

Effects of Sea Level Rise and Sea Dike Construction on the Downstream End of the Saigon River Basin (Can Gio Bay)

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Abstract

Located at the downstream end of the Dong Nai-Saigon river basin, near the mouth of the Saigon River, which is known as the “green lungs” of Ho Chi Minh City (HCMC) due to the ecosystem functions of the Can Gio mangrove forest, is a very complex hydrodynamic and geomorphic region with crossing estuaries, forming the so-called Can Gio Bay. Given its flat, low-lying topography, this area is strongly influenced by two main factors: (1) upstream flooding and (2) tidal regimes. The historical flood event of 2000 indicated that the downstream region of HCMC suffers from serious flooding, and that the Can Gio area is the worst affected, with approximately 90% of its area being inundated. This research aims to investigate the impact of tides and inflows in Can Gio Bay in the context of sea level rise and a sea dike structure connecting Go Cong to Vung Tau. A two-dimensional hydrodynamic model combined with a wetting and drying scheme is used to determine the locations of inundated areas. This research also shows how sea level rise and upstream flows cause flooding in Can Gio Bay, and identifies the negative and positive impacts of sea dike construction on Can Gio Bay.

Discipline: Agricultural engineering

Additional key words: Two-dimensional hydrodynamic model, wetland, tidal regime, wetting and drying scheme, climate change

Introduction

Ho Chi Minh City (HCMC) is the largest commercial city in Vietnam, located in the southern part of the country. It is ideally located, as many large rivers, including the Dong Nai-Saigon river system, flow through it, and given its flat, low-lying topography, it is frequently inundated under the influence of tidal regimes from the East Sea, with flood waters being discharged from upstream. In recent decades, HCMC has faced increasingly serious inundation problems (Ho 2007). The key causes of increasing inundation include urbanization, land subsidence, heavy rainfall, flooding due to upstream inflow, and sea level rise (Nguyen et al. 2015). Specifically, in 2000, a historical flood event caused serious flooding in HCMC, with about 42% of the area being inundated, including approximately 90% of

the Can Gio area. In addition, climate change is clearly occurring and affecting the region, as evidenced by ultra-abnormal typhoon strengths and rising sea levels. According to statistics provided by Vung Tau station, the sea level rose by 13 cm from 1954 to 2007 (IPCC 2007). Of particular significance is the fact that the highest water level recorded in 61 years was 1.68 m at Phu An station (located downstream of HCMC) on October 20, 2013, and the resulting natural disaster caused severe inundation in HCMC, accompanied by fatalities as well as extensive economic and social damage.

To cope with the serious rapidly increasing inundation in HCMC, the Vietnamese government has undertaken projects to protect HCMC, such as JICA 2001—a project to upgrade the Nhieu Loc–Thi Nghe drainage system to protect the center of HCMC from heavy rainfall. However, there was no decrease in inundation, and the

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number of inundated sites actually increased. Recently, project 1547/QĐ-TTg proposed by the HCMC government in 2008 aimed to protect the central urban areas of HCMC from tides and flooding. However, this project was widely discredited due to its inadequate protection capability. The main scope of this project is to protect the core zone (urban zones of HCMC) by dividing sewers, barriers and ring dikes. Thus, the upstream flooding has no room to overflow into urban zones and is forced to flow over other areas such as the suburbs, rural areas and the vicinity, such as Binh Duong, Dong Nai, Vung Tau, and Long An. Consequently, these areas are not only unprotected but also increase the risk of upstream flooding. Currently, the super sea dike project proposal aims to construct sea dikes connecting Go Cong to Vung Tau in order to control flooding, mitigate inundation, and provide both short- and long-term anti-salinity protection to the entire HCMC area under the impact of climate change, especially sea level rise (SLR). Thus far, the negative and positive impacts on the environmental water in rivers as well as in Can Gio mangrove forest are highly debatable. This project also received significant attention from researchers. To construct such sea dikes, it is necessary to focus on the prolonged effects with future studies.

Many researchers have tried to analyze the positive and negative impacts of sea dike construction, and most of them have focused on studying the capability to control the water level in urban areas and flood discharge from upstream areas (Nguyen et al. 2015). Several important studies were conducted over the past decades in this area, with new and valuable results being obtained. These noteworthy outcomes include the findings of Nguyen (2014) and Ngoc et al. (2013). However, these studies only identified water level change under the impact of sea dike construction, and did not consider inundation in wetlands of the Can Gio coastal area.

The Can Gio area is situated at the mouth of the Saigon River, where connecting coastal zones drain into the East Sea. This district is well known as a mangrove biosphere reserved for HCMC. It plays an important role as an ecological system, and was recognized as an international biosphere reserve zone by UNESCO (2000). The area of Can Gio is approximately 70,400 ha. Can Gio Bay has a complex estuarine system that is affected by tidal regimes from the East Sea and upstream flows of the Dong Nai-Saigon river system. The tidal regime in Can Gio Bay is predominantly semi-diurnal (Loon et al. 2007), with an average tidal range of -2.5 m to +1.5 m, with two tidal peaks having approximately the same value and two low tide levels that differ considerably. The Can Gio region observes a typical tropical monsoon with

two distinctive seasons, and discharge flowing into this bay has a strong seasonal variation with approximately 70% of water collection occurring in the wet season from the end of May to the end of October, and only 30% taking place in the dry season from November to May (Ngoc et al. 2014).

In this study, a two-dimensional hydrodynamic model based on the depth-averaged governing equation is adopted to simulate the hydrodynamics of Can Gio Bay under the effects of tides and upstream inflow. A wetting and drying scheme widely used in depth-averaged two-dimensional models for estuaries (Leclerc et al. 1990, Park et al. 2002) was integrated into this model to indicate where inundation occurs in Can Gio Bay. The results of the proposed model clearly indicate the contributions of mudflats and islets, as well as the appearance/disappearance of exposed dunes under the impact of changing tidal ranges, flows, SLR, and sea dike construction.

