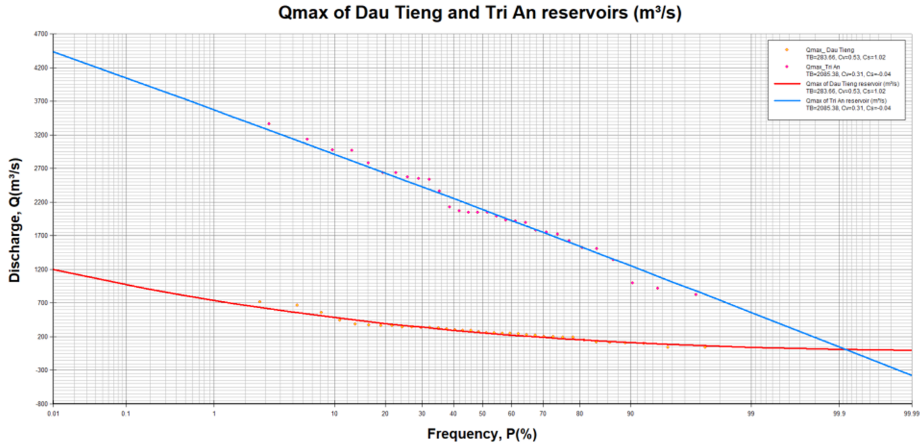


Fig. 7. Frequency distribution curves Q_{max} of Dau Tieng and Tri An reservoirs

From the frequency distribution curves in Figure 7, the Qmax values (P = 0.1%) were determined to be 1054.5 m3/s (Dau Tieng reservoir) and 4870.16 m3/s (Tri An reservoir), respectively. Reservoir discharge data are used to generate upstream input data files for the Mike 11 model, shown in Figure 8.

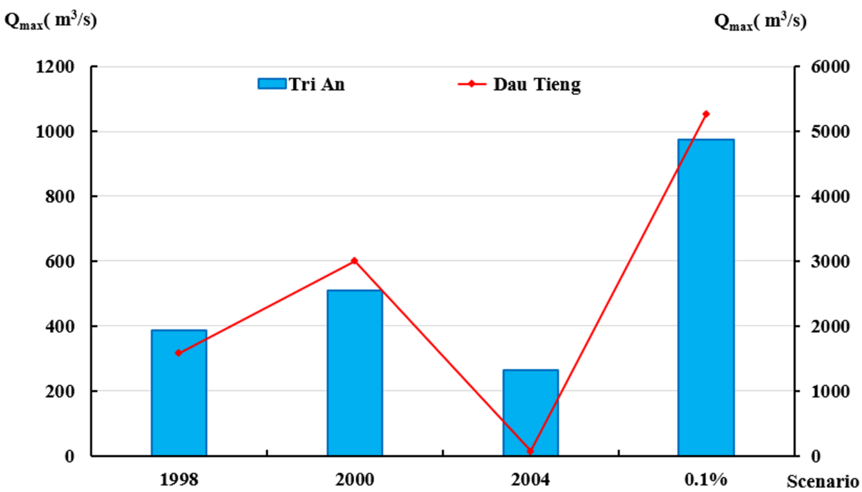


Fig. 8. Data on water consumption in reservoirs

Meanwhile, the tide levels at Vung Tau measuring stations in 1998, 2000, and 2004 are used as input to the bottom of the Mike 11 model, taken equal to 1.48m (the highest value in the period from 1980-2014).

3 Results and Discussion

3.1 Calibration and verification of the model

The model is calibrated using actual data measured at hydrological stations from October 1, 2012, to December 31, 2012. Manning coefficients (Manning) and initial water levels in rivers are corrected for the difference between simulated and real water levels measured at the lowest at stations Thu Dau Mot, Bien Hoa, Phu An, Nha Be, and Ben Luc. Hourly water levels during calibration and verification at Bien Hoa, Phu An stations from October 1, 2000, to October 16, 2000, are shown in Figure 9. A good agreement can be seen between the simulated and observed water levels at different time periods.

