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The multi-channel system of the Vietnamese Mekong Delta: impacts on the flow dynamics under relative sea level rise scenarios

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Abstract

The Mekong Delta has the world's third largest surface area. It plays an indisputable role in the economy and livelihoods of Vietnam, Cambodia, with repercussions at regional and global scales. During recent decades, the Vietnamese part of the Mekong Delta underwent profound human interventions (construction of dykes and multi-channel networks), which modified the hydrodynamic regime, especially cycles of field submersion. In this study, we first applied a full 2D numerical hydraulic model, TELEMAC-2D, to examine the effects of the complex channel and river networks on the spatial and temporal distribution of the flow in the 40,000 km² of the Vietnamese Mekong Delta. Then, two scenarios of relative sea level rise in 2050 and 2100 are implemented to simulate the future patterns of water fluxes in the delta. The results show that the dykes and multi-channel networks would reduce by 36 % the inundation area and lessen by 15 % the peak water level and 24 % discharge over the floodplains. Despite this protection, under relative sea level rise of 30 cm and 100 cm, the maximum flooded area could occupy about 69 % and 85 % of the whole delta in 2050 and 2100, respectively.

Keywords: Vietnamese Mekong Delta, TELEMAC – 2D, hydrodynamics, channel system, sea-level rise
1. Introduction

River deltas have been of fundamental importance to civilization for thousands of years (Wright et al., 1978 and Bianchi, 2016) because of their fertile flat lands, abundant freshwater for living and agricultural practices, fishing grounds and suitability for fluvial transport (Garschagen et al., 2012). However, the natural state of these deltas is now being modified dramatically by ongoing human interventions (Best et al., 2018). Unsurprisingly, this holds true for the Mekong Delta (Kondolf et al., 2022).

The Mekong Delta covers an area of 55,000 km$^2$ in Cambodia and Vietnam (Dung et al., 2013, Balica et al., 2014), with an area of 26% in the former country and 74% in the latter (Le et al., 2007). This delta is at the core of various interdependent and endangered economic sectors, encompassing agriculture, fishery and forestry (Västilä et al., 2010; Le Meur et al., 2021). The Cambodian portion of the delta exhibits significant differences from Vietnam’s. In Cambodia, the floodplain has witnessed little anthropogenic influences and can be considered smoothly impacted, with only a few control structures, whereas the Vietnamese part is under large regulations by a huge system of navigation and irrigation channels, sluice gates, pumps and extensive dyke systems. These systems have considerably altered the natural hydrodynamics and sediment transport (Hung et al., 2012 and Eslami et al., 2019a). Recently, researchers have paid more attention to the whole domain by extensive monitoring networks (Dang et al., 2016 and Gugliotta et al., 2017), satellite observations (Balica et al., 2014; Yamazaki et al., 2014) and by applying 1D (Hoa et al., 2008; Duong et al., 2018b and Dang et al., 2018a), semi/quasi 2D (Triet et al., 2017) or 1D - 2D coupled flow simulation models (Le et al., 2007; Eslami et al., 2019a). Other studies concentrated on the impacts of dyke systems on the hydrodynamics (Fujihara et al., 2016; and Aires et al., 2020). Even so, only few research works have assessed comprehensively the flow dynamics at a large scale. It must be stressed that overland flow and water exchange between irrigation compartments influence delta conditions (Manh et al., 2014, Dang et al., 2018b) in ways that cannot be simulated by 1D models.

The present study utilizes a two-dimensional numerical model, TELEMAC-2D (http://www.opentelemac.org/), to evaluate the flux of water in a fully spatialized domain, i.e., examine the effects of the multi-channel network on spatial and temporal distribution of flow in this large-scale domain. Two simulation scenarios are taken into consideration: (i) delta in a natural
state, without channels and dykes, and (ii) delta in its current conditions, to evaluate the alterations by both natural conditions and development activities. Additionally, the Vietnamese Mekong Delta (VMD), as other large lowland drainage systems around the world, is also affected by natural drivers, e.g., fluvial sediment reduction (Darby et al., 2016), salinization (Wolanski et al., 1996, Eslami et al., 2019b), coastal erosion (Anthony et al., 2015, Marchesiello et al., 2019), land subsidence (Erban et al., 2014, Fujihara et al., 2016, Minderhoud, 2019) and climate change, especially global sea level rise (Wassmann et al., 2004, Le et al. 2007, Van et al. 2012, Smajgl et al., 2015, Triet et al., 2020). Based on the report of Climate change and Sea level rise scenarios for Vietnam, established by the Ministry of Natural Resources and Environment (MONRE, 2016), four additional scenarios are taken into account in this study to assess the impacts of relative sea level rise on hydrodynamics in the VMD by 2050 and 2100. Based on the six studied scenarios, the full 2D model will be used for:

- Simulating the spatial and temporal distribution of the inundation processes;
- Reevaluating impacts of the multi-channel network on the flow dynamics;
- Forecasting the future patterns of water flux under different scenarios of relative sea level rise in 2050 and 2100.

