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The combined impact on the flooding in Vietnam's Mekong River delta of local man-made structures, sea level rise, and dams upstream in the river catchment

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Abstract

The Mekong River delta plays an important role in the Vietnamese economy and it has been severely impacted during this century by a series of unusually large floods. In the dry season the delta is also impacted by salinity intrusion and tides. These effects have caused severe human hardship. To mitigate these impacts, a large number of engineering structures, primarily dykes and weirs, have been built in the delta in recent years and are still being built, mainly to control floods and saltwater intrusion. These control measures are still being upgraded. A GIS-linked numerical model shows that the flood levels in the delta depend on the combined impacts of high river flows in the Mekong River, storm surges, sea level rise, and the likely, future siltation of the Mekong Estuary resulting from the construction of dams in China as well as many other dams proposed throughout the remaining river catchment. The model suggests that the engineering structures in the delta increase the flow velocities in the rivers and canals, increasing bank erosion, and cause the water to be deeper in the rivers and canals. This increases flooding in the non-protected areas of the delta and increases the risk of catastrophic failure of the dykes in the protected areas. The model also predicts that a sea level rise induced by global warming will enhance flooding in the Mekong River delta in Vietnam, and that flooding may worsen in the long term as a result of estuarine siltation resulting from the construction of dams. At the scale of the Mekong River basin, a multinational water resources management plan is needed that includes the hydrological needs of the delta. At the scale of the delta, a compromise is needed between allowing some flooding necessary for agriculture and preventing catastrophic flooding to alleviate human suffering.

Keywords: Mekong River delta; model; flood; storm surge; sea level rise; siltation; dam

1. Introduction

The 4800 km long Mekong River is the longest river in Southeast Asia and it drains an area of 0.795×10^6 km^2 (Gagliano and McIntire, 1968). The river discharge into the Mekong River delta (MRD; Fig. 1a) varies seasonally between typically 2100 m^3 s^{-1} in April (the low-flow season) and 40,000 m^3 s^{-1} in September (the high-flow season; see Fig. 1; Wolanski et al., 1996, 1998). The river discharges annually about 5×10^{11} m^3 of water into the MRD, of which 85% occurs in the wet season and 15% in the dry season. The sediment discharge is about 1.6×10^8 t year^{-1}, i.e. about the same as that of the Mississippi, it is 85% that of the Yangtze River and it is 12% larger than that of the Amazon (Syvitski et al., 2005).

The MRD is located downstream of Kompong Cham, Cambodia, and covers a total area of 4.95×10^4 km^2, about 74%