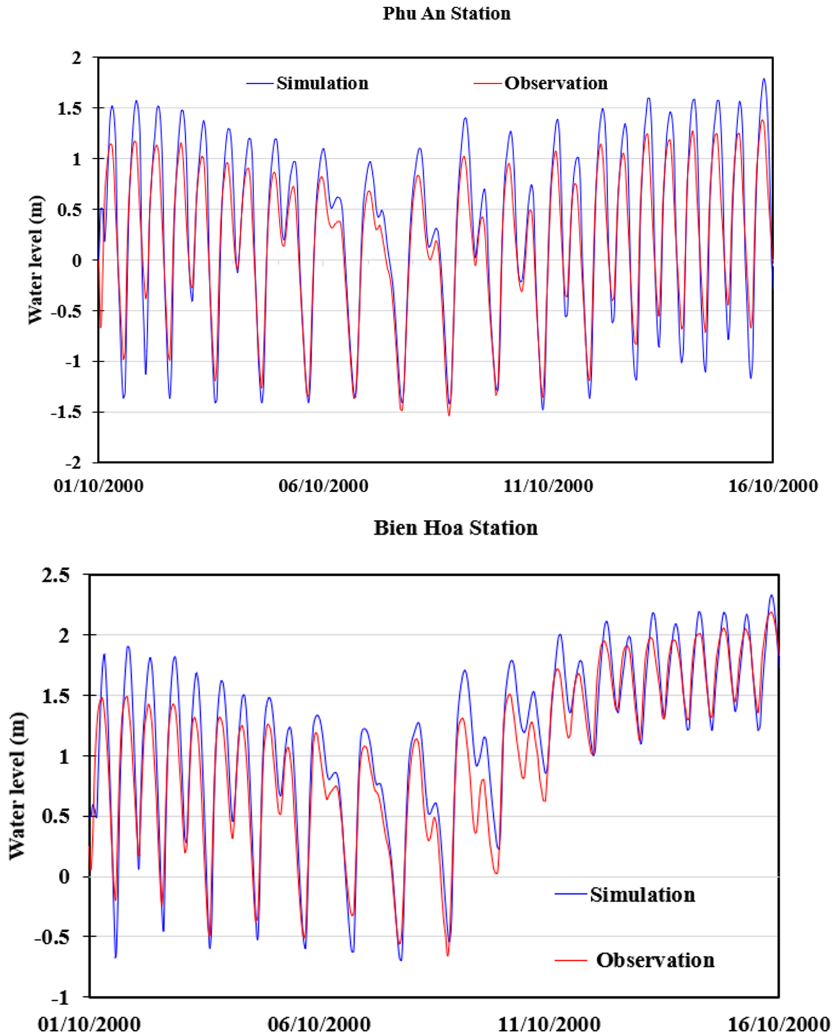


Fig. 9. Comparison graph of observed and simulated water level at stations of Phu An, Bien Hoa.

The accuracy of the numerical results was evaluated using the coefficient of determination (R2) and the Nash–Sutcliffe coefficient (Ef) / Nash–Sutcliffe model efficiency coefficient (NSE). The NSE values for hourly calibration and validation at all stations are shown in

Table 3. According to the performance criteria of Moriasi [23], the coefficients R_2 and E_f show that the model has high reliability in modeling the downstream of the Sai Gon - Dong Nai River.

Table 3. Performance of MIKE 11 for simulation of water level.

Station	Calibration (01.10.2012 - 31.12.2012)		Validation (01.10.2000 - 16.10.2000)	
	R^2	E_f	R^2	E_f
Bien Hoa	0.95	0.81	0.93	0.87
Phu An	0.97	0.86	0.96	0.81

3.2 Results

To better consider the change in runoff flow on the Sai Gon and Dong Nai Rivers with a change in the volume of reservoir flow, in addition to the main measuring points, points C1-C4 on the Sai Gon River and D1-D8 on the Dong Nai River were selected for analysis in this paper. These points are marked in Figure 10; the results of the scenario calculations are presented in Tables 4 and 5.