This paper is organised as follows: Section (2) introduces the study area; Section (3) presents the model set-up; in Section (4), model calibration and validation are run; Section (5) shows the simulation results for the six scenarios; Section (6) discusses the impacts of the multi-channel network and relative sea level rise in the Vietnamese Mekong Delta; finally, conclusions about the impacts of the multi-channel system on flow and sediment dynamics in the VMD are drawn.

2. Study area

The Mekong Delta was formed by the deposition of sediment from the Mekong River over thousands of years (Tri et al., 2012, Anthony et al., 2015 and Zoccarato et al., 2018), resulting in a total area of 55,000 km² (Dung et al., 2013, Balica et al., 2014), the third largest delta in the world (Anthony et al., 2015). The Vietnam Mekong Delta (VMD) is located in the southernmost part of the Mekong Delta. It covers an area of approximately 40,000 km² (Triet et al., 2020), accounting for 12 % of the Vietnam territory area, homelands of 18 million people (Renaud and Kuenzer, 2012, Garschagen et al., 2012). It plays an indisputable role in the Vietnamese economy...
and local residential livelihoods as three-quarters of this region is utilized for agricultural production (Kakonen, 2008). About 56%, 50% and 70% of Vietnam's rice, fish and fruit production originates from the VMD.

The delta is one of the lowest-lying tropical areas (Minderhoud et al., 2019) with a mean topography elevation of 0.82 m (above sea level, a.s.l.). The elevation of the central part ranges from 1.0 to 1.5 m whereas coastal areas have lower elevation of 0.3 - 0.7 m (Tri et al., 2012). The delta’s hydrodynamics is driven by two major tributaries (Duong et al., 2018a): the Tien River (the Mekong River) and the Hau River (the Bassac River), which drain into the East Sea of Vietnam through eight estuaries (Fig. 1a). The delta is commonly divided into four sub-basins: the Long Xuyen Quadrangle (LXQ, number 1 in Fig. 1b), the Plain of Reeds (PoR, number 4 in Fig. 1b), the area between the Tien River and Hau River (number 2 in Fig. 1b) and the Ca Mau Peninsula (number 3 in Fig. 1b) based on their characteristics and functions.

Fig 1. (a) Hydrological stations (orange dots) applied for model calibration and validation. Vam Nao station is located in the conjunction of the Tien and Hau Rivers. My Thuan and Can Tho stations are on the Tien River and Hau River, respectively. Vung Tau, Vam Kenh, Ben Trai, My Thanh and Ganh Hao stations are representative stations distributed along the coast; and (b) sub-regions of the VMD (Simon, 2014).

A distinct feature of the VMD is the intensive management of the multi-channel and dyke systems, in order to mitigate flood, saltwater intrusion and to optimize agricultural activities and fluvial
transportation (Tran Anh et al., 2018; Aires et al., 2020). Nowadays, these structures comprise 7000 km of main channels, 4000 km of secondary on-farm channel systems, 193 spillways, 409 reservoirs, 528 junctions, 29 sluices and 749 compartments (Van et al., 2012). The system is concentrated in the flood-prone areas to efficiently drain out floodwater from the LXQ and the PoR to the Gulf of Thailand (the West Sea of Vietnam) and to the Vam Co River before debouching into the East Sea of Vietnam (Gugliotta et al., 2019). The channel system in the VMD is fully interconnected, without separation between irrigation channels and drainage ones (Renaud and Kuenzer, 2012). The main channels take water directly from the Tien River and the Hau River. They are 70 - 100 m in width and 3 - 5 m in depth. Compartments between dykes are connected to the main channels by a network of secondary channels, which are 30 - 50 m in width and 2 - 3 m in depth. Large parts of the VMD are controlled by sluice gates and pumps, which are managed by local authorities (Hung et al., 2012).

Together with the channel network, the dyke systems have been expanded since 1975 (Dang et al., 2018a), when the demand of food increased sharply after the Vietnam reunification (Hoanh et al., 2014). After the devastating flood of 2000, the dyke systems were especially reinforced in order to maintain agricultural cultivation during flood seasons. The dyke systems comprise low- and high-ring dykes. The low dyke rings, with an average crest level of about 2.0 - 2.5 m a.s.l. (Dang et al., 2016), aim to protect paddy fields against the early flood peak from mid-July to mid-August, so that farmers can cultivate two rice crops per year (Triet et al., 2017). The high dyke rings were designed with the average crest level of about 4.0 - 4.5 m a.s.l. (Hung et al., 2012), approximately 0.5 m above the flood peak of the year 2000, located mainly along the banks of the Tien River and Hau River (Dang et al., 2016). The high dyke rings aim at protecting rice fields during the whole year and regulating climate change related floods. Thus, they can facilitate the cultivation of three crops per year in An Giang and Dong Thap provinces (Fig. 1a and Fig. 2). However, this infrastructure system has been the subject of much debate in the Vietnamese scientific communities and abroad because it causes an alteration of flood pulse and sedimentation in the floodplain, posing several socio-economic issues (Van Binh et al., 2020).

