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# Flow dynamics in the Long Xuyen Quadrangle under the impacts of full-dyke systems and sea level rise

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**Abstract.** A one-dimensional (1D) hydrodynamic model for the river network of the Long Xuyen Quadrangle, Vietnamese Mekong Delta, was developed in HEC-RAS based on: (i) Available data of river network and cross-sections deployed in the ISIS-1D hydrodynamics model for the whole Mekong Delta (including the Vietnamese and Cambodia parts); and, (ii) Field-based data to update the existing river network and full-dyke systems. Developed scenarios included: (i) Scenario 1: The measured geometric data in 2000 (no dykes constructed), and upstream discharge and sea level measured in 2000; (ii) Scenario 2: The developed full-dyke systems, and upstream discharge and sea level measured in 2000; and, (iii) Scenario 3: The geometry and upstream discharge remained similar to Scenario 2 while the sea level was supposed to be 30 cm greater than that in 2000 (in both the East and West Sea). By comparing Scenario 1 and 2, possible impacts of the full-dyke systems to the area could be examined while by comparing Scenario 2 and 3, impacts of sea level rise would be evaluated in the context of the deployed full-dyke systems.

*Keywords*: One dimensional (1D) hydrodynamics model, flow dynamics, full-dyke systems, HEC-RAS, and Long Xuyen Quadrangle.

## 1. Introduction

The Long Xuyên Quadrangle (LXQ), located in the An Giang, Kiên Giang and Cần Thơ provinces, the Vietnamese Mekong Delta (VMD), is formed by the common border between Việt Nam and Cambodia, the Bassac River, the Cái Sắn canal and the West Sea (Figure 1). It is characterized by the low-lying plain with the average elevation of the land surface of about 0,4 - 2,0 m above mean sea level (a.msl) (except mountainous landscape with the maximum height of greater than 250 m a.msl). During the annual flood period (July – November), the LXQ is often inundated with the greatest recorded stage of about 5,5 m a.msl [1].

In the recent years, with great impacts of the on-going climate change in conjunction with rapid development of hydraulic constructions (e.g. concrete dyke systems or full-dyke systems), flow nature of the study area has been strongly changed leading to negative impacts on the agriculture and aquaculture activities [2]. In fact, the trends of raising full-dyke to protect the rice field enhancing the triple rice crop farming system per year have led to considerable negative impacts of the flow nature both in channels and adjacent floodplains [3].

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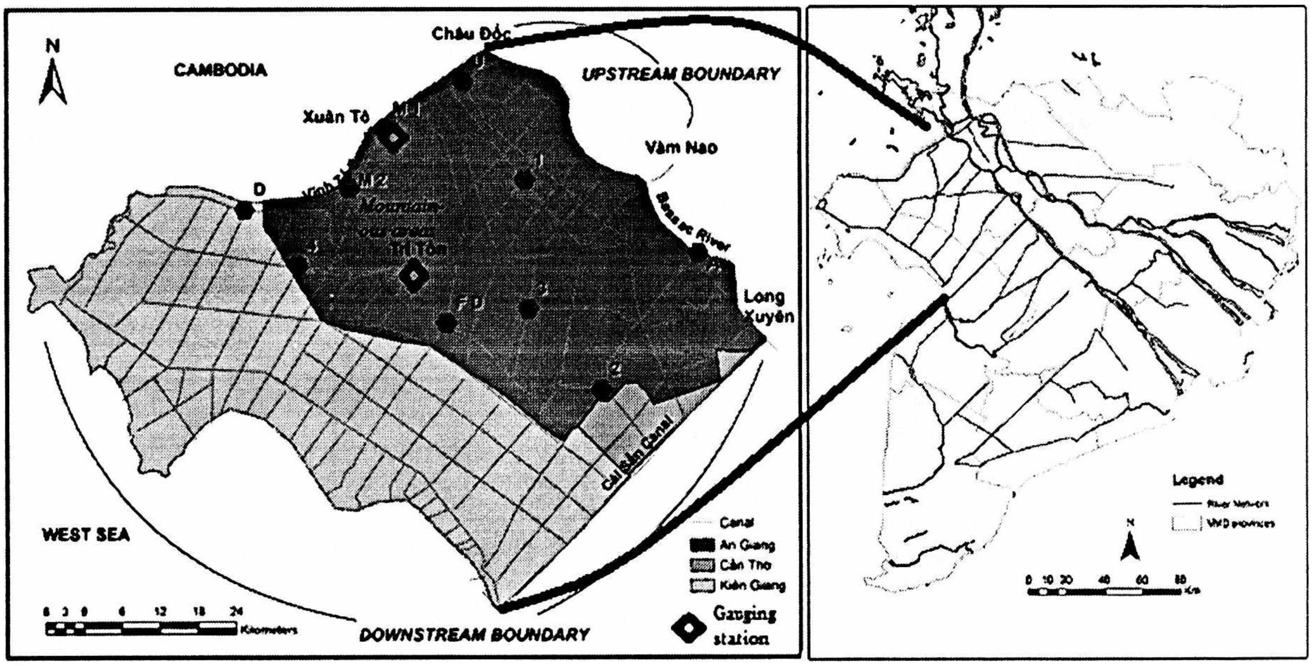


