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Ocean tide modelling for urban flood risk assessment in the Mekong Delta

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Abstract:

This study develops a tide propagation model in order to forecast water levels and velocities at a given time and location for the largest city in the Mekong Delta, Can Tho City. The simulation model is applied to a complex waterway system that is characterised by a number of small canals and tributaries, which connect with the main stream. The model, which is verified by comparison with observed water levels during a typical dry season, enables examination of the mechanisms of tidal propagation, which have an impact on floods, inundation and saline water intrusion. The model analysis indicates that the difference in tidal amplitude between a connecting tributary and the main stream is small, whereas the flow velocity largely varies depending on the location. The flow velocity in the tributary, which exceeded 1 m/s, is almost three times that of the main river. This kind of local amplification in flow velocity is important when evaluating flood/inundation risks in urban areas of the Mekong Delta, as small ships are likely to encounter difficulties in handling or risk being overturned due to unexpectedly rapid flows that occur during these abnormal high tides or typhoon storm surges.

KEYWORDS Mekong Delta; Can Tho City; ocean tide; urban flood; numerical simulation; field measurement

INTRODUCTION

Vietnam, with its 3,260 km coastline and two vast low-lying deltas (the Red River and Mekong Deltas), could be considered one of the most vulnerable countries to coastal disasters and climate change (Nguyen *et al.*, 2014; Takagi *et al.*, 2015). The Mekong River flows southwards covering a distance of approximately 4,800 km from its source to the sea, draining a total catchment area of 795,000 km² that falls within six different countries: China, Myanmar, Lao PDR, Thailand, Cambodia, and Vietnam. The Mekong ranks 10th amongst the world's great rivers on the basis of its mean annual flow at the river mouth (Mekong River Commission, 2005). This great basin is considered to be one of the most sensitive areas in the world to climate change (World Wide Fund for Nature, 2009). It has been predicted that the hydrological changes that can be expected to occur over the next century will be greater than changes which rivers have experienced

due to climate variability during the last 9,000 years (Aerts *et al.*, 2006).

Takagi *et al.* (2014a) reveals that ocean tides predominantly determine water elevation even in an upstream location such as Can Tho City, 80 km inland from the river mouth (Figure 1). Three tidal components of semidiurnal, diurnal, and annual cycles were found to be dominant factors in water level variations of the river. Tides further propagate up to towns close to the Cambodian border, such as Chau Doc (Figure 1, situated about 190 km inland from the river mouth), but disappear afterwards (Mekong River Commission, 2005).

Given these oceanic influences on deltaic regions, flood/inundation forecasting which incorporates precise ocean tidal modelling is one of the key developments in order to establish effective disaster management for urban areas with large populations and high economic value. Thus, this paper develops a tidal model, and investigates the mechanisms of tidal propagation and its influence on flooding in urban areas of the Mekong Delta. The authors have chosen Can Tho because this city is the regional capital and has the highest population (around 1.2 million inhabitants) in the Mekong Delta.

METHODOLOGY

In this section, the numerical tidal model focusing on an urban area in the Mekong Delta is described and validated using water levels measured by the authors in March 2012.

Harmonic tidal analysis

In the estuary of the Hau River there are currently two tide-monitoring stations at Can Tho and Dinh An (Figure 1), which are operated by the Mekong River Commission (MRC) and the Vietnamese government, respectively. The authors obtained tidal data at these two stations and carried out a harmonic tidal analysis in order to obtain the tidal constituents. This technique was also used to investigate the frequency characteristics of each tidal constituent. Since Dinh An is located at the river mouth, the water elevation at this station is considered to be predominantly dependent on oceanic tides and relatively independent of river discharge. Hence, the characteristics of tidal propagation along the river can be investigated by comparing the data sets obtained

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Table I. Six principal tidal constituents at Can Tho Station: Amplitude (cm) and phase (degree)

M2		N2		S2		K1		O1		Sa	
Amp. (cm)	Phase (deg)	Amp. (cm)	Phase (deg)	Amp. (cm)	Phase (deg)	Amp. (cm)	Phase (deg)	Amp. (cm)	Phase (deg)	Amp. (cm)	Phase (deg)
51.9	152.4	9.7	118.7	17.7	198.0	35.1	18.2	21.3	324.3	35.4	220.1