Located in the North Pacific monsoon climate region, the VMD experiences tropical monsoon characteristics, with two separate seasons per year. The wet season normally lasts from June to November, whereas the dry season lasts from December to May (Eslami et al., 2019a). The precipitation in the wet season contributes to approximately 85 % of the annual rainfall (MRC,
2005), and leads to flooding of large areas in the delta (MRC, 2005). In addition, the region is impacted by tropical cyclones (Darby et al., 2016), causing difficulties in predicting flood behaviors and inundation (Best et al., 2018). This flooding dynamics however also contributes to the area’s highly fertile alluviums and fish productivity for centuries (Eastham et al. 2008, Hapuarachchi et al. 2008).

Fig. 2. Simple river and floodplain cross-sections highlighting the effect of flood prevention infrastructure in the floodplains (Arias et al., 2019; Dang et al., 2018b)

The total annual water discharge of the VMD is about 500 billion m$^3$ (84.4 % from the upstream and 15.6 % from the regional rainfall). The flow is the highest during the flood season, particularly in September and October, when it can reach up to 25,500 m$^3$/s. The flow during the dry season is rather low, with a mean discharge no larger than 6,000 m$^3$/s, which leads to saline intrusion in some river mouths (Tri et al., 2012).

The VMD estuaries experience semidiurnal tides (M2, S2, N2, K2) originating from the East Sea of Vietnam with amplitudes of 1 - 3.5 m and diurnal tides (O1 and K1) from the West Sea of Vietnam with amplitudes of 0.8 - 1 m (Le et al., 2007). The tides also influence the hydrodynamic condition in the VMD, as identified by Gugliotta et al. (2017) through bed sample analysis and by Marchesiello et al., (2019) through coupled numerical and in situ/satellite observations.
3. Model set-up

3.1 TELEMAC 2D

The TELEMAC-MASCARET system (http://www.telemacsystem.com), which was introduced by the National Hydraulics and Environmental Laboratory, a part of the R&D group of Electricité de France (EDF), is a numerical modelling system focusing on environmental processes in free surface transient flows. The primary purpose of TELEMAC is to simulate the flow dynamics in a waterbody via the solution of the shallow water equations (Vu et al., 2015). Using a finite-element method, TELEMAC-2D solves the continuity and momentum equations on an unstructured mesh made up of triangles. The governing equations read:

\[ \frac{\partial h}{\partial t} + \vec{u} \cdot \nabla h + h \text{div}(\vec{u}) = S_h \]  
\[ \frac{\partial u}{\partial t} + \vec{u} \cdot \nabla u = -g \frac{\partial Z}{\partial x} + S_x + \frac{1}{h} \text{div}(h \theta_t \nabla u) \]  
\[ \frac{\partial v}{\partial t} + \vec{u} \cdot \nabla v = -g \frac{\partial Z}{\partial y} + S_y + \frac{1}{h} \text{div}(h \theta_t \nabla v) \]

where \( h \) is the water depth (m); \( u \) and \( v \) are depth-averaged horizontal velocity components (m/s), with \( \vec{u} = (u, v) \); \( g \) is the gravitational acceleration (m/s\(^2\)); \( Z \) is the free surface elevation (m), positive upward; \( t \) is time (s); \( x \) and \( y \) are horizontal cartesian coordinates (m); \( S_h \) is the source or sink of water (m/s) and \( S_x \) and \( S_y \) encompass the Coriolis force as well and the bottom and surface stress terms (m/s\(^2\)), \( \theta_t \) is the horizontal kinematic viscosity (m\(^2\)/s) and \( \nabla \) is the (horizontal) del operator.

3.2. Data utilization

All data used as inputs for the model were obtained from official sources, summarized in Table 1. Fig. 1(a) shows the location of hydrological stations used for model validation. Hourly data allows capturing tidal influences and investigating the phase coherence between different gauges.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Frequency</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>River network and channel cross-sections</td>
<td>Surveyed from 1995 to 2000 with updates between 2005 and 2010</td>
<td>- HoChiMinh city University of Technology, Vietnam</td>
</tr>
</tbody>
</table>
Hydraulic infrastructure operations

Hydraulic infrastructure embedded in the model are based on official regulations for 2010 - 2011

- Southern Institute for Water Resources Research, Vietnam MRC

Hydrological data

Can Tho and My Thuan (hourly Q and H in 2010 and 2011)

Lower Mekong Coastal Delta Zone project

Tan Chau and Chau Doc (hourly Q and H) in 2010 and 2011

- National Center for Meteorological and Hydrological Forecasting, Vietnam

Vung Tau, Ben Trai, Ganh Hao, Vam Kenh (hourly H) in 2010 and 2011

- Vietnam – German University

Offshore wind

The hourly wind data at 10 m

NCEP NOAA

Offshore tidal constituents

Amplitude and phase of tidal constituents

TPXO 8.0

3.3. Computational mesh

Fig. 3 shows the domain and bathymetry of the VMD, which was developed from several sources and derived from the 100 m x 100 m grid resolution Digital Elevation Map (DEM), with reference to the Hondau datum (the Vietnamese official benchmark system, identical to mean sea level). In the upper part of the domain, the model is bounded at Tan Chau (the Tien River) and Chau Doc (the Hau River). In the estuarine area, the river tributaries drain into the sea and the model boundary is expanded approximately 70 - 80 km offshore.
Fig 3. Bathymetry of the Vietnamese Mekong Delta.