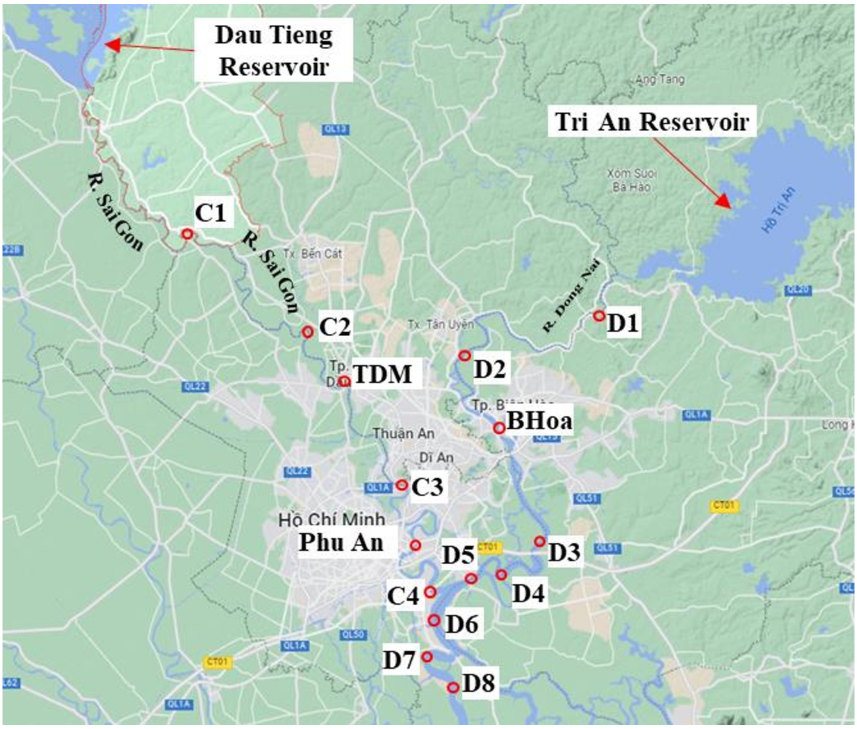


Fig. 10. Location of additional points on Sai Gon - Dong Nai River

The calculation results are presented in Tables 4 and 5.

Table 4. Water level (m) at measuring stations is calculated when sluices are opened.

	C1	C2	TDM	C3	Phu An	C4	D1	D2	B. Hoa	D3	D4	D5
2004	1.55	1.57	1.55	1.53	1.65	1.70	3.96	1.96	1.83	1.74	1.72	1.68
1998	1.71	1.62	1.58	1.57	1.67	1.73	5.99	2.60	1.87	1.78	1.74	1.70
2000	2.29	1.76	1.70	1.67	1.77	1.80	8.97	4.19	2.20	1.88	1.85	1.80
0.1%	3.48	2.01	1.94	1.86	2.00	2.04	12.51	6.63	3.06	2.13	2.08	2.01

Table 4 shows that with an increase in the flow rate from the reservoirs according to the corresponding scenarios, the water level at the measuring posts on the Sai Gon and Dong Nai rivers changes, but this change is not the same in the two rivers. In the calculated scenarios, the water level gradually rises from C1 station to Thu Dau Mot station on the Sai Gon River. Sharply decreases at C3 station and rises again at Phu An and C4 stations, but the water level rises slightly. This shows that the flow from the Dau Tieng reservoir directly affects only the section of the river from the lake to the measuring station Thu Dau Mot; the remaining section of the Sai Gon River is also affected by the East Sea's tide. Meanwhile, the change in water level at measuring stations throughout the Dong Nai River from Tri An Lake to the sea follows the same rule that in each scenario, the lower the water level decreases, the lower the water level decreases downstream. The measuring stations are closer to the reservoir (D1, D2, Bien Hoa), and the change in the water level according to the scenarios is more pronounced than other stations (D3, D4, D5). Moreover, the water level at st. D5 practically does not change in all 4 scenarios, although the volume of upstream runoff has multiplied. This shows that the tides influence this measuring station; even stations D3, and D4 are subject to similar influence, although the level of influence is unclear compared to station D5. This rule is more clearly seen in the graph in Figure 11.