Material and methods

1. Hydrodynamic models

Recently, three-dimensional models have been widely used for simulating coastal areas (Chen et al. 2003, Jiang et al. 2007, Reza et al. 2016). However, this study focuses only on assessing the water level and inundation area of Can Gio Bay. Thus, a two-dimensional model is the most effective model. Moreover, this bay is shallow given the very small depth of this area compared to its width. In addition, tidal flow controls the flow of Can Gio Bay. Hence, the horizontal flow is greater than the vertical flow. Therefore, the horizontal two-dimensional/depth-averaged model often utilized for shallow water (Hu & Kot 1997) was used to identify the water level change and inundation areas. To simulate the hydrodynamics process for shallow water areas, a two-dimensional mathematical model (Tabata et al. 2013) was developed using the leapfrog finite difference method. This model is based on the two-dimensional continuity and momentum equations (Eqs. 1-3) for simulating the flow in Can Gio Bay. The governing equations of the model are as follows:

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x} \{U(\eta - h)\} + \frac{\partial}{\partial y} \{V(\eta - h)\} = 0, \quad (1)$$

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} = fV - g \frac{\partial \eta}{\partial x} + A_h \left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) - \frac{gn^2 U \sqrt{U^2 + V^2}}{(\eta - h)^{4/3}}, \quad (2)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} = -fU - g \frac{\partial \eta}{\partial y} + A_h \left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) - \frac{gn^2 V \sqrt{U^2 + V^2}}{(\eta - h)^{4/3}}, \quad (3)$$

where η is the water level, t is the time, h is the bottom level, $f = 2\Omega \sin\phi$ is the Coriolis parameter, indicating the effect of Earth's rotation (Ω is the angular rate of revolution; ϕ is the geographic latitude), g is the acceleration due to gravity, n is the Manning coefficient of roughness, which depends on the topography of the study area, U and V are the horizontal velocity components in the x and y directions in a Cartesian coordinate system, respectively, and A_h is the coefficient of eddy viscosity determined by the Smagorinsky model (Smagorinsky 1963) as follows:

$$A_h = \frac{1}{2} S_m A_G \left\{ \left(\frac{\partial U}{\partial x} \right)^2 + \frac{1}{2} \left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right)^2 + \left(\frac{\partial V}{\partial y} \right)^2 \right\}^{1/2}, \quad (4)$$

where S_m is the Smagorinsky coefficient and A_G is the mesh area. Can Gio Bay is a flat low-lying area; thus, the wetting and drying scheme with a land mask function was used to determine tidal flats (Uchiyama 2004). In this model, the land mask function (*LMF*) used to determine and mask all the land meshes during model simulations was defined by two values: 1 for a wet area; 0 for a dry area. In the wetting and drying scheme, water depth $D_{i,j}$ ($=\eta_{i,j} - h_{i,j}$) at grid cell (i, j) is compared with threshold depth d_{th} that is determined depending on the topography of the study area. If the water depth is greater than the threshold depth, this mesh becomes wet and will remain so in the computational domain. Otherwise, the grid cell is regarded as potentially dry. Then, the four cells located next to the potentially dry cell will be tested under the following three conditions:

- 1) $\min(\eta_{i-1,j}, \eta_{i+1,j}, \eta_{i,j-1}, \eta_{i,j+1}) \leq \eta_{i,j}$,
- 2) $\min(D_{i-1,j}, D_{i+1,j}, D_{i,j-1}, D_{i,j+1}) \leq d_{th}$,
- 3) $\max(LMF_{i-1,j}, LMF_{i+1,j}, LMF_{i,j-1}, LMF_{i,j+1}) = 0$.

If at least one condition is satisfied, the potential dry grid is considered a land area and will be removed from the computational domain; $LMF = 0$. If none of the conditions are satisfied, the cell is considered wet; LMF is set to 1.

Table 1 lists the values of parameters used in the numerical simulation. The Manning coefficient (n) and threshold depth (d_{th}) parameters were decided by trial-and-error processing based on references (Uchiyama

Table 1. Parameter values

Parameter	Value
Δt (s)	1.0
$\Delta x, \Delta y$ (m)	50
f (1/s)	2.6×10^{-5}
S_m	0.2
g (m/s ²)	9.81
n (s/m ^{1/3})	0.02
d_{th} (m)	0.2

2004, Tabata et al. 2013).

2. Topographic data, initial and boundary conditions, periods of simulation

The digital elevation model (DEM) of Can Gio Bay, which was obtained from the Department of Science, Technology, and International Affairs, Thuyloi University (south campus), was used to calculate the bottom level of the study area. GIS software was used to construct the 50-m mesh depth data set shown in Figure 1.

The boundary conditions used to drive the model consisted of a tidal boundary at the ocean entrance of the study area and river inflows of the Thi Vai, Phu Xuan, Vam Co, Cua Dai, and Cua Tieu rivers. These data were obtained from the Department of Science, Technology, and International Affairs, Thuyloi University (south campus). The observed tidal level at Vung Tau station obtained from the Ocean Institute, National Information Center, Vietnam was used for calculating tidal variation at the entrance.

The observed water levels of the Soai Rap, Dong Tranh, Nga Bay and Thi Vai stations were collected from the Institute of Coastal and Offshore Engineering and used for calibrating the model.

At initial time $t = 0$, the velocity was set to 0, and the water level was constant.

The simulation period was eleven days from 00:00 on October 20 to 23:00 on October 30, 2000.

3. Scenario analysis

(1) Sea level rise scenarios

According to the report "Climate change, sea level rise scenarios for Vietnam" by the Vietnam Ministry of Natural Resources and Environment (MONRE 2012), three levels of SLR based on different emission scenarios—low, medium, and high—were developed and published. In this study, two SLR scenarios with high emission conditions were considered: a sea level rise up to 33 cm by 2050 (CC2050) and up to 100 cm by 2100 (CC2100).

(2) Sea dike scenarios

Following the results of the project of state DTDL. 2011-G/38 (Nguyen 2014), two assumption scenarios were proposed: (1) a sea dike connecting Go Cong to Vung Tau (GCVT), as shown in Figure 2 a; and (2) a sea dike connecting Go Cong to Can Gio (GCCG), as shown in Figure 2 b. Both sea dike construction scenarios were considered to investigate the hydrodynamic processes in Can Gio Bay.