Figure 1. Vietnamese Mekong Delta, Long Xuyen Quadrangle and developed river network.

With rapid development of computer science over the last decade, (numerical) hydrodynamics models have been upgraded significantly supporting flood propagation simulation over a large river network, and projecting future patterns according to changes of the boundary conditions (upstream discharge, downstream water level, and in-situ hydraulic constructions). Different hydrodynamics models were developed (e.g. VRSAP, MIKE, ISIS, Hydro-GIS, HEC-RAS) to study the flow dynamics in different river networks in the world. In Vietnam, examples of the related works could be accounted for [2, 4-6]; however, most of the previous works paid great attention to flood extents over a large area of the deltaic scale or even with smaller scale (regional scale) [7] but little attention was paid to study the hydraulic nature (changes) (including: simulated stage and discharge) within the local river network at different period of time. This paper aims at developing a one-dimensional (1D) hydrodynamics model (HEC-RAS) to study the flow dynamics of a complex river network in the LXQ. Such developed model, after calibrated, would be applied to study the flow changes after different pre-defined scenarios (Table 1).

## 2. Methodology

### *2.1. Governing equations*

In this research, an unsteady-flow hydrodynamics model was developed in HEC-RAS (a completed model software developed by the Institute for Water Sciences, Hydrologic Engineering Center and suitable to study the hydraulic nature of open channels [8]). The HEC-RAS model is mainly governed by Equ. 1 and 2 [8]. In addition, the Manning's $n$ hydraulic roughness coefficient (Equ. 3) was used to calibrate the developed model.

Continuity equation

$$\frac{\partial A}{\partial t} + \frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0 \qquad (1)$$

Energy equation

$$\frac{\partial Q}{\partial t} + \frac{\partial (VQ)}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \qquad (2)$$

Manning's $n$ hydraulic roughness equation

$$Q = \frac{1}{n} AR^{2/3} S_f^{\ 1/2} \qquad (3)$$

where, $A$: Wetted area (m$^2$); $t$: Time (s); $S$: Storage in the wetted area (m$^3$); $Q$: Discharge (m$^3$s$^{-1}$); $x$: Distance along the thaweg (m); $q_l$: Lateral flows along a river section (between two cross-sections) (m$^3$s$^{-1}$); $V$: Mean velocity (ms$^{-1}$); $z$: Water level (m); $Sf$: Water surface slope (mm$^{-1}$); $n$: Hydraulic roughness (sm$^{-1/3}$); and, $R$: Hydraulic radius (m).