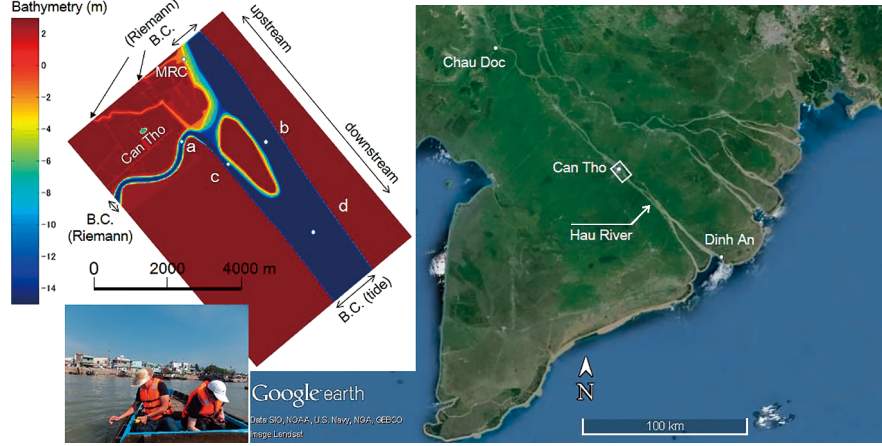


Figure 1. Can Tho, which is the largest city along the Hau River, in the Mekong Delta, is located in southern Vietnam. The white rectangle on the satellite image of Google Earth indicates the computational domain of the Can Tho region, encompassing the main river (Hau River), tributaries, and small water ways. The panel on the top left shows the domain used for the numerical simulation with information on the open boundary conditions, also indicating the locations of simulation output (a, b, c, d, and MRC). The lower bottom photograph shows a snapshot of the bathymetric survey

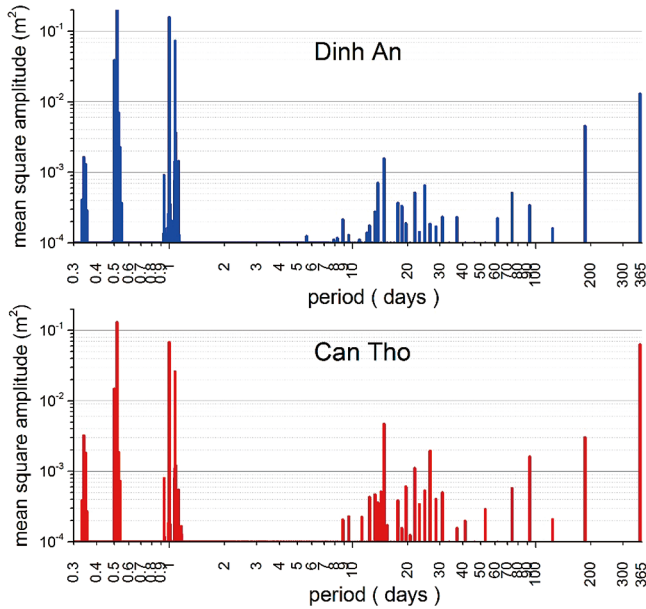


Figure 2. Power spectrum of water elevations at Dinh An and Can Tho, both are situated along the Hau River: Dinh An is adjacent to the sea, while Can Tho is located 80 km inland

at both Can Tho and Dinh An. Figure 2 shows that the frequency characteristics of water elevations appear to be similar between the two sites. The semidiurnal and diurnal com-

ponents can be considered to be the governing factors of water elevation, followed by the annual component. Amongst all the tidal components, the semidiurnal tidal constituents with a period of around 12 hours appears to have the strongest influence. It is noted that the authors limited their analysis to one year-long water-level record at each of these stations for the period from July 2009 to June 2010, because substantial data gaps were found in the other data available. The authors consider that an analysis using a one year-long data series can represent both the tidal and fluvial regimes in this region, which are typically characterized by one year cycle. The present study analysed the data monitored at Can Tho station and derived a total of 60 tidal constituents by harmonic analysis, as represented by the six major components in Table 1.

Ocean tidal modelling and validation

Delft3D-FLOW (Deltares, 2011) was used to simulate ocean tides that travel from the deep sea to the shallow waters of the continental shelf, up the Hau River, and eventually flood over the downtown Can Tho. Although this model is applicable for such a wide region, this study limited the computational domain to include only Can Tho City and its surrounding area (Figure 1). This was in order to reduce the computational cost and enable a detailed analysis, which considered the local topography and bathymetry, characterized by tributaries, channels, and low-lying lands. In this manner the present model may have an advantage in evaluating the detailed hydraulic characteristics within the domain, although it cannot provide an overall outlook on



Figure 3. The water elevations visually measured between March 10–11, 2012. Left: high tide, Right: low tide

tidal propagation along the long stretch of the Hau River.