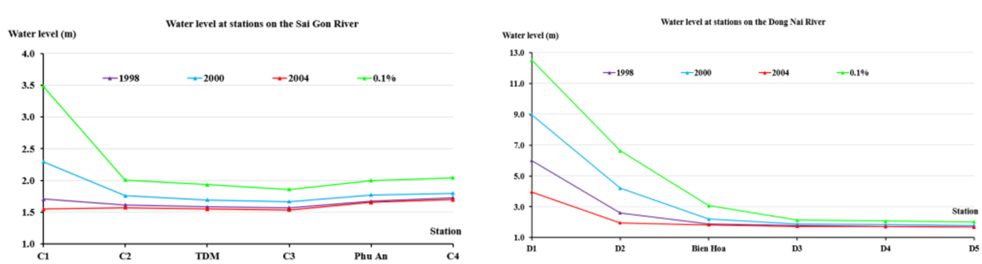


Fig. 11. Maximum water level at stations when gates of flood control structures are opened.

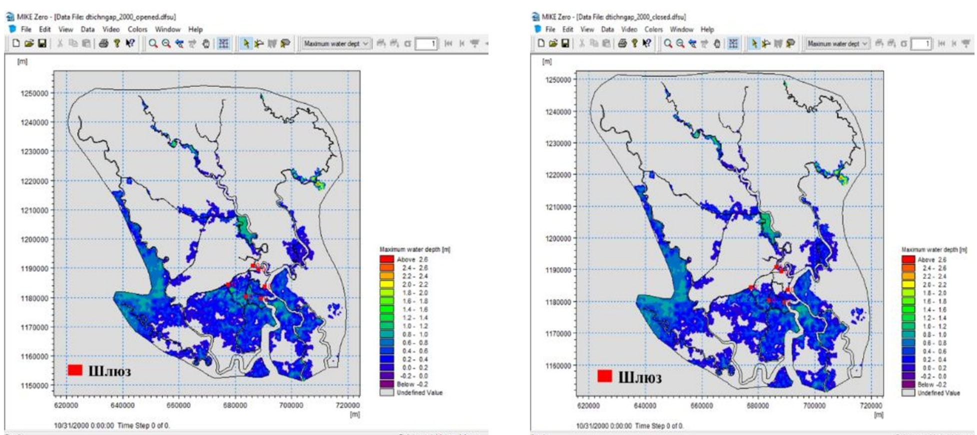
Assess the impact of flood control structures on water levels in rivers. The results of calculations at measurement stations according to the model (presented in Table 5) are used for the analysis.

Table 5. The water level (m) at the measuring stations is calculated when the sluices are opened and closed.

	When the gates open					When the gates close				
	Phu An	**C4**	**D6**	**D7**	**D8**	**Phu An**	**C4**	**D6**	**D7**	**D8**
2000	1.77	1.8	1.73	1.64	1.57	1.81	1.84	1.75	1.67	1.59
2004	1.65	1.7	1.61	1.59	1.54	1.7	1.74	1.64	1.61	1.56
1998	1.67	1.73	1.65	1.57	1.46	1.72	1.77	1.68	1.59	1.48
0.1%	2	2.04	1.91	1.85	1.75	2.06	2.09	1.94	1.88	1.78

The data in Table 5 found that when the locks of flood control structures are closed, the water level at the water metering posts rises, but the increase in the water level is uneven. The amplitude of water level fluctuations at Phu An and C4 stations is greater than at other stations, although the location of stations D6 and D7 is closer to flood control structures than Phu An and C4 stations. In addition, although the water level at 2 stations Phu An and C4 has a greater rise in amplitude than at other stations, in general, the rise is not large (only 4-6cm).