(3) Proposed modeling scenarios

Based on the analysis, the year 2000 was the baseline scenario (BL2000), as it marked the most severe

historical flood event. Eleven scenarios combining SLR and sea dike construction were selected for simulation, as summarized in Table 2. The scenarios had three discharge conditions: actual discharge in 2000 as the highest discharge (HD), mean discharge of Phu Xuan in 2000 as the lowest discharge (LD), and normal actual discharge in 2009 as the normal discharge (ND). Actually, the

upstream discharge in 2000 was considered a historical upstream flood with a frequency of 2% (Nguyen et al. 2015). Phu Xuan is the main stream flow into the Can Gio area where it directly impacts the lowland area of Can Gio, while Thi Vai discharge is too small to affect the Can Gio area, and discharge at Vam Co, Cua Dai and Cua Tieu is a little bit high, but given these locations, these

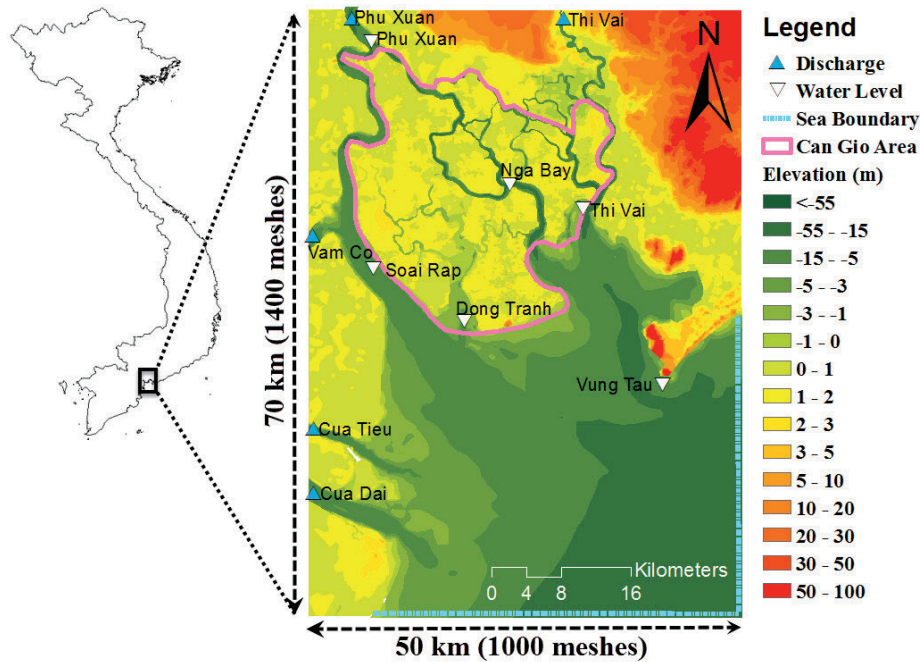


Fig. 1. Map of the study area - Can Gio Bay, the 2000 bathymetry of Can Gio Bay with a 50-m depth showing the location of the Can Gio mangrove forest area, sea boundary, water discharge points of the Thi Vai, Phu Xuan, Vam Co, Cua Tieu and Cua Dai rivers, and water level points at Vung Tau, Phu Xuan, Soai Rap, Dong Tranh, Nga Bay and Thi Vai.

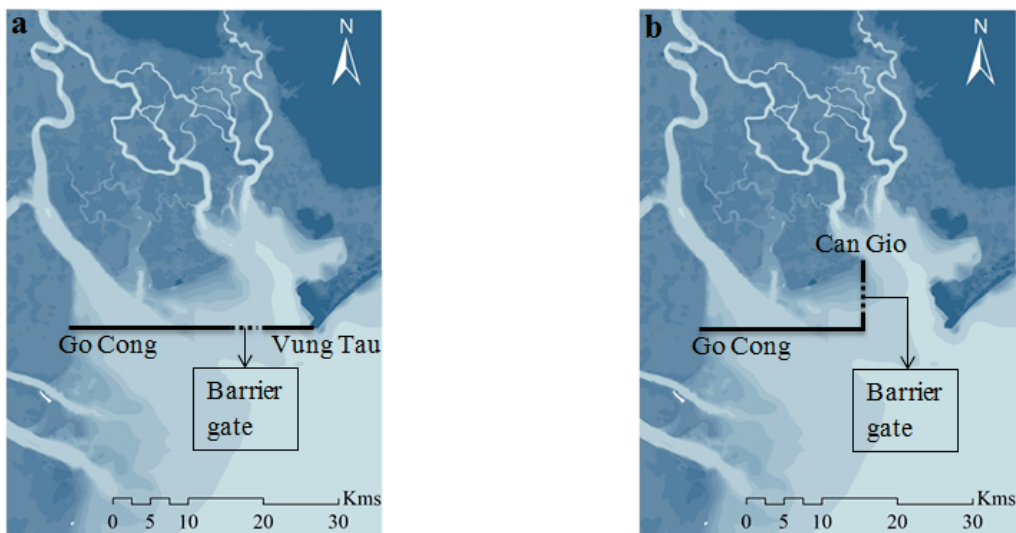


Fig. 2. Scenarios of sea dike construction.

(a) Connecting a sea dike from Go Cong to Vung Tau (GCVT) protected all parts of the Can Gio mangrove forest area; (b) Connecting a sea dike from Go Cong to Can Gio (GCCG) protected part of the Can Gio Mangrove forest area.

flows have relatively low impact.

Model validation and results

1. Model calibration and validation

To calibrate the model, the observed water levels at four positions (i.e., Soai Rap, Dong Tranh, Nga Bay and Thi Vai stations) were considered from 00:00 on August 7 to 00:00 on August 14, 2009. In general, a number of statistical indicators were used to evaluate model performance (Wilcox et al. 1990). In particular, the Nash-Sutcliffe efficiency index (E_2) (Nash & Sutcliffe 1970) and root mean square error ($RMSE$) (David et al. 1999) were used to analyze the correlation between the observed and calculated results in evaluating model performance. Figure 3 shows a comparison of the calculated and observed water level variations from 00:00 on August 7 to 00:00 on August 14, 2009, at 1-h intervals.