River bathymetry data were partially obtained by the authors, using a portable echo sounder (Figure 1). The data, which were collected at about 30 locations in the computational domain, are expected to give a reasonable representation of the bathymetry. However, tidal flats formed in a particular location were not reproduced at a high accuracy in the model because the survey ship was not able to access shallow muddy areas. It is noted that these areas may reduce tidal amplitudes due to high viscosity, although the present study did not sufficiently account for the influence of tidal flats.

The simulation was run for 5 days, which included the days of March 10–11, 2012, during which time visual observations of the tidal fluctuation were conducted (Figure 3). The computational grid size was set at 10 m throughout the domain. The Manning's n value was set at 0.02 for the riverbed and 0.05 for the land area (Takagi *et al.*, 2016). The tidal constituents, which were presented in the previous section, were assigned along the downstream open boundary. The tidal constituents obtained from the data at the MRC observatory in Can Tho (Figure 1) were assigned along the downstream boundary to generate ocean tides which propagate across Can Tho, while the upstream boundary as well as the other tributaries were kept as open boundaries which enable progressive waves to pass through without reflection. Although several kilometres of gaps exist in the location between the MRC observatory in Can Tho and the downstream boundary, the authors confirmed that the constituents obtained can be used without any particular modification. Since the computational domain used is relatively small in size, stretching up to 8 km, ocean tides appear to propagate from the downstream end to the upstream end in a few minutes without significant attenuation. These characteristics make it possible to directly use the tidal constituents at the station in Can Tho in order to generate tides at the downstream boundary (Figure 1).

Although the model is applicable for a 3D domain, the present study used a 2D horizontal grid, and thus the code is equivalent to a non-linear long wave model, which is the one most commonly used for tidal simulation. The 2D model substantially reduces computational cost and thereby enables coverage of the computational domain with fine gridding. However, it should be noted that the 2D horizontal model neglects vertical dynamic motions which often result in the loss of fluid energy (Takagi and Bricker, 2014).

Figure 4 shows the tidal fluctuations at a chosen riverbank

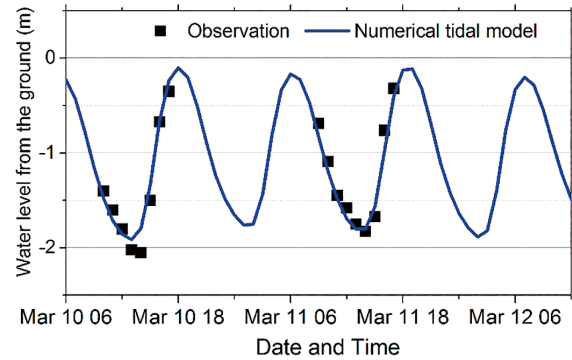


Figure 4. Comparison between the numerically simulated and visually observed water levels at every hour during the daytime on March 10–11, 2012

of Can Tho, after converting the original data to the ground reference. It shows that the simulated and observed water levels agree well with one another, in terms of both amplitude and phase. The highest tides during the measurement periods reached up to approximately 10 cm below ground level. This was also corroborated by visual observations obtained in the survey (see Figure 3).

RESULTS AND DISCUSSION

Having a precise numerical model enabled the authors to further investigate the spatial and temporal characteristics of tidal propagation in an urban area, which typically has a complex canal–tributary system connecting to the main river. Figure 5 presents the simulated water levels and depth-averaged velocities at five different locations in the river basin (Figure 1). The water level at point (a) in the riverfront district of Can Tho is approximately 10 cm lower than those at the other points, (b), (c), (d), and (MRC), which are located in the main stream. The point referred to as MRC indicates the location of the monitoring station, which is operated by the Mekong River Commission. Both tidal amplification and damping appear in a narrowing channel such as the connecting tributary, determined by the balance between frictional energy loss and energy concentration due to the convergence (e.g., Savenije, 2001). For this study area, we speculate that the tidal amplitude could eventually be reduced when waves divert into the narrower channels