Fig 4. Computation mesh for Scenario S1 with main rivers, multi-channels, roads and culverts.
The model is set up to represent the approximately real conditions of the VMD (Scenario S1). We model two main rivers (the Tien River and Hau River), eight estuaries, the primary and secondary channels. The tertiary and quaternary channels are neglected because this system connects with the two main rivers and drains directly into the sea. Roads and dykes are represented by high elevations in the bathymetry (see Fig. 3 and Fig. 4).

Triangular elements with small sizes of 80 – 100 m are used in the channels; a maximum size of 300 m is for the main rivers; a size of 300 - 2000 m is for the floodplain and the largest size of 4000 m are for offshore settings. The total number of triangular elements is 524,097 with 268,010 nodes.

In order to assess the impacts of the numerous channels on the flow dynamics and sediment transport in the VMD, another computational mesh (see Fig. 5) is generated with the two main rivers (the Tien River and Hau River) and eight estuaries, without the channel network (Scenario S2). The computational area is similar to that of Scenario S1. The mesh of this scenario is made up of 113,559 elements and 56,665 nodes. This second scenario (S2) can be viewed as representative of the delta situation prevailing before the construction of the dykes and channels,
and comparison of the results of scenarios S1 and S2 will thus allow assessing the impacts of these infrastructures.

3.4. Parameters and simulation set-up

3.4.1. Boundaries

The upstream boundary conditions consist of measured hourly discharges imposed at Tan Chau (the Tien River) and Chau Doc (the Hau River). The tidal data base of TPXO (https://www.tpxo.net/global) is applied as a real sea water level dataset in both the West and East Seas for the downstream boundaries. A coefficient to calibrate sea level and a coefficient to calibrate tidal range are also adjusted to transfer the information between a large-scale model and the boundaries of a local model (Pérez-Ortiz et al., 2013).

3.4.2. Parameters of hydrodynamic simulation

The bed friction is parameterized by having recourse to the Nikuradse roughness length scale, $k_s$ (Nikuradse, 1950), as shown in Tassi et al. (2014) and Julien (2010):

$$k_s \approx 3d_{50}$$

(7)

where $d_{50}$ is the median grain diameter (m)

The simulation uses a constant (horizontal) viscosity throughout the domain equal to $10^{-6} \text{ m}^2/\text{s}$. The default value incorporates both molecular viscosity and eddy viscosity in the constant viscosity model.

Wind is variable in time and space. Hourly wind data at 10 m from NCEP NOAA (https://www.ncep.noaa.gov/) are used in the simulation. According to the introduction by the Institute of Oceanographic Sciences of the United Kingdom, the wind influence coefficient is set to $0.565 \times 10^{-6}$ because most of the wind velocity is $< 5 \text{ m/s}$ (TELEMAC - 2D User Manual). The atmospheric pressure is taken to be $10^5 \text{ Pa}$. The threshold depth of wind is applied to avoid unphysical wind velocities with a constant value of 3 m.

The initial water elevation is 0 m. The simulation time-step was fixed at 20 s by trials and errors in order to ensure a balance between model stability and computational cost.

In order to assess the impacts of multi-channel networks on the flow dynamics in the VMD, two main scenarios (Scenario S1 and Scenario S2), as described above, are set up. However, as reported
by MONRE (2016), Västilä et al. (2010), Van et al. (2015), Smajgl et al. (2015) and Minderhoud et al. (2019), the VMD is one the deltas that is most vulnerable to climate change. Relative sea level rise is likely to be the main driver of climate change impacts in the delta. Thus, four additional scenarios are established corresponding to the two main scenarios with the projected relative sea level rises of 30 cm in 2050 and 100 cm in 2100 (MONRE, 2016). These scenarios are summarized in Table 2.