### *2.2. Available data*

The river network of the LXQ was extracted from the ISIS-1D hydrodynamics model provided by the Mekong River Commission [2]. Details of the developed HEC-RAS model for the LXQ include (Figure 1.):

- 257 river reaches (including the Bassac River) associated with 1,280 cross-sections, 145 nodes (junctions), and 130 storage areas;

- Boundary conditions (time step = 1 hour), including: (i) Upstream boundary conditions – time series calculated discharge at the Châu Đốc and Vàm Nao stage gauges; and, (ii) Downstream boundary conditions – time series measured water level at 25 locations adjacent to the West Sea and 1 locations in Long Xuyên. The upstream discharges were extracted from the deltaic scale model (ISIS-1D) in comparison with the interpolated discharge in 2000 at Châu Đốc. The overland flows were not considered in this study due to the lack of available information; however, the developed model was calibrated to reflect the measured stages at different locations in the area (Xuân Tô and Tri Tôn from July to November, 2000). In addition, each storage area was created isolatedly from the others through a dense canal network in the study area.

The secondary data of the river banks and river bed elevation in 2000 were collected to validate and update available data in the ISIS-1D hydrodynamics model. In addition, data related to the existing dykes system in 2011 was also collected and deployed in the model; the collected data includes: geographical locations of the existing dyke systems, area of the protected areas, and dyke-height in the field. In this study, only cross-sections developed in the ISIS-1D hydrodynamics model was applied with adjustment according to the field data observations and the full-dyke systems were applied with 'assumed' dyke height which would prevent flood to enter intensive rice-cultivated areas. The assumption was made in order to examine the hydraulic changes of the floods in the case that all actual rice farming stystems in An Giang were fully protected.

The storage areas in HEC-RAS would be introduced into the developed model as dyke-protected areas. In the scenarios of existing full-dyke system, the storage area would be kept dry (no over-bank flows from river entering the cultivated area) while in the scenario where full-dyke systems was not developed, flows from the river would be routed into the storage area after reaching the elevation of the bank surface. In fact, when the water surface elevation in the river channels was greater than the dyke height, flows would be routed from channels into the storage area ($Q_{lateral} > 0$). The storage areas could be linked with one or more river channels via the on-bank constructions. Areas of the storage area was measured in ArcGIS in the available map of existing dyke system and then assigned in HEC-RAS. The bed elevation of the storage area was established via the field survey and secondary data. In this study, impacts of rainfall were neglected as it would result in minor impacts on the hydraulic nature of flows in the study river network. In fact, inundation in the VMD is mainly driven by upstream discharges, the buffering flood wave in the Great Lake, Cambodia and tidal regimes in the East and West sea [9].

The developed hydrodynamics model was calibrated by adjusting the hydraulic roughness coefficient (Manning's *n*) of each river channel (i.e. changing the applied Manning's n coefficient of a group of cross-sections rather than each individual cross-section [10]). The calibrating process was done based on the existing hydraulic roughness of the cross-section in the available deltaic model and adjusted gradually until the Nash-Sutcliffe index value ($R^2$) (Equ. 4) calculated according to the measured and simulated stages met the requirement. In fact, the calculated Nash-Sutcliffe index should close to 1 [7, 11].

The Nash-Sutcliffe index

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left[Q_{obs,i} - Q_{sim,i}\right]^2}{\sum_{i=1}^{N}\left[Q_{obs,i} - \overline{Q}_{obs}\right]^2} \quad (4)$$

where: $Q_{sim}$, $Q_{obs}$: Simulated and measured data; and, $\overline{Q}_{obs}$: Mean measured data.

### 2.3. Model set-up

Scenarios were developed (Table 1) in order to evaluate the flood dynamics and extent on the study area (i) when there was no full-dyke system (Scenario 1); (ii) with the existence of full-dyke systems with the spatial extents of the year 2011 and sea water level was the measured on in 2000 (Scenario 2); and, (iii) with similar assumptions in Scenario 2 except the sea level, which was assumed to be 30 cm greater than that in 2000 (corresponding to the medium emission scenario B2 [12]) (Scenario 3).