Though trial-and-error processing, the set of parameters listed in Table 1 was selected for simulating actual case 2009 (BL2009). The calculated water level results were in good agreement with the observed data, as shown in Figure 3. The peaks of water level and the time to peak in the calculated results were similar and concurrently compared with the observed data. However, there were slight differences in the ebb tide due to the use of DEM in 2006 for the simulation in 2009. The DEM could be different due to changes in this area's morphological evolution. Such changes could be easy because of Can Gio Bay's characteristics, as mentioned above. However, the changes did not significantly affect the precision of the model. The results also indicated the power and accuracy via the Nash-Sutcliffe efficiency index (E_2) and the root mean square error ($RMSE$). A similarly powerful

hydrograph was achieved with high values of E_2 (i.e., 0.938, 0.921, 0.947, and 0.953 at Soai Rap, Dong Tranh, Nga Bay, and Thi Vai, respectively). $RMSE$ was also very small (i.e., 0.198, 0.233, 0.204, and 0.184 m at Soai Rap, Dong Tranh, Nga Bay, and Thi Vai, respectively).

To validate the model, the most severe flood event in the period from 00:00 on October 20 to 23:00 on October 30, 2000 was considered. Figure 4 shows the inundation

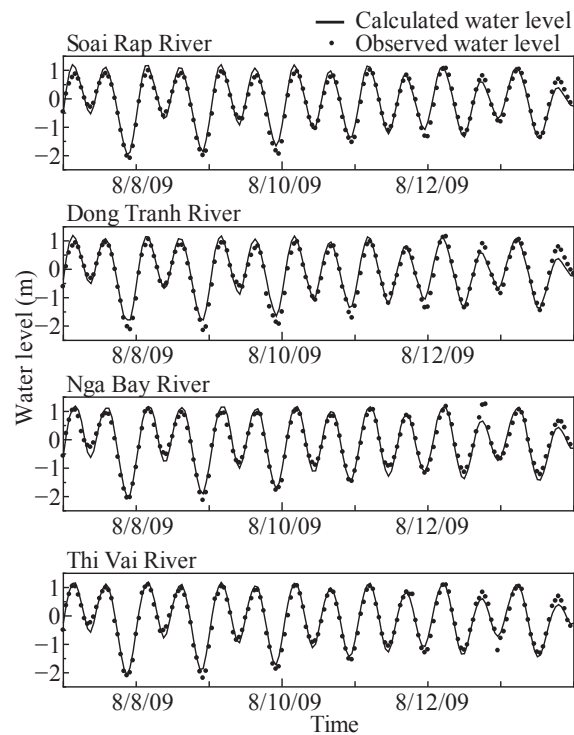


Fig. 3. Observed and calculated water levels of rivers from 00:00 August 7 to 00:00 August 14, 2009.

Table 2. Proposed modeling scenarios

No.	Scenario	Infrastructure condition	Boundary condition	
			Sea level rise (SLR)	Water discharge (WD)
1	BL2000	Actual case in 2000	Actual case in 2000	WD in 2000
2	BL2000M	Actual case in 2000	Actual case in 2000	Mean discharge in Phu Xuan
3	BL2009	Actual case in 2009	Actual case in 2009	WD in 2009
4	BL2000_CC2050	Actual case in 2000	2050 (SLR 33 cm)	WD in 2000
5	BL2000_CC2100	Actual case in 2000	2100 (SRL 100 cm)	WD in 2000
6	GCVT	Sea dike connecting Go Cong to Vung Tau	Actual case in 2000	WD in 2000
7	GCVT_CC2050	Sea dike connecting Go Cong to Vung Tau	2050 (SLR 33 cm)	WD in 2000
8	GCVT_CC2100	Sea dike connecting Go Cong to Vung Tau	2100 (SRL 100 cm)	WD in 2000
9	GCCG	Sea dike connecting Go Cong to Can Gio	Actual case in 2000	WD in 2000
10	GCCG_CC2050	Sea dike connecting Go Cong to Can Gio	2050 (SLR 33 cm)	WD in 2000
11	GCCG_CC2100	Sea dike connecting Go Cong to Can Gio	2100 (SRL 100 cm)	WD in 2000

map between the observed and calculated maps. The total inundated area was approximately 90% and 80% via observing the field survey method and calculated maps in 2000, respectively. This difference may be due to a different DEM used for calculation in 2006, whereas the real flood event occurred in 2000. However, this historical flood of 2000 occurred when the observed data were insufficient. Moreover, the most severe flood disaster in 2000 was investigated by conducting a field survey and interviews, meaning that this was the probable maximum flooding map, not a maximum flooding map at the peak point at 14:00 on October 27, 2000, as the calculated result. In addition, the inundated area was reduced as a consequence of changing land use in the mangrove forest to a residential area by leveling the land. However, the locations of the inundation zones and shapes of the

flooding areas in the calculated map overlapped and look similar compared to those in the observed map obtained by the field survey in 2000. Thus, the constructed model is accurate and satisfactory, and was used to simulate and analyze the flood event in 2000 as well as in other cases.

2. Results and discussions

Based on modeling the actual case from 2000, the BL2000_HD (scenario No. 1), Figure 5 (a: highest flood tide; b: ebb tide) shows the results of the inundated area and dry land area in Can Gio Bay by simulating the flood event of 2000 from 00:00 on Oct. 20 to 23:00 on Oct. 30, 2000. With the highest tide (+1.11 m) recorded at 14:00 on 27 October, 2000, the water level was the highest and water flowed into Can Gio Bay, causing severe inundation across the entire Can Gio area. The inundated area was