To more specifically assess the impact of flood control structures on the water level of the Sai Gon-Dong Nai River, the extent of flooding in this paper uses the Mike Flood program to simulate the 2000 flood. The simulation results show a two-dimensional map of flooded areas, shown in Figure 12.



A *B*

Fig. 12. Maximum water level in lower reaches of SG - DN river
(A - when opening the gates, B - when closing the gates)

Figure 12 shows that the flooding area with closed locks is less than with open locks. In particular, the central area, located inside 6 locks, significantly reduced the area of flooding. According to the results of model calculations, in the absence of flood control structures, the area of flooded areas is 1451.48 km^2. When these works are carried out, the area of flooded areas is reduced by only 55.14 km^2, leaving only 1396.34 km^2 (see Table 6).

Table 6. The area of the flooded area according to H_{max} (km^2)

H_{max}	When opening the gates	When closing the gates
$H_{\text{мак}} \leq 1$ m / $H_{max} \leq 1$m	1413.32	1361.66
1 m < $H_{\text{мак}} \leq 2$ m / 1m < H_{max} < 2m	35.54	31.98
2 m < $H_{\text{мак}} \leq 3$ m / 2m < H_{max} < 3m	2.48	2.52
$H_{\text{мак}} > 3$ m / $H_{max} > 3$m	0.15	0.17
Total area	1451.48	1396.34

Table 6 shows that during the operation of anti-flood structures, the area of flooded areas will decrease, while those of heavily flooded areas with H_{max} > 2m will increase. These areas are mainly concentrated along the Dong Nai River in Vinh Cuu District of Dong Nai Province and Tan Uyen Town of Binh Duong Province, Cu Chi area; Ben Suc Bridge also has a large flood level (H_{max} is about 2m). When the locks are closed, Thanh My Loi, Phu Huu, Long Truong, and Long Phuoc in Thu Duc City, Tam An District in Dong Nai Province will also be flooded with a maximum water level of 0.2m to 1m.

4 Conclusions

Mike 11, Mike 21, and Mike Flood were used to assess the impact of reservoirs and flood control structures on the water level of the lower Sai Gon-Dong Nai River. The calculation model was created, calibrated, and tested from 01/06/2011 to 06/16/2011. The calculation model was tuned, calibrated, and tested from October 1, 2000 to October 16, 2000. R^2 and E_f coefficients above 0.80 indicate that the model and the parameters set in the model are sufficiently reliable for modeling the hydraulic regime in the lower reaches of the Sai Gon - Dong Nai River.

Data on water flow in the Dau Tieng and Tri An reservoirs show that the flow of the Sai Gon - Dong Nai river changes every year according to the scheme: high water years are replaced by low water years. From here, 4 calculation scenarios were constructed for flood (2000), low-water (2004), medium-water (1998), and high-water years with a frequency of P = 0.1%.

The calculation results showed that: the water level on the Sai Gon River from the upper reaches to the measuring station Thu Dau Mot directly depends on the Dau Tieng reservoir, and Tri An Lake directly affects the water level in the river section from behind the Tri An dam to the D3 station (Long Phuoc - Tam An area).

When the flood gates are closed, the water level in the river rises, but unevenly. The amplitude of water level fluctuations at Phu An and C4 stations is the largest (from 4-6 cm). Due to the historic flooding of 2000, the closing of the flood gates will reduce the inundation of the central area (the inundation area will decrease by 55.14 km2) but will increase the level of inundated water in the areas of Thu Duc City and Tam An district.

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