Table 1. Developed scenarios

| Scenarios | Upstream discharge (Q) | Water level (H) | Dyke system |
|---|---|---|---|
| Scenario 1 | $Q_{2000}$ | $H_{2000}$ | Actual status in 2000 |
| Scenario 2 | $Q_{2000}$ | $H_{2000}$ | Full-dyke system |
| Scenario 3 | $Q_{2000}$ | Sea level in 2000 + 30 cm | Full-dyke system |

## 3. Results

### 3.1. Calibration

With the hydraulic roughness of 0,029 (within the arrange of accepted hydraulic roughness for alluvial channels [0,010 - 0,035] [13, 14]) applied for all cross-sections of the developed model, the simulated stages were similar to the measured ones, especially during the peaks of flood (Figure 2); the calculated Nash-Sutcliffe indexes were greater than 0,8 (Table 2).

Table 2. The calculated Nash-Sutcliffe indexes at the selected locations (Xuân Tô and Tri Tôn)

| Station | Nash-Sutcliffe index |
|---|---|
| Xuân Tô | 0,88 |
| Tri Tôn | 0,81 |

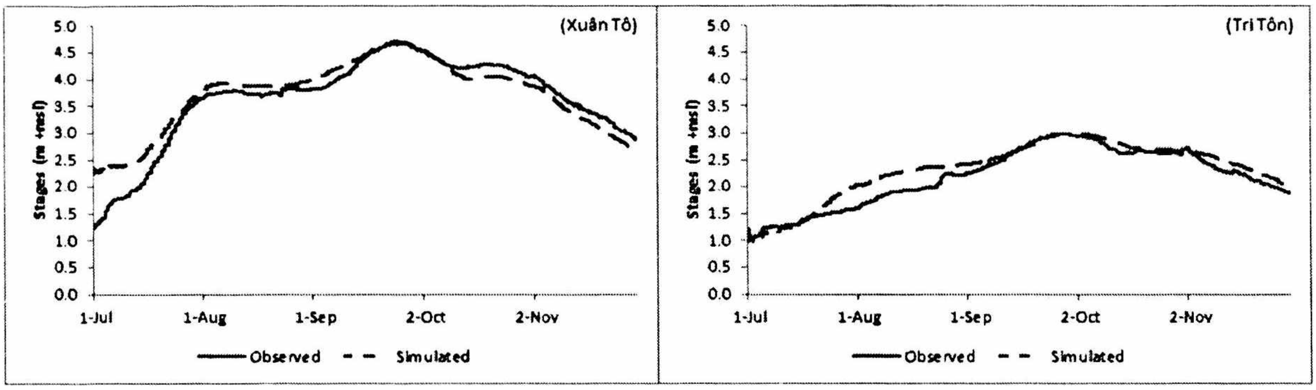


Figure 2. Measured and simulated stages at Xuân Tô (a) and Tri Tôn (b).

*3.2. Simulated stages in different scenarios*

In order to reflect the hydrodynamics in the VMD after the defined scenarios, different locations were selected (i.e. Location 1, 2, 3 and 4 in Figure 1 to fully represent the flow dynamics at different parts of the river network). In general, there were significant changes in simulated stages in different locations according to Scenario 1 and 2 (Figure 3) (i.e. simulated stages in Scenario 2 was greater than those in Scenario 1 in the rising phase of the flood period while it was turned to an opposite dynamics in the falling phase of the flood period). The findings prove that with the development of the full-dyke systems, hydrodynamics of the river network was changed significantly. In fact, in the rising phase, in the scenario with the existence of the full-dyke system, flood discharges were mainly routed along the channels but not the floodplain; therefore, the simulated stages rose much higher than those in the case of dyke-free system. In the falling phase of the flood period, in the case where there was no dyke, discharges were routed from the floodplain (which were conveyed in during the early phase of the flood period) to the river; therefore, the stages in the river were greater than those in the case with the existence of the full-dyke systems. In other words, with the existence of full-dyke systems, the stages in the channel were only dependent on the upstream flow while in the case of a dyke-free system, stages also depended on the flow recharged from the floodplain to the river network.