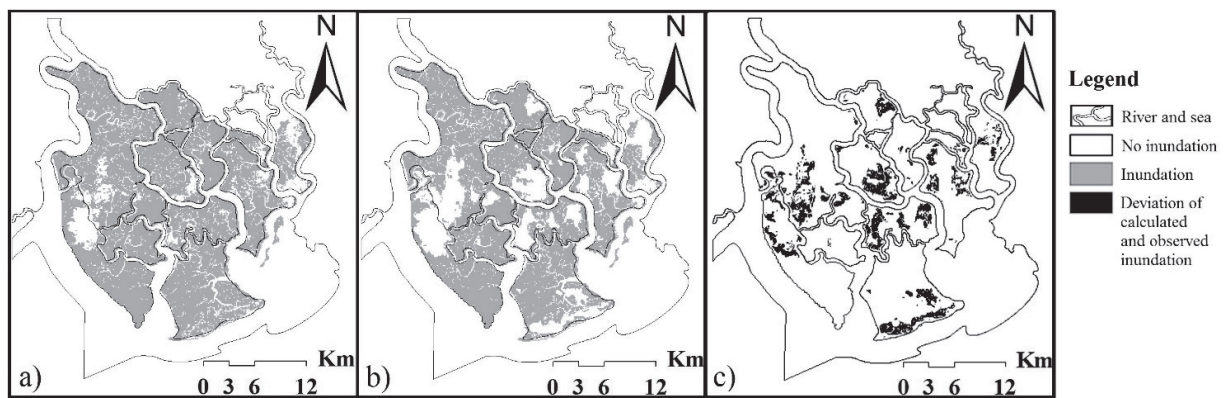


Fig. 4. Comparison of inundation between calculated and observed maps. (a) observed inundation in 2000; (b) calculated inundation in 2000; and (c) deviation of observed and calculated inundation in 2000.

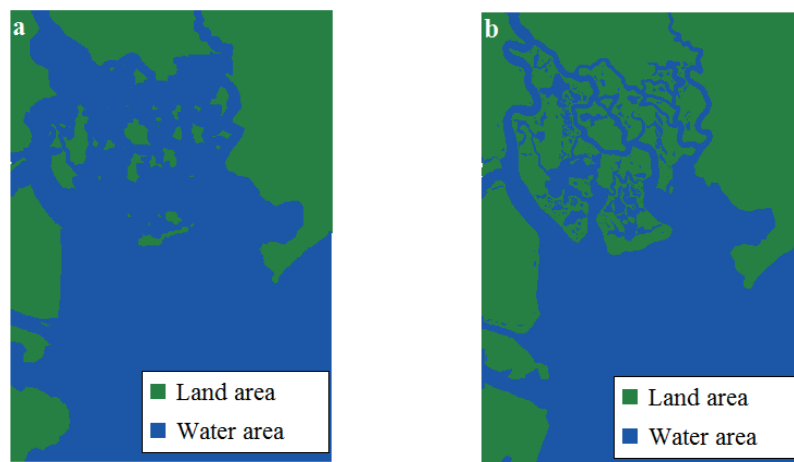


Fig. 5. Map of the calculated results of inundation in Can Gio Bay. (a) Highest flood tide at 14:00 (GMT+7) on October 27, 2000; (b) Lowest flood tide at 20:00 (GMT+7) on October 27, 2000.

approximately 80% of the total area of Can Gio Bay (56,240 ha), and when the tide went out, the inundated area of Can Gio Bay decreased drastically (37%). Despite the lowest ebb tide (-1.09 m), the Can Gio Bay area was significantly flooded with an inundated area of 26,510 ha. Thus, when the tide withdrew, the upstream floods maintained a high discharge (4286 m³/s) flowing into Can Gio Bay, and the area upstream of Can Gio Bay and its low-lying area were submerged.

Table 3 summarizes the maximum water level results based on the proposed scenarios at sea (the entrance boundary) and the five observation points: Soai Rap, Dong Tranh, Nga Bay, Thi Vai, and Phu Xuan (see locations in Figure 1). The two rightmost columns of Table 3 indicate the inundated areas affected by upstream discharges, SLR, and sea dike construction.

By varying upstream discharges at Phu Xuan, the water levels significantly changed from upstream to the sea. When discharge at Phu Xuan changed as the mean discharge (equal to the average annual discharge) changed, the water level had a tendency to decrease from the sea to Soai Rap, Dong Tranh, Nga Bay, Thi Vai, and Phu Xuan with values of 1.20, 1.18, 1.23, 1.24, and 1.04, respectively. Consequently, the inundated area was dramatically reduced from 80% (56,240 ha) in BL2000_HD (scenario No. 1) to 64.16% (45,167.25 ha) in BL2000M_LD (scenario No. 2). This revealed that the discharge decreased at Phu Xuan from 14,499

m³/s (BL2000_HD) to approximately 10,500 m³/s (BL2000M_LD), and water levels in the Can Gio area decreased, and then significantly dropped at Phu Xuan, which was directly affected by the upstream discharge. The reduction in water levels weakened in descending order depending on the distance to upstream points. In this case, the water levels in the Can Gio area decreased by 20–35 cm compared to scenario No. 1: BL2000_HD, but the water level at Nga Bay was almost unchanged due to its proximity to the sea boundary, and the change at Thi Vai was slight as it was on a different branch. Clearly, in 2009 (scenario No. 3: BL2009_ND) when the upstream discharge at Phu Xuan reached approximately 12,500 m³/s, the inundated area was 36,203 ha (51%), and the water level at Phu Xuan was 1.04 m, which is the same water level as BL2000M_LD (scenario No. 2). However, the water levels at Soai Rap, Dong Tranh, Nga Bay, and Thi Vai were different due to differences in the sea water boundary level (i.e., flood tide of 1.11 m in BL2000_HD and 0.92 m in BL2009_ND). Water levels at Soai Rap, Dong Tranh, Nga Bay, and Thi Vai dropped from 1.20, 1.18, 1.23, and 1.24 m in BL2000M_LD (scenario No. 2) to 0.53, 0.49, 0.83, and 0.53 m in BL2009_ND (scenario No. 3), respectively. This indicated that when the sea water level decreased, the upstream change of discharge still affected the Can Gio area, but only slightly.