Table 2. Modelling scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Two main rivers and the multi-channel network, as the current status of the VMD</td>
</tr>
<tr>
<td>S2</td>
<td>Two main rivers without the multi-channel network, as representative of the delta situation prevailing before the construction of the dykes and channels</td>
</tr>
<tr>
<td>S3</td>
<td>Same as Scenario S1 with a projected relative sea level rise of 30 cm</td>
</tr>
<tr>
<td>S4</td>
<td>Same as Scenario S2 with a projected relative sea level rise of 30 cm</td>
</tr>
<tr>
<td>S5</td>
<td>Same as Scenario S1 with a projected relative sea level rise of 100 cm</td>
</tr>
<tr>
<td>S6</td>
<td>Same as Scenario S2 with a projected relative sea level rise of 100 cm</td>
</tr>
</tbody>
</table>

In Scenario S1, the initial set-up of the model is based on the current status of the VMD, the flood data is in the year 2011. The flood event in 2011 is one of two recent severe floods in Vietnam (Triet et al., 2020 and Chen et al., 2020). The measured daily discharge at Tan Chau and Chau Doc stations are used as the upstream boundary conditions, and the hourly sea levels at the East Sea and the West Sea are used as the downstream boundary condition.

In Scenario S2, the VMD consists of only Tien River and Hau River with eight estuaries, which correspond to the configuration of the delta before human intervention. The data for simulation is the flood event in 2011. The measured daily discharge and the hourly measured sea levels are the same with the previous scenario.

The model set-up for Scenarios S3 and S4 is similar to Scenario S1 and S2, respectively, with the same upstream discharges. However, the hourly sea levels at the downstream boundary are increased by 30 cm in both the East and West Seas, corresponding to the rising sea level scenario in 2050. This value of 30 cm is extracted from the report of Climate changes and sea level rise scenarios for Vietnam, which was conducted by the Ministry of Natural Resources and Environment (MONRE) in 2016.
Scenarios S5 and S6 have the same procedure as the previous scenarios with the rise of 100 cm sea level at the downstream boundary condition, corresponding with the rising sea level scenario in 2100.

4. Calibration and validation

To assess the model performance during different periods and hydrological conditions, the periods of 10 - 19 September and 25 September - 4 October 2011 are selected for the model calibration and validation because they are representative for the flood season in the VMD.

The model was calibrated by adjusting the Nikuradse roughness length scale in six areas (Table 3); and the tidal coefficient parameter of -0.4 m and tidal range of 1.2 to transfer the information between a large-scale model (https://www.tpxo.net/global) and the boundaries of a local model (Pérez-Ortiz et al., 2013).

The water levels were evaluated at eight measurement stations (Fig. 1a, Fig. 6, Fig 7 and Table 4), which are key stations with the highest data accuracy in the Mekong Delta. The quality of match between simulated and observed water levels after calibration was evaluated by the Nash-Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe, 1970), Mean Absolute Error (MAE) and Root Mean Square Error (RMSE).

The NSE is defined as:

\[
NSE = 1 - \frac{\sum_{i=1}^{n}(H_{\text{obs},i} - H_{\text{simu},i})^2}{\sum_{i=1}^{n}(H_{\text{obs},i} - \bar{H}_{\text{obs}})^2}
\]  

where \(\bar{H}_{\text{obs}}\) is the mean value of observed water depths, \(H_{\text{obs},i}\) is the observed water depth at time \(t = i \Delta t\) and \(H_{\text{simu},i}\) is the numerically simulated water depth at time \(t = i \Delta t\), \(n\) being the total number of time steps.

The MAE and RMSE criterions are applied to measure the absolute differences between simulations and observations:

\[
MAE = \frac{\sum_{i=1}^{n}|H_{\text{obs},i} - H_{\text{simu},i}|}{n}
\]  

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n}(H_{\text{obs},i} - H_{\text{simu},i})^2}{n}}
\]
The statistical matches are reported in Table 4, with the parameters values presented in Table 3.

The numerical simulations show good agreement with observed data in almost all stations, except Vam Nao station, where the Tien and Hau Rivers join, with very specific impacts on local bathymetry due to sand mining (Gugliotta et al, 2017) and flow redistribution between the Tien and Hau Rivers (Brunier et al. 2014).

Table 3. Nikuradse roughness for subdomains and the study area

<table>
<thead>
<tr>
<th>No.</th>
<th>Subdomain</th>
<th>Nikuradse roughness (m)</th>
<th>No.</th>
<th>Subdomain</th>
<th>Nikuradse roughness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tien river</td>
<td>0.1</td>
<td>4</td>
<td>Co Chien estuary</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>Hau river</td>
<td>0.12</td>
<td>5</td>
<td>Ham Luong estuary</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>Vam Nao conjunction</td>
<td>0.1</td>
<td>6</td>
<td>The remaining area</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 4. Hydrodynamic model validation