There were minor changes between Scenario 2 and 3 (Figure 3). In fact, the selected locations (Location 1, 2, 3 and 4) were rather further away from the East Sea therefore sea level rise did not give much influences on the simulated stages; this agrees with what was found in [4]. At the Location 1, simulated stages in Scenario 3 were lower than those in both Scenario 1 and 2, which could be explained as greater discharges were routed along the Bassac River in both Scenario 2 and 3 than those in Scenario 1 (Figure 6) due to the impacts of the developed dyke system.

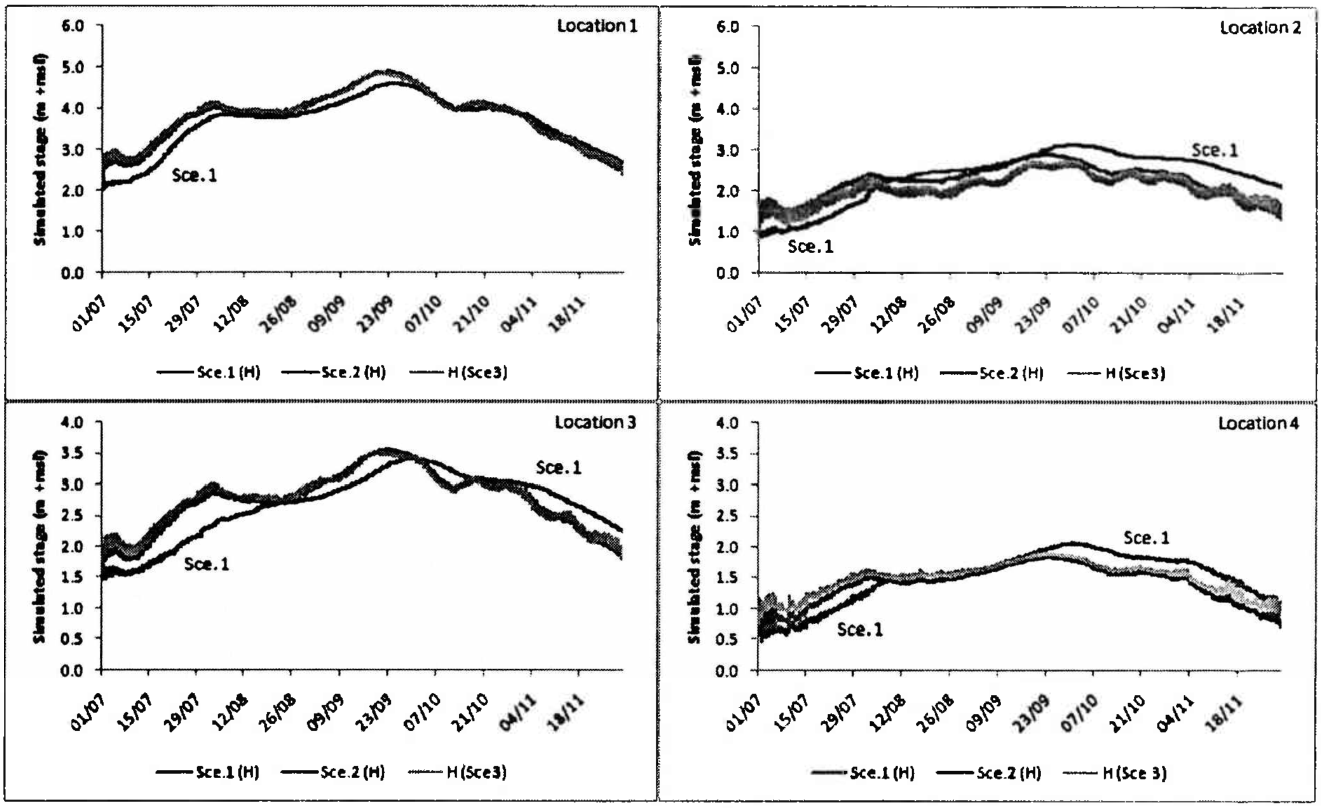


Figure 3. Simulated stages at different locations (Figure 1) according to the three scenarios.