The tide range is also a key factor influencing inundation in the Can Gio area. Results showed that

Table 3. Water level and inundation results based on proposed scenarios

Scenario	Max water level (m)						Inundated area (ha)	% Inundated
	Sea	Soai Rap	Dong Tranh	Nga Bay	Thi Vai	Phu Xuan		
BL2000_spring tide	1.11	1.36	1.35	1.25	1.32	1.39	56,239.75	79.89
BL2000M_spring tide	1.11	1.20	1.18	1.23	1.24	1.04	45,167.25	64.16
BL2009_spring tide	0.92	0.53	0.49	0.83	0.53	1.04	36,202.75	51.42
GCVT_spring tide	1.11	0.59	0.58	0.65	0.66	0.76	25,965.25	36.88
GCCG_spring tide	1.11	0.69	0.68	1.18	1.25	1.13	47,573.00	67.58
BL2000_ebb tide	-1.82	-1.86	-1.76	-1.93	-1.86	-1.41	20,847.50	29.61
BL2000M_ebb tide	-1.82	-1.89	-1.77	-1.98	-1.87	-1.26	16,346.00	23.22
BL2009_ebb tide	-1.64	-1.89	-1.77	-1.96	-1.79	-1.71	16,041.75	22.79
CGVT_ebb tide	-1.82	0.08	0.06	-0.50	-0.58	-0.24	19,243.50	27.33
GCCG_ebb tide	-1.82	0.23	0.23	-1.69	-1.77	-0.32	22,474.00	31.92
BL2000_CC2050	1.44	1.64	1.63	1.53	1.61	1.71	64,843.00	92.11
BL2000_CC2100	2.11	2.16	2.18	2.11	2.2	2.41	70,397.75	100.00
GCVT_CC2050	1.44	0.91	0.90	0.97	0.97	1.09	38,980.75	55.37
GCVT_CC2100	2.11	1.60	1.58	1.62	1.62	1.70	64,443.00	91.54
GCCG_CC2050	1.44	1.01	0.99	1.44	1.54	1.44	61,329.75	87.12
GCCG_CC2100	2.11	1.74	1.72	2.01	2.15	2.10	69,119.75	98.18

the tide range was 2.93 m as in 2000 in BL2000M_LD (scenario No. 2), and the maximum inundated area ranged from 23% to 64%, corresponding to low and high tides (changed by 41%). When the tide range was 2.56 m in BL2009_ND (scenario No. 3), the change to the inundated area was 28%, from 23% to 51% in the case of the lowest and highest tides. When the high tide range combined with an upstream flood as in BL2000_HD, the inundated area was dramatically augmented from 30% to 80% (increased by about 50%). Tidal oscillations are a major factor contributing to the change in inundated area, and upstream flooding is a main cause of additional increases in the inundated area of Can Gio Bay. When including the impact of SLR, the results obtained show that the water levels at all five mobile stations tended to increase when the sea water level rose. More specifically, when the sea level rises to 33 cm in 2050, the water level at sea will linearly rise from 1.11 m (as was the actual case in 2000) to 1.44 m in 2050, and the water levels at the five points—Soai Rap, Dong Tranh, Nga Bay, Thi Vai, and Phu Xuan—would have the same increasing trend, from 1.36, 1.35, 1.25, 1.32, and 1.39 m (as was actual case in 2000) to 1.64, 1.63, 1.53, 1.61, and 1.71 in BL2000_CC2050 (scenario No. 4), respectively. For SLR of 100 cm in 2100 (scenario No. 5), when the water level will increase by 0.8, 0.83, 0.86, and 0.88 m at Soai Rap, Dong Tranh, Nga Bay, and Thi Vai, respectively, the water level at Phu Xuan will rise 1.02 m. Thus, Phu Xuan will have an additional increase of 1 m while the other stations only experience an increase of 0.8-0.88 m. This indicates that Phu Xuan is located upstream of Can Gio Bay, where there are strong interactions between upstream flows and tidal regimes. Rising sea levels in Can Gio Bay, whereby the inundated areas are drastically increased by 12% (92% of the total area in 2050) compared to the actual case in 2000 (80%), would cause Can Gio Bay to be totally inundated when the sea level rises by 100 cm.

Under the impact of sea dike construction, Figure 6 shows the change in water levels at Phu Xuan, Soai Rap, Dong Tranh, Nga Bay, and Thi Vai. When the sea dike connecting Go Cong to Can Gio (GCCG) (scenario No. 9) was constructed, the calculated results revealed that the maximum water levels within the area of sea dike control tended to significantly decrease by 0.67 and 0.26 m from 1.36, 1.35, and 1.39 m in BL2000_HD to 0.69, 0.68, and 1.13 m in GCCG at Soai Rap, Dong Tranh, and Phu Xuan, respectively. However, the maximum water levels at Nga Bay and Thi Vai slightly decreased by 0.07 m from 1.25 and 1.32 in BL2000_HD to 1.18 and 1.25 m in GCCG, respectively. Due to the characteristics of this construction, the sea dike was only constructed from Go Cong to Can Gio, covering half of the Can Gio Bay

area, but with the other half not being controlled. Thus, three observed points—Soai Rap, Dong Tranh, and Phu Xuan—were inside the controlled area while two observed points—Nga Bay and Thi Vai—were outside the controlled area. Remarkably, when the sea dike connecting Go Cong to Vung Tau (GCVT) (scenario No. 6) was constructed, the maximum water levels considerably decreased (by 0.77 m at Soai Rap, 0.77 m at Dong Tranh, 0.66 m at Thi Vai, 0.6 m at Nga Bay, and 0.63 m at Phu Xuan) at all five observed points with values of 0.59, 0.58, 0.66, 0.65, and 0.76 m, respectively. However, the simulated results also showed that sea dike construction not only reduced the peak water level inside Can Gio Bay, but also increased the ebb water level that this construction protected. In detail, the ebb water levels at Phu Xuan, Soai Rap, Dong Tranh, Nga Bay, and Thi Vai increased by 1.17, 1.28, 1.43, 1.82, and 1.94 m, respectively, in CGVT and by 1.09, 0.09, 0.24, 1.99, and 2.09 m, respectively, in GCCG. As a consequence, at the ebb water level, the inundated area increased by 2-8% compared to various scenarios without sea dike construction. The average lowland ranged from 1.4 m to 2.0 m, although the ebb water level tended to increase due to sea dike control, but still remained lower than