<table>
<thead>
<tr>
<th>No.</th>
<th>Station</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NSE (%)</td>
<td>MAE (m)</td>
</tr>
<tr>
<td>1</td>
<td>Can Tho</td>
<td>74.69</td>
<td>0.178</td>
</tr>
<tr>
<td>2</td>
<td>My Thuan</td>
<td>82.95</td>
<td>0.830</td>
</tr>
<tr>
<td>3</td>
<td>Vam Nao</td>
<td>74.04</td>
<td>0.004</td>
</tr>
<tr>
<td>4</td>
<td>My Thanh</td>
<td>87.14</td>
<td>0.263</td>
</tr>
<tr>
<td>5</td>
<td>Ben Trai</td>
<td>79.98</td>
<td>0.249</td>
</tr>
<tr>
<td>6</td>
<td>Ganh Hao</td>
<td>90.83</td>
<td>1.472</td>
</tr>
<tr>
<td>7</td>
<td>Vung Tau</td>
<td>87.26</td>
<td>0.225</td>
</tr>
<tr>
<td>8</td>
<td>Vam Kenh</td>
<td>92.97</td>
<td>0.175</td>
</tr>
</tbody>
</table>
Fig. 6. Model calibration. The red lines present the measured data and the blue lines present the simulated one.
Fig. 7. Model validation. The red lines present the measured data and the blue lines present the simulated one.
5. Results

Flooding in the VMD usually occurs in two regimes: (1) upstream floods, driven by the hydrological forcing inland and (2) tidal-induced floods triggered by the tidal flows from the East and West Seas (Balica et al., 2014). The period 25 - 30 October 2011 is selected to simulate the extreme flood dynamics in the VMD, because the maximum water level in 2011 was higher than that of the historic flood event in 2000 (Dung et al., 2013, Apel et al., 2016). For this event, a late flood peak (in October 2011) coincided with a spring tide period (Triet et al., 2017), which caused the highest water level observed so far in the VMD.

5.1. Inundation level and area

Fig. 8 shows that the water level in the upper VMD is always higher than in the downstream parts, especially in the PoR and LXQ, which are considered as two flood-prone areas of the VMD. Water level in the PoR is higher than 1.8 m while water level in the LXQ is higher than 1.0 m, which redistributes the flow in the VMD by discharging floodwater into the Gulf of Thailand to protect local residents and crops. Thanks to the multi-channel network, inundation areas between Tien and Hau rivers with water levels higher than 1.0 m are limited to the upstream of Can Tho and My Thuan. It confirms that the multi-channel network does not influence both branches through the hydraulic links in the channel system.

In this paper, inundation areas are defined with water level of 0.5 m or more inland. It is considered as a threshold value beyond which there can be high property damages and no cultivation (Van et al. 2012 and Balica et al., 2014). The total inundation area in Scenario S1 is 11.710 km², accounting for 29 % of the whole VMD area, which agrees with the studies by Hoa et al. (2008) and Renaud and Kuenzer (2012).
To assess the effects of the multi-channel network on the flow dynamics of the VMD, the hourly flow velocity is extracted at the stations in two main rivers and their channel systems (locations of the stations are shown in Fig. 8).

The flow velocity at the upstream station of the Hau River (Chau Doc) is rather constant with cross-section average value of 0.75 m/s (Fig. 9a). At Vam Nao confluence, the flow velocity increases to 0.82 m/s because of the flow balance mechanism between the Tien River and Hau River (Gugliotta et al., 2017). In Can Tho, under the influence of the tidal regimes, the flow velocity oscillates, between 0.46 and 1.2 m/s, with a mean value of 0.8 m/s. Two time series extracted from the channels of the Hau River at Tan Hiep station (33 km from the main river) and Phuoc Long station (88 km from the main river) show mean values of 0.5 m/s and 0.3 m/s, respectively (Fig. 9a).

Fig. 9 (b) presents the flow velocity in the upstream station of the Tien River (Tan Chau) with a relatively constant value of 1.16 m/s. The fluctuation of the flow velocity in My Thuan is higher than in Can Tho, ranging from 0.66 to 2.24 m/s, with a mean value of 1.45 m/s. Because the
influence of the semidiurnal tidal amplitude from the East Sea on the Tien River is stronger than
the diurnal tide from the Gulf of Thailand (Manh et al., 2014, Marchesiello et al., 2019), velocities
in Hung Thanh station (35 km from the main river) and Tan An station (25 km from the main river)
exhibit mean values of 0.1 m/s and 0.3 m/s, respectively.

Generally, the flow velocity in the channel system decreases with the distance from the main rivers.
In the upper part of the VMD (Chau Doc, Tan Chau and Vam Nao), it is dominantly affected by
the river flow, whereas the middle part (CanTho and My Thuan) is under the effects of tidal
propagation.

Fig. 9. Flow velocity in Hau river (a) and Tien river (b) from the upstream to downstream and their locations in the
VMD

6. Discussion

6.1. Impacts of the multi-channel network

Scenario S2 (without channels, see Fig.5) is run and compared with results from Scenario S1
(rivers and multi-channel networks, see Fig. 4) to assess the impacts of the current multi-channel
networks on the flow dynamics in the VMD.
6.1.1. **Inundation level and area**

In the Scenario S2, the average inundation level in the PoR and LXQ is approximately 1.0 m and reaches up to 2.0 m in some small areas (see Fig. 10), whereas the results from Scenario S1 (the full network scenario) show the maximum water level of the PoR can reach 4.0 m. The total inundation area with water levels of > 0.5 m in Scenario 2 (without channels) reaches 25.918 km², accounting for 65% of the VMD area in comparison with 29% for Scenario S1 (Fig. 10). Lower water levels and larger inundation areas from Scenario S2 indicate that the channel system is a substantial driver of the hydraulic scheme in the VMD. It works efficiently to drain flood waters from the LXQ and the PoR to the Gulf of Thailand and to the Vam Co River, before discharging to the East Sea, respectively (Thi Ha et al., 2018).