### *3.3. Impacts of upstream flows on the downstream stages*

With greater flows entering the Vĩnh Tế canal in Scenario 2 and 3 in comparison to those in Scenario 1 (Figure 1, denoted as U), the simulated stages at the upstream section of the Vĩnh Tế canal in Scenario 2 and 3 were greater than those in Scenario 1 in the rising phase of the flood period while they were all similar in the falling phase (U and M1 in Figure 4).

According to the Manning's *n* equation (Equ. 3), during the falling phase of the flood period, when the discharge increased with relatively similar stages, the water surface slope would increase. This led to the decrease of stages in the lower parts of the Vĩnh Tế canal (M2 and D in Figure 4). Nearby the downstream boundary conditions (the West Sea), simulated stages in Scenario 1 and 2 were similar while the simulated stages in Scenario 3 were significantly different from those in Scenario 1 and 2, which were caused by the defined scenario of sea level rise. The findings confirm that the upstream part of the study area would be strongly influenced by the upstream discharge changes as well as hydraulic construction development in the upstream section while the downstream section was strongly affected by the sea level rise [4]. In addition, changes of water surface slope might lead to changes of flow velocity, which in turn would lead to changes of the morphology of the river / channel network [15-17].

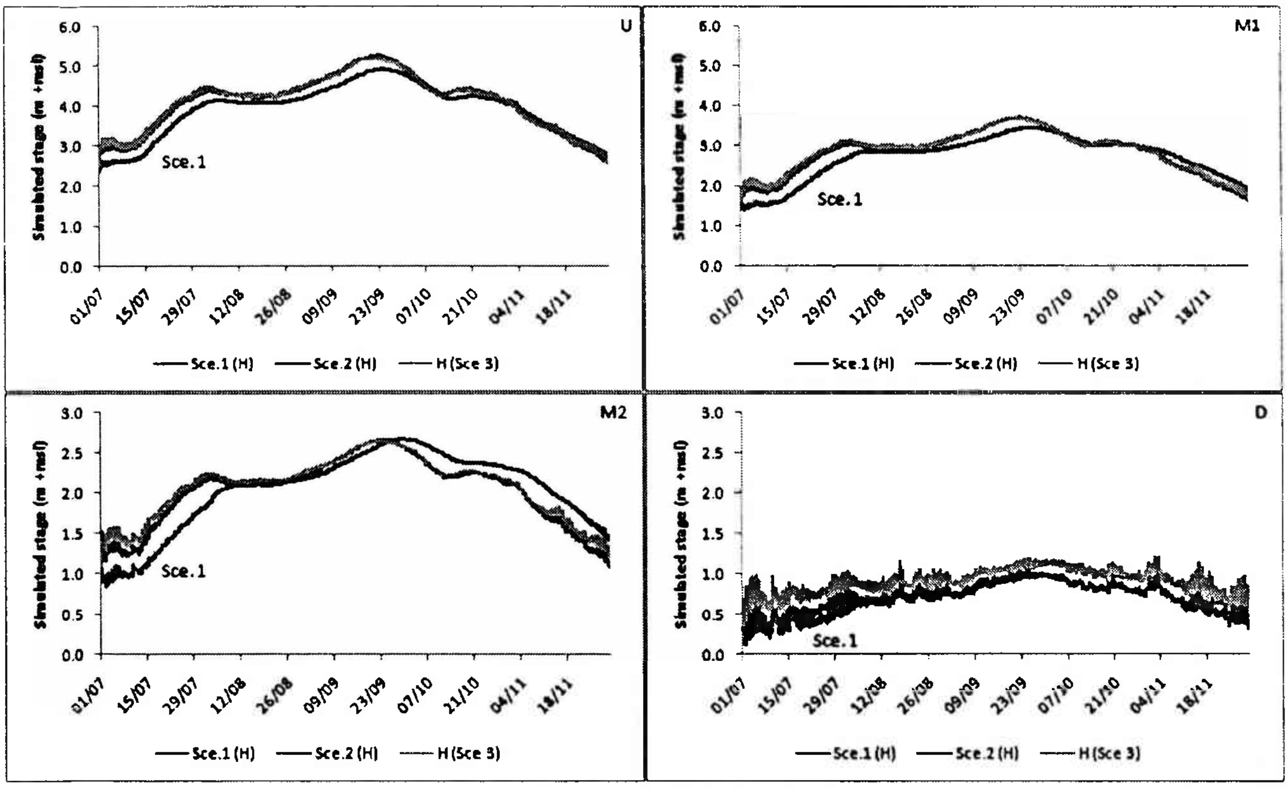


Figure 4. Simulated stages (from upstream to downstream) at different locations along the Vinh Te canal according to the three scenarios.

Due to the complexity of the river platform, the flow dynamics were also highly convoluted. Considering location FD in Figure 1, simulated discharges were strongly influenced by the development of the full-dyke system. In fact, without the existence of the full-dyke system in the upstream part of the study area (Scenario 1), flows were strongly routed from the upstream to the sea; however, with the impacts of the developed dyke systems (Scenario 2 and 3), less flows were routed along the secondary channel from inland to the sea (in comparison to Scenario1) (Figure 5) but rather to be routed along the Bassac.

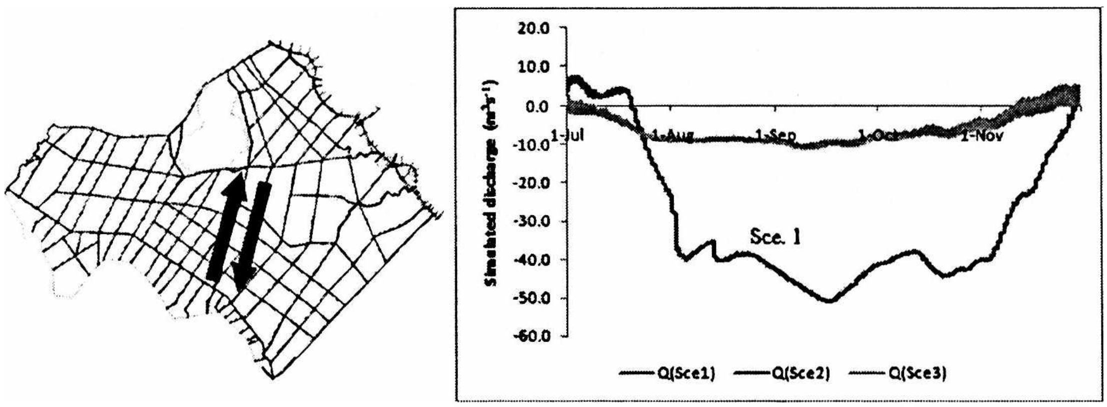


Figure 5. Flows changed according to changes of boundary conditions in different scenarios.