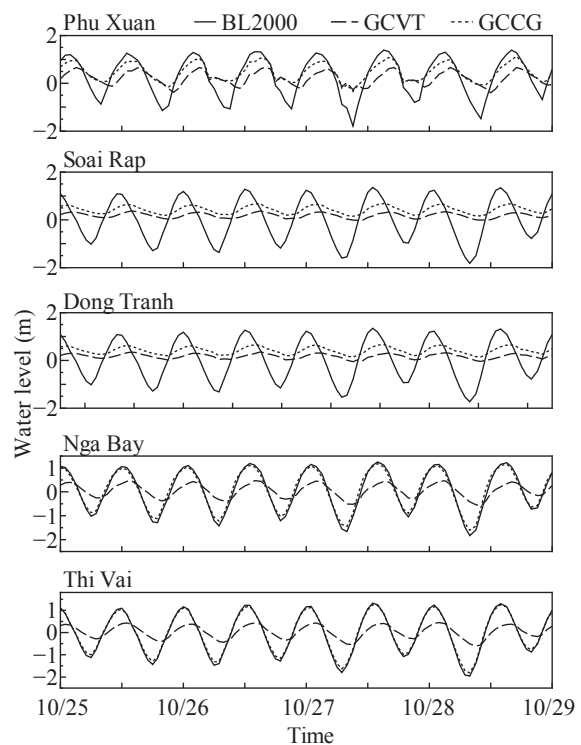


Fig. 6. Calculated water levels at Phu Xuan, Soai Rap, Dong Tranh, Nga Bay, and Thi Vai under the impact of sea dike construction scenarios in 2000.

the average land level. Thus, this inundation increase in the Can Gio area is not significant. Following these sea dike construction scenarios, the entire Can Gio Bay area was closed; hence, the water level inside was driven. This highlights the fact that the GCVT scenario (scenario No. 6) had an accentuated controlling effect in terms of decreasing the water level (Figure 6) and inundation (Figure 7). Once the high tide is reduced, even the low tide increased, but the average-hydraulic slope flow increased, which may be a reason to make such discharge in Can Gio Bay flow out into the sea more easily as compared with the reverse direction. The results obtained demonstrated that the total inundated area in CGVT (scenario No. 6) had a significant decrease by 43% compared with BL2000_HD (scenario No. 1). The decline in GCCG (scenario No. 9) was also 12% compared to BL2000_HD (scenario No. 1).

Considering the impact of both SLR and sea dike construction, Figure 8 shows the water levels at the five points. It is easy to see that sea dike construction can reduce the inundated area for Can Gio Bay by controlling the water level inside. When the sea dike connecting Go Cong to Vung Tau is constructed, the water level in Can Gio Bay can be monitored more efficiently. The water level can be reduced by about 0.3 m among the inflow points and 0.55 m near Dong Tranh, Soai Rap, and Nga

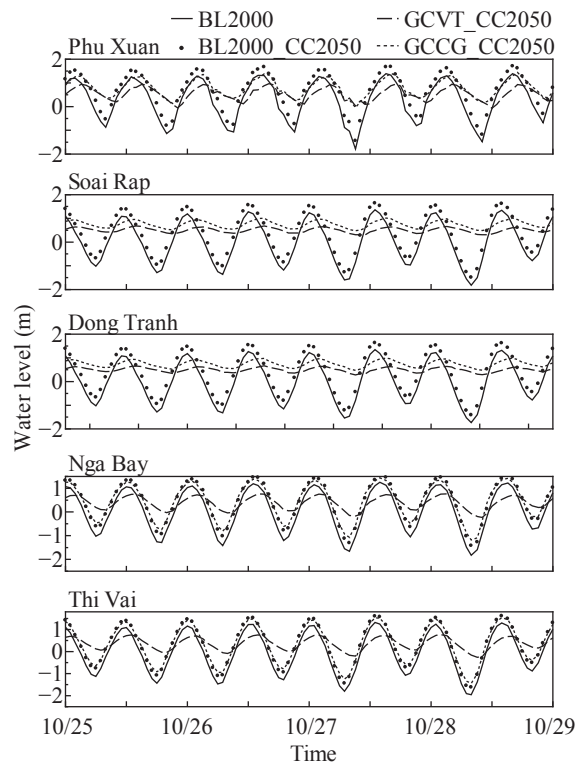


Fig. 8. Calculated water levels at Phu Xuan, Soai Rap, Dong Tranh, Nga Bay and Thi Vai in 2000 considering SLR for the year 2050 and sea dike construction in 2000.

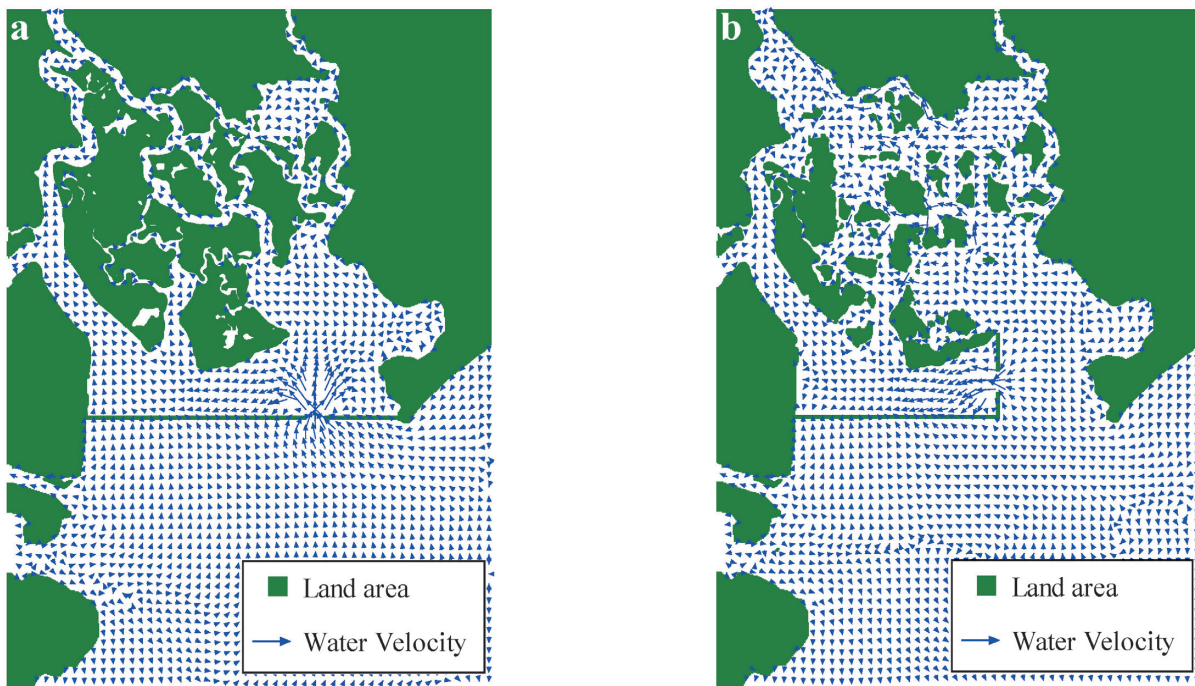


Fig. 7. The difference in inundation and velocity distribution per 20 meshes of a two-scenario analysis. (a) Sea dike connecting Go Cong to Vung Tau (GCVT); (b) sea dike connecting Go Cong to Can Gio (GCCG).