6.1.2. **Water elevation and discharge at Can Tho and My Thuan stations**

Two main stations (Can Tho and My Thuan) are selected to reevaluate the impacts of the complex channel system on the hydrodynamics in the VMD. These stations correspond to two important cities in this region (i.e., Can Tho and My Thuan), with high density population, intensive agricultural production and key economic hotspots.
Water elevation increases from 0.11 to 0.43 m in Can Tho and from 0.18 to 0.45 m in My Thuan in Scenario S1 and Scenario S2, respectively. Considering Scenario S2 (without channels), discharge at Can Tho station increases slightly (about 2000 m$^3$/s); but discharge at My Thuan station increases noticeably about 5400 m$^3$/s, and reaches the maximum value of approximately 24,000 m$^3$/s.

At these stations, the tidal signal is clearly visible even during the highest flood event (Hung et al., 2012 and Eslami et al., 2019a). However, the multi-channel systems have reduced the tidal effects and variation of floodwater elevation in both rivers (see Fig. 11, scenario S1, blue curves).
The historical flood year 2011 caused a large inundation area in the VMD (see Fig. 10 and Triet et al., 2017). The maximum simulated floodwater elevation at the main stations in both scenarios are compared with the Vietnam flooding alarm elevation No. 1 (Alarm No. 1) to define the flooded areas and assess the impacts of the channel network on flood protection.

Fig. 12. The highest water elevations at main stations in comparison with the Vietnam alarm elevation No. 1. Blue texts show the results from Scenario S1 (with channels), red texts present the results from Scenario S2 (without channels). Positive values mean the water elevation at the station higher than the Vietnam alarm elevation No. 1, negative values means the water elevation lower than the Vietnam alarm elevation No. 1. The light blue area delimits the inundation area common to both scenarios.
Water elevations at almost all stations in the upper VMD are higher than the Alarm No. 1 in both scenarios because the upstream flood plays a dominant influence on the flow dynamics, especially the PoR and the LXQ. These regions store water in the wet season and supply water in the dry season for the whole VMD. The water elevation in the coastal area was generally lower than the Alarm No. 1 (Phung Hiep, Tra Vinh, My Tho and Dai Ngai), except Vam Kenh and Hoa Binh.

Water elevations in Scenario S1 are lower than those in Scenario S2 because the channel network works as a water conveyor from the VMD to the seas and mitigates flooding. Thus, water levels in Can Tho and My Thuan in Scenario S1 are approximately at the Alarm No.1 level. The intercomparison of scenarios, which are synthesized in Fig. 12, underline the effect of the multi-channel network on flood reduction, especially in the coastal areas and key cities of the VMD.

### 6.2. Impacts of sea level rise

Four additional scenarios (S3, S4, S5, S6), as introduced in Table 2, are simulated to evaluate the impacts of relative sea level rises on the flow patterns of the VMD, with visions to 2050 (+30 cm) and 2100 (+100 cm).

#### 6.2.1. Water elevations and discharges

Relative sea level rise will likely pose additional pressures on the development of this region (Dang et al., 2018a; Kondolf et al., 2022). It may propagate flooding and cause higher water level and discharge in the hotspot cities of the VMD, namely Can Tho and My Thuan. The results of these scenarios are provided in Fig. 13 - 14 and Table 6. With the multi-channel network, water levels in Can Tho increase by 0.28 m and 0.55 m for the projected relative sea level rises of 30 cm (in 2050) and 100 cm (in 2100), respectively. Water levels in My Thuan increase by 0.29 m and 0.55 m for the same conditions. The discharge also increases to 6004 m$^3$/s and 7479 m$^3$/s in Can Tho, and to 6844 m$^3$/s and 9276 m$^3$/s in My Thuan, respectively. Because water is added to the main rivers from the floodplain and relative sea-level rise pushes ocean tides upstream. Without the multi-channel network (S4 and S6), the water level in Can Tho increases by 0.24 m and 0.47 m respectively, while the increases in My Thuan are of 0.30 m and 0.63 m, respectively. The discharges increase to 4530 m$^3$/s and 6066 m$^3$/s in Can Tho, and to 2985 m$^3$/s and 5418 m$^3$/s in My Thuan, respectively.
The increase of water levels and discharges without the multi-channel network (Scenario S2, S4, S6) are greater than those with the multi-channel network (Scenario S1, S3, S5) because the tidal regimes directly influence the flow regimes of the Hau River and the Tien River (see Fig. 13 and Fig. 14). The tidal amplitudes of Can Tho and My Thuan reach the maximum value of 2.0 m and 2.1 m, higher than the values of 1.0 m and 1.7 m in the scenarios with the multi-channel network. The multi-channel network buffers hydrodynamics in the floodplain and may lessen the floodings and associated damages.