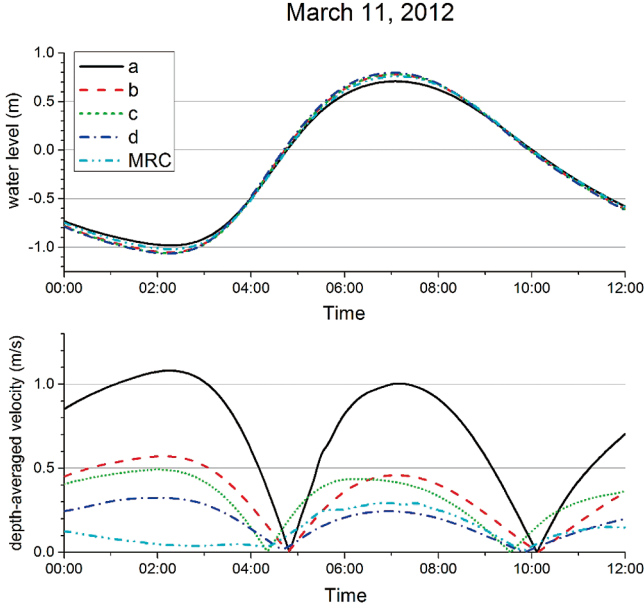


Figure 5. Simulated water level (top) and depth-averaged velocity (bottom) during a semi-diurnal cycle, on March 11, 2012. The outputs correspond to the five locations indicated in Figure 1

due to diffraction and bottom friction damping. The diffraction at the confluence of the main river and the tributary appears to cause a reduction in wave amplitude. On the other hand, a reduction in wave amplitude associated with bottom friction damping can be partly explained based on the long wave equation, including friction (Dean and Dalrymple, 1984)

$$\frac{\partial^2 \eta}{\partial t^2} + A \frac{\partial \eta}{\partial t} = gh \frac{\partial^2 \eta}{\partial x^2} \quad (1)$$

where η is the tidal surface elevation, h is the water depth, x is the position, t is the time, and g is the gravitational acceleration. A is defined as $A = fU_m/3\pi h$, where f is the Darcy-Weisbach friction factor and U_m is the maximum magnitude of horizontal velocity.

If a periodic progressive wave is assumed, then Equation (1) can be solved as

$$\eta = \frac{H_i}{2} e^{-k_r x} \cos(k_i x - \sigma t) \quad (2)$$

where H_i is the initial wave height, k_i , k_r are the wave numbers for incident and reflected waves, respectively, and σ is the angular frequency.

The relative reduction in amplitude over one wave period T is expressed as

$$\frac{\eta(t+T)}{\eta(t)} = e^{-(A/2)T} \quad (3)$$

Therefore, wave amplitude decreases rapidly with velocity U_m in the case when the water depth and friction factor are kept constant.

Contrary to these relatively minor differences in wave amplitude, the depth-averaged velocity varies largely depending on the locations in the river basin. Particularly,

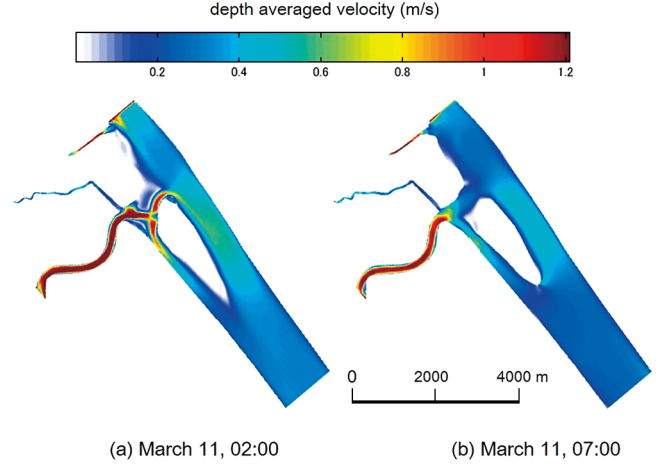


Figure 6. Flow intensification observed in the numerical simulation. Left: ebb tide phase, Right: rising tide phase

the flow velocity at point (a), which exceeded 1 m/s, was almost three times that at point (d) in the main stream. It is obvious that the flow intensification that occurs as water from the downstream river enters into the narrower channels and vice versa, caused this type of gradually varying flow (Figure 6). This local intensification of the flow velocity could be an important characteristic when considering the flood risks in the urban areas of the Mekong Delta. This phenomenon could occur during unusually high tides, periods of high river discharge, and typhoon storm surges. Due to the fact that a large number of local fishermen, tourist guides, and floating market merchants use small wooden ships (see Figure 3), there is a considerable risk that they may encounter difficulties in handling or risk being overturned due to these unexpected, unusually rapid flows.