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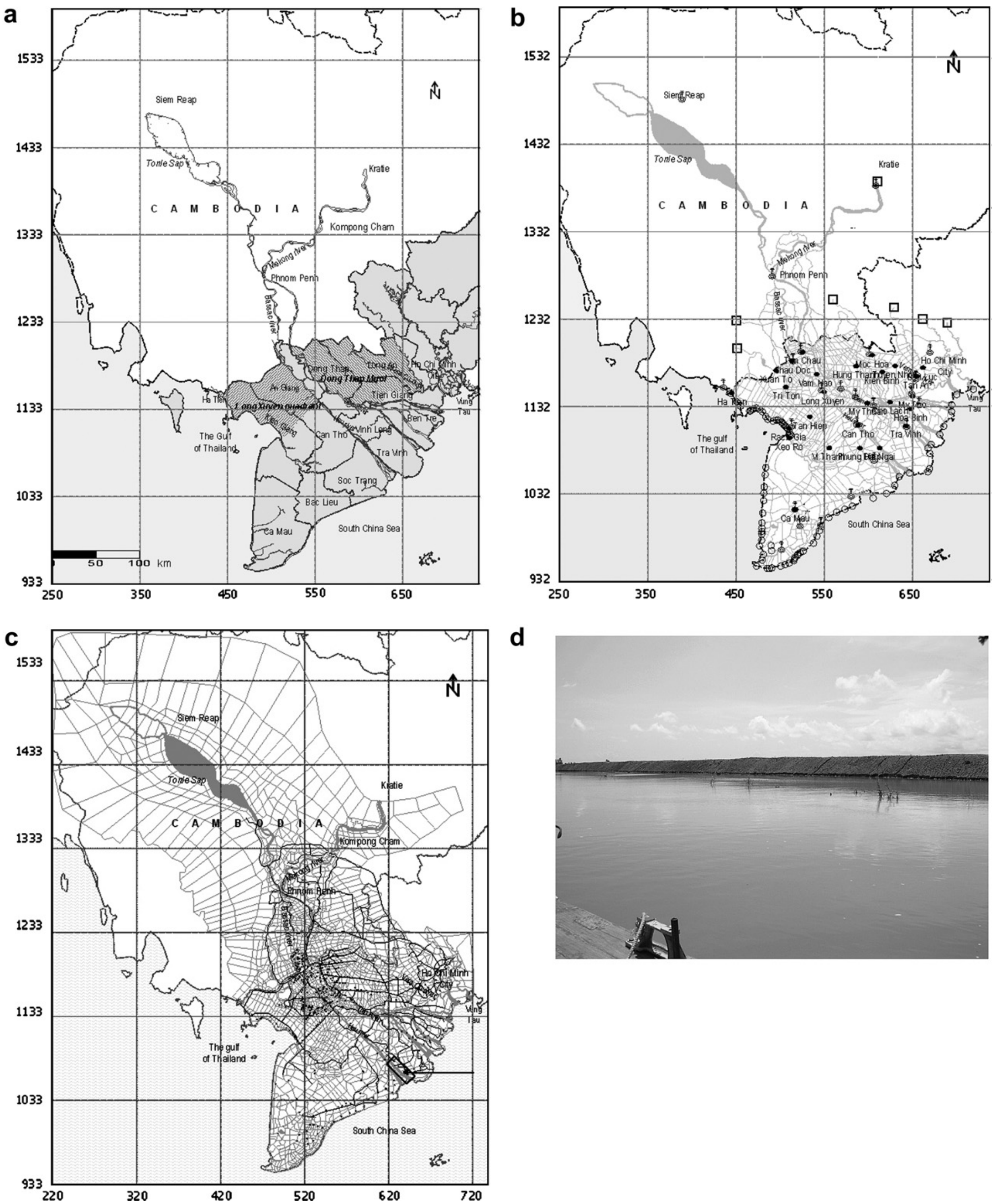

Fig. 1. (a) A location map; (b) the model network grid and the upstream (square) and downstream (open circles) open boundaries, the hydro-meteorological stations (masts) and the gauging sites (filled circles); (c) the thick lines are the present dykes along the main canals. The dykes were constructed before 2000, but several were upgraded after the year 2000 flood. The arrow points to the box outlining the lower Basaac River estuary; (d) a photograph of the dyke along the Cai Co canal.

of which is located in Vietnam. Vietnam's MRD is a flat and low-lying area with very complex network of rivers, channels and flood plains (Fig. 1). The climate is tropical monsoonal with the wet season from May to October and the dry season from November to April. This region is affected by two tidal sources, regular, 3.5 m semidiurnal tides from the South China Sea and irregular, 0.8–1 m diurnal tides from the Gulf of Thailand. About 12×10^6 people live in the MRD in Vietnam. They suffer from storm surges following typhoons, flooding in the wet season, saltwater intrusion in the dry season, and coastal erosion. Three big floods occurred in successive years in 2000, 20001 and 2002, and caused severe human suffering.

Based on the available flood data that span from 1926 to 2004, the year 2000 flood had a 20-year return period. The storm surge of Typhoon Linda in 1997 with a wind force of 11 on the WMO scale occurred at high tide, caused the water levels in the estuaries in Vietnam's MRD to be the highest for the previous 20 years, killed and missing nearly 4000 people according to the statistics of the Central Committee for Flood and Storm Control, and caused massive destruction of natural and man-made resources.

In Vietnam's MRD, there are more than 1000 man-made canals. Recently, massive engineering structures have been constructed in Vietnam's MRD (Fig. 1b) for transport, salinity protection, land reclamation and urbanization, and storm protection. These structures include roads and dykes against flooding, weirs to mitigate salinity intrusion, sewers that affect water quality, and embankments and landfills for urbanization. All these structures affect the flow field.

Vietnam's MRD may be further affected if sea level rises due to global warming.