Table 6. Summary of results from the 6 scenarios considered in this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. water level at Can Tho (m)</td>
<td>1.68</td>
<td>2.09</td>
<td>1.96</td>
<td>2.33</td>
<td>2.23</td>
<td>2.56</td>
</tr>
<tr>
<td>Max. water level at My Thuan (m)</td>
<td>1.62</td>
<td>1.87</td>
<td>1.91</td>
<td>2.17</td>
<td>2.17</td>
<td>2.50</td>
</tr>
<tr>
<td>Max. discharge at Can Tho (m³/s)</td>
<td>20,396</td>
<td>22,358</td>
<td>26,400</td>
<td>26,888</td>
<td>27,875</td>
<td>28,424</td>
</tr>
<tr>
<td>Max. discharge at My Thuan (m³/s)</td>
<td>18,348</td>
<td>23,765</td>
<td>25,192</td>
<td>26,750</td>
<td>27,624</td>
<td>29,183</td>
</tr>
<tr>
<td>Inundation area (km²)</td>
<td>11,710</td>
<td>25,918</td>
<td>12,750</td>
<td>27,617</td>
<td>20,385</td>
<td>34,199</td>
</tr>
<tr>
<td>Percentage in the VMD</td>
<td>29 %</td>
<td>65 %</td>
<td>32 %</td>
<td>69 %</td>
<td>51 %</td>
<td>85 %</td>
</tr>
</tbody>
</table>
Fig. 13. Water elevation in Can Tho (a, b) and My Thuan (c, d) stations corresponding with scenarios S1, S3, S5 and Scenario S2, S4, S6
Our modeling results suggest that hydrological regimes of the coastal and estuarine parts of the VMD would be much more heavily affected by the relative sea level rise than in the upper part (see Fig. 15). The largest inundation area in the VMD, calculated in Scenario S1 is 11,710 km², corresponding to 29% of total VMD area. This area increases to 12,750 km² in 2050 (Scenario S3, RSLR+30cm) and 20,385 km² in 2100 (Scenario S5, RSLR+100cm) towards the coastal part of the VMD (Van et al., 2012, Dang et al., 2018a) corresponding to 32% and 51% of the total area, respectively. However, without the effects of the multi-channel network, the maximum inundation area by floodwater would have rise up to 27,617 km² (Scenario S4, RSLR+30cm) and 34,199 km² (Scenario S6, RSLR+100cm), accounting for 69% and 85% of the total area, respectively. The study of Minderhoud et al. (2019) also confirms this threat to the VMD at the end of this century, with higher risks of flooding than previously assessed.
Fig. 15. Inundation areas with water level > 0.5m in different scenarios. (a) VMD with the multi-channel network, (b) VMD without channel network.
7. Conclusion

This study confirms the capacity of a full 2D model to simulate flood dynamics in a large-scale domain under many drivers such as man-made structures and natural conditions (flood events, tidal motions and wind stress). Our study provides information regarding the vulnerability of the VMD to flood nowadays and in the future. This spatial prediction may be useful for the local residents and stakeholders to adopt proper prevention measures.

The results also shed light on the link between hydrodynamic alterations and human interventions in the VMD. The inundation area in the VMD in 2011 was calculated to be approximately 12,000 km\(^2\) with water level ranging from 0.5 to 4.0 m. The historical construction of the channel network reduced flooding areas, helping local communities to lessen flood-driven damage and increased agricultural production areas. Without the multi-channel network, the inundation area would have been larger, extending to approximately 26,000 km\(^2\) and causing serious damages and human suffering.

Relative sea level rise will also likely bring additional pressures on the water-related safety and sustainability of this region, as pointed out by many authors (Van et al., 2012; Smajgl et al., 2015; Hoang et al. 2016; Dang et al., 2018a). The cumulative impact of subsidence and sea level rise will increase risks of inundation both in space and frequency. The maximum inundation area could reach about 35,000 km\(^2\), accounting for 85 % of the whole VMD area in 2100. Thus, large scale measures to mitigate or counterbalance the effects of relative sea level rise and other drivers such as land subsidence and storm surges are now essential to maintain agricultural cultivation and to minimize human suffering in the VMD.

In the light of the results of this numerical study, we can assume that a sustainable development of the multi-channel network will bring an optimal regulation of water cycles and sediment transport patterns in the VMD. It could contribute to improve agricultural production and livelihoods in the region, even in the extreme conditions of climate change and sea level rise. For future studies, the sediment distribution pattern in rain season, the flow distributions and saltwater intrusion in dry season should be addressed to anticipate this additional threat.
CRediT authorship contribution statement


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