By using the model shown in Figure 5, it is expected that the water levels and velocities at a given time and location can be predicted, as is also confirmed by the top panel of Figure 7. However, it should be noted that the field survey conducted in this study was carried out in March, which is the typical dry season with very limited rainfall (Mekong River Commission, 2015). The weather in Vietnam is characterized by two monsoon seasons: the southwest monsoon, from April to September, and the northeast monsoon, from October to late March or early April. Southern Vietnam, including the Mekong Delta, experiences the majority of its rainfall between May and October. Therefore, the water levels in March are not significantly influenced by discharge from upstream rivers (Takagi *et al.*, 2014b).

In October 2013, at the end of rainy season, a number of local communities across the delta suffered a historical flood (Viet Nam News, 2013). The bottom panel of Figure 7 shows that the water level rose to approximately 50 cm above the predicted tidal levels, indicating significant pluvial and fluvial influences. Although Delft3D-FLOW is capable of posing river discharge from the upstream boundary in addition to tides, the present simulation was limited to tidal forcing. The reason for this treatment is attributed to the difficulty in estimating tidal damping. It was demonstrated that river flow causes tidal damping and effectively reduces the energy

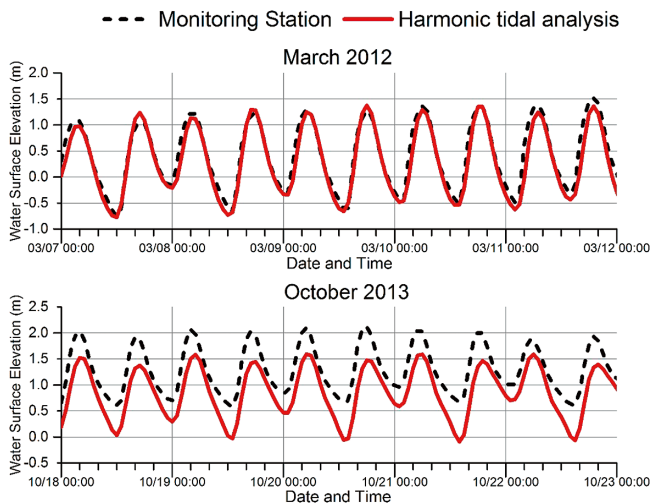


Figure 7. Comparison between water levels: the observation vs. harmonic analysis, with tidal constituents derived from the MRC water levels. Top: dry season, Bottom: rainy season

of the incoming tides. This tidal damping is especially pronounced during the rainy season, when the reduction rate of tidal amplitude can reach up to 67% (Takagi *et al.*, 2014b). Therefore, it should be recognised that the tidal model presented in this paper cannot be used to reproduce such an abnormally high water level induced by high river discharge.

Additionally, water levels in deltas are known to be influenced by storm surge, sea-level rise or ENSO events (Takagi *et al.*, 2012; Nguyen *et al.*, 2014; Esteban *et al.*, 2015). Saline water intrusions further inland are also projected to become more severe due to the impacts of population growth, urbanisation, industrialisation, and the construction of new water-control structures at the upstream sections of the Mekong River (Trung and Tri, 2014). Le *et al.* (2007) also pointed out that the construction of dams will inevitably alter the variability of seasonal flow in the upper Mekong River. Furthermore, local changes, driven by urbanization, could significantly influence the prediction of future flooding in Can Tho. Land subsidence could also worsen flooding; although at present there are no reliable studies on the land subsidence rate in this city (Huong and Pathirana, 2013).

CONCLUSIONS

This study developed an ocean tidal model which is able to forecast water levels and velocities at a given time and location in the urban area of Can Tho City, which is characterized by many tributaries, channels, and low-lying lands. The model accuracy was verified by comparison with water levels during a typical dry season, March, 2012, as measured by the authors. This model could contribute to the understanding of the mechanisms of tidal propagation in complex waterway systems, and thereby be used for identifying potential urban flood risks associated with oceanic tides. The authors pointed out that locally intensified flows could have potentially dangerous consequences, such as difficulties in handling or a risk of overturning of small ships due to the

unexpectedly rapid flows that may occur during abnormally high tides. At this stage, however, the model detailed in this paper can only be applied for simulations during the dry season, as it does not consider abnormal water level rise and tidal damping, both of which are induced by high river discharge during the rainy season. These effects are important to incorporate into the model and thus should be the subject of future research.

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