Bay. Specifically, the water levels in BL2000_CC2050 (scenario No. 4) were 1.64, 1.63, 1.53, 1.61, and 1.71 m in Soai Rap, Dong Tranh, Nga Bay, Thi Vai, and Phu Xuan, respectively, and showed a significant decrease to 0.91, 0.90, 0.97, 0.97, and 1.09 m in GCVT_CC2050 (scenario No. 7), respectively. Hence, the inundated area in Can Gio Bay was dramatically reduced from 92% in BL2000_CC2050 (scenario No. 4) to 55% in GCVT_CC2050 (scenario No. 7). See Figure 7 for the details.

In the GCCG scenario of the sea dike connecting Go Cong to Can Gio, half of the Can Gio Bay area is closed by construction and the other half is open. As a result, the GCCG scenario can reduce the water level in Dong Tranh and Soai Rap (by about 0.62 m) more effectively than in Thi Vai and Nga Bay (by 0.07 m). Thus, the water levels in BL2000_CC2050 (scenario No. 4) were 1.64, 1.63, 1.53, 1.61, and 1.71 m in Soai Rap, Dong Tranh, Nga Bay, Thi Vai, and Phu Xuan, respectively, and showed a significant decrease to 1.01, 0.99, 1.44, 1.54, and 1.44 m in GCCG_CC2050 (scenario No. 10), respectively. Consequently, the inundated area in Can Gio Bay was reduced from 92% in BL2000_CC2050 (scenario No. 4) to 87% in GCCG_CC2050 (scenario No. 10).

With SLR of 100 cm, the water levels in Can Gio Bay were significantly reduced by approximately 0.50-0.70 m in GCVT_CC2100 (scenario No. 8) and by about 0.10-0.40 m in GCCG_CC2100 (scenario No. 11). Specifically, the water levels at Soai Rap, Dong Tranh, Nga Bay, Thi Vai, and Phu Xuan decreased from 2.16, 2.18, 2.11, 2.20, and 2.41 m in BL2000_CC2100 (scenario No. 5) to 1.60, 1.58, 1.62, 1.62, and 1.70 m in GCVT_CC2100 (scenario No. 8), respectively. In the GCCG_CC2100 scenario (scenario No. 11), the water levels at Soai Rap, Dong Tranh, and Phu Xuan were significantly reduced to 1.74, 1.72, and 2.10 m, but the water levels at Nga Bay and Thi Vai were only slightly reduced by 0.1 and 0.05 m to 2.01 and 2.15, respectively. This is due to sea dike construction in the GCCG scenario as previously discussed.

Although sea dike construction can control water levels, Can Gio Bay remained substantially submerged and its inundated area covered up to 92% in GCVT_CC2100 (scenario No. 8) and 98% in GCCG_CC2100 (scenario No. 11). This demonstrates that sea dike construction can reduce the inundated area once SLR of 33 cm occurred, but its effect diminishes as SLR increases to 100 cm. Furthermore, the sea dike construction also caused a delay in the tidal peak. The highest tide was postponed by one hour in the GCCG scenario (scenario No. 9) and by two hours in the GCVT scenario (scenario No. 6). Figure 6 clearly shows the water level at Phu Xuan lagged in phase and the tidal range decreased. The highest tide was diminished due to tide prevention by the sea dike;

thus, it reduced half of the inundated area from 80% in BL2000_HD to 68% and 37% in the GCCG and GCVT scenarios, respectively (see the rightmost columns of Table 3). Figure 7 shows that the GCVT scenario (Figure 7 a) drastically reduced the inundated areas caused by flood tides compared to the GCCG scenario (Figure 7 b). Otherwise, the purpose of constructing a sea dike is to prevent flood tides in urban areas of HCMC and preserve the eco-environment in the Can Gio mangrove forest. Many researchers have debated this matter, and a number of them have supported the GCCG scenario as they believe that it could preserve the ecosystem in Can Gio Bay more efficiently. Nonetheless, this issue must be investigated in greater detail. This paper did not focus much on the environment, but future studies will do so.

Conclusions

The scenarios analyzed above demonstrated the ability of the wetting and drying scheme used in the two-dimensional hydrodynamic model. This model can be a useful tool for simulating morphological and functional design in shallow water areas such as the coast, harbors, and offshore.

We concluded that the tide and flood discharge from the upstream inflow are the main factors affecting the inundation of Can Gio Bay. Once the spring tide is low, the magnitude of upstream discharge will dominate, leading to inundation in the Can Gio area. Nevertheless, inundation caused by upstream flooding weakens when the tide peak reaches up to 1.11 m, and the inundated area is driven by the tide.

As the average elevation in the Can Gio area is approximately 1.4-2.0 m, sea level rise is a key factor that may contribute to a dramatic increase in inundation in Can Gio Bay, and the entire Can Gio Bay area would be completely submerged when the sea level increases by 100 cm.

Sea dike construction proved to be an efficient mechanism for controlling the water level and reducing inundation even for SLR of 33 cm (CC2050). As the sea dike construction connects Go Gong to Vung Tau, Can Gio Bay becomes less navigable; thus, in the GCVT scenario, the water level could be controlled and the inundated area more effectively reduced than in the GCCG scenario.

When the sea water level increased by 100 cm, however, the effectiveness of the sea dike mechanism for both the CGVT and GCCG scenarios for controlling the water level declined, and the effect of inundation reduction was weakened.

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