### *3.5. Possible impacts of full-dyke system and sea level rise on the flow dynamics in the main river channels*

Time-series data of simulated stages and discharges along the Bassac River were closely interrelated, in which stage rose / fell with discharge during the flood period. The simulated flows and stages in Scenario 1 were lower than those in Scenario 2 and 3. In fact, with impact of the full-dyke systems, flows were mainly routed along the main channel but not into the floodplain; therefore, the flows routed along the Bassac increased in both Scenario 2 and 3 (Figure 6). The findings raised a concern that rising dyke to protect the upstream areas against flood may cause greater damages in the downstream sections (including flood depth and duration period) [18, 19]. In comparison between Scenario 2 and 3 (i.e. with and without sea level rise), even though the simulated discharges between the two scenarios were relatively similar, the simulated stages in the condition of sea level rise would be slightly smaller in the rising phase during the flood period while it would be greater in the falling phase. Such relationship between the flows and stages proves that flows in the Bassac would be more strongly affected by the tidal regimes (rather than upstream discharge driven only), leading to an actual requirement for a detailed study to evaluate impacts of sea level rise on the hydraulic nature of the Bassac River.

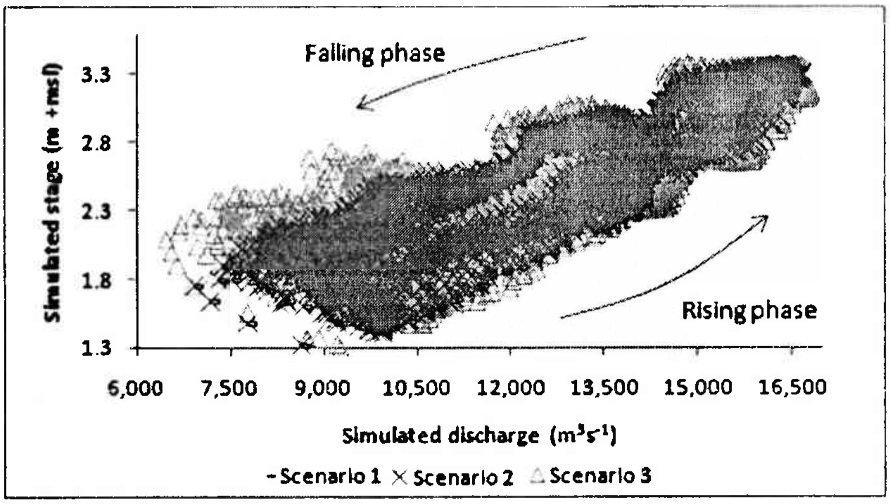


Figure 6. Flow and stage dynamics in the Bassac River (denoted as A, Figure 1.).

## 4. Conclusions

A 1D hydrodynamics model developed in HEC-RAS could be used to study the flow dynamics of the river network in the LXQ according to different scenarios of boundary condition changes (sea level rise and full-dyke system development). With such the developed hydrodynamics model, details of hydraulic nature were studied in more details (in comparison to the deltaic-scale hydrodynamics model [2, 5, 6]) especially in the context of boundary condition changes.

With impacts of the developed full-dyke systems, water levels in the main channels were greater than those in the case of the dyke-free system. The simulated water surface slope in Scenario 2 (existence of full-dyke and measured sea level in 2000) was greater than that in Scenario 1 (dyke-free), which may cause great changes of the morphology of the river network. Such morphological changes are of great concerns as they may lead to unexpected deposition or erosion along the river network which then might lead to negative impacts on livelihood of local residents [18-21]. In addition, when full-dyke system was built, flows were mainly transported along the main channel (the Bassac), leading to rises of water level in the upstream areas (along the Bassac) and caused negative impacts on the agriculture and aquaculture activities in the North-West area of An Giang. Moreover, the projected sea level rise led to major hydrological changes in the coastal plains in comparison to the consequent impacts in the upstream sections of the VMD, which fully agrees with the findings from previous study [2, 4].

In this study, the developed hydrodynamics model was not validated (due to limited available data); it is suggested that related data should be continuously collected to make sure the model is well-calibrated and validated. In addition, in this study, attention was great paid to study the flow and stage changes but the consequent impacts on morphology were not well explored.

The hydraulic roughness of a river channel might vary according to the river depth and water surface slope [14, 22]. Therefore, the assumption of having one value of hydraulic roughness for a large series of river stages might not be appropriate and it is suggested to improve the developed hydrodynamics model for the future studies.

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