The desire for hydropower led China to construct the Manwan hydroelectric dam on the main river in 1994 and Thailand to build the Pak Mun dam on the Mun River, a tributary of the Mekong. Dam construction is now accelerating. China is presently building a cascade of eight dams on the Mekong River and these dams will essentially destroy the seasonal flow variability in the upper Mekong River. There have been no published studies that we could find of the resulting environmental and socio-economic impact in Vietnam's MRD. This potential problem is further aggravated by a further 100 hydroelectric dams and water diversion schemes planned for construction upstream of Vietnam (Wolanski and Nguyen, 2005).

An integrated water management plan for the entire Mekong River is needed. In the interim, we used a numerical model to predict the flood heights and duration in the MRD caused by combined impact of upstream flows, tides, storm surge, engineering structures, sea level rise, and estuarine siltation. The modeling tool combines numerical modeling, GIS, and statistical analysis. The model suggests that the engineering structures increase the flow in the river and canals, thereby increasing bank erosion. The model also predicts that sea level rise induced by global warming will significantly enhance flooding in Vietnam's MRD. It also suggests that the damming of the Mekong River upstream of Vietnam's MRD will initially reduce flooding in the MRD because river flood peaks are decreased. However, possibly in as little as 30 years it will increase flooding to well above present levels, as a result in siltation of the Mekong Estuary Together with occasional typhoon-driven storm surges, the model suggests that all these effects will compound to increase flooding and human suffering.

2. Methods

The hydraulic model HydroGis developed at the Ministry of Natural Resource and Environment of Vietnam was used. This model couples a numerical free-surface flow model and GIS tools (Nguyen et al., 2000, 2002, Nguyen and Tran, 2003; Le et al., 2005). The hydrodynamic model includes a 1-D model with the fully non-linear Saint-Venant equations for river flows, a 2-D model without inertial terms in the momentum equations for floodplain cells, and the infrastructures are modeled with the energy equations for weir flows. The grid is shown in Fig. 1. The model runs with a time step of 15 min.

The bathymetric data were digitized from hydrometric readings. Details of the man-made structures (dykes and canals) were provided by the Vietnamese Ministry of Transportation's inland waterway administration for the year 2000. After the year 2000 flood, many embankments (dykes) were raised and constructed along stretches of many rivers and canals in Vietnam's MRD. These data were incorporated in a new topography file for the year 2002. The elevation data for the floodplain cell network are based on a digital elevation model with a resolution of 100×100 m provided by the Mekong River Commission. The embankment elevation data were made available by the Southern Institute of Hydraulic Science. Hourly water level data were obtained from the Hydro-meteorological Service of Vietnam. Information about changes in dykes and embankment elevations was obtained from local governments.

The topographical, daily rainfall and three-hourly meteorological data, including information on flood control structures, were separately updated for the floods of 2000, 2001 and 2002.

The model includes 2535 flood cells, 13,262 cross sections, and 467 sewers, bridges, and sluices. There are 82 downstream boundaries, shown in Fig. 1b and located at the mouth of estuaries, for which hourly water level data were used. These data were tidal elevation predicted from tidal harmonic analyses in the absence of a typhoon, or combined tides and storm surge elevations predicted from a separate coastal oceanography model of the South China Sea in the presence of a typhoon. Seven daily upstream discharge boundaries were used and are shown in Fig. 1b.

A satellite image was provided by the Remote Sensing and GIS Division of the Physical Institute of Vietnam, of the spatial distribution of the flood in October 2000.

The siltation of the Basaac River, which is the main estuary of the MRD, resulting from decreased river flood peaks and increased tidal pumping as a result of construction of dams was predicted using the tidal pumping model of Wolanski et al. (2001) calibrated against the Mekong Estuary tidal, currents and sediment dynamics data of Wolanski et al. (1998).

3. Results

3.1. Model verification

The observed and predicted time series of water level for the year 2000 flood at stations located along the main channels as well as in the delta itself in the Dong Thap Muoi and Long Xuyen quadrants, show good agreement (Fig. 2). A similar good agreement was found for the years 2001 and 2002 floods (not shown).

A good agreement also exists between the observed and predicted spatial distribution of the flood wave in October 2000 (Fig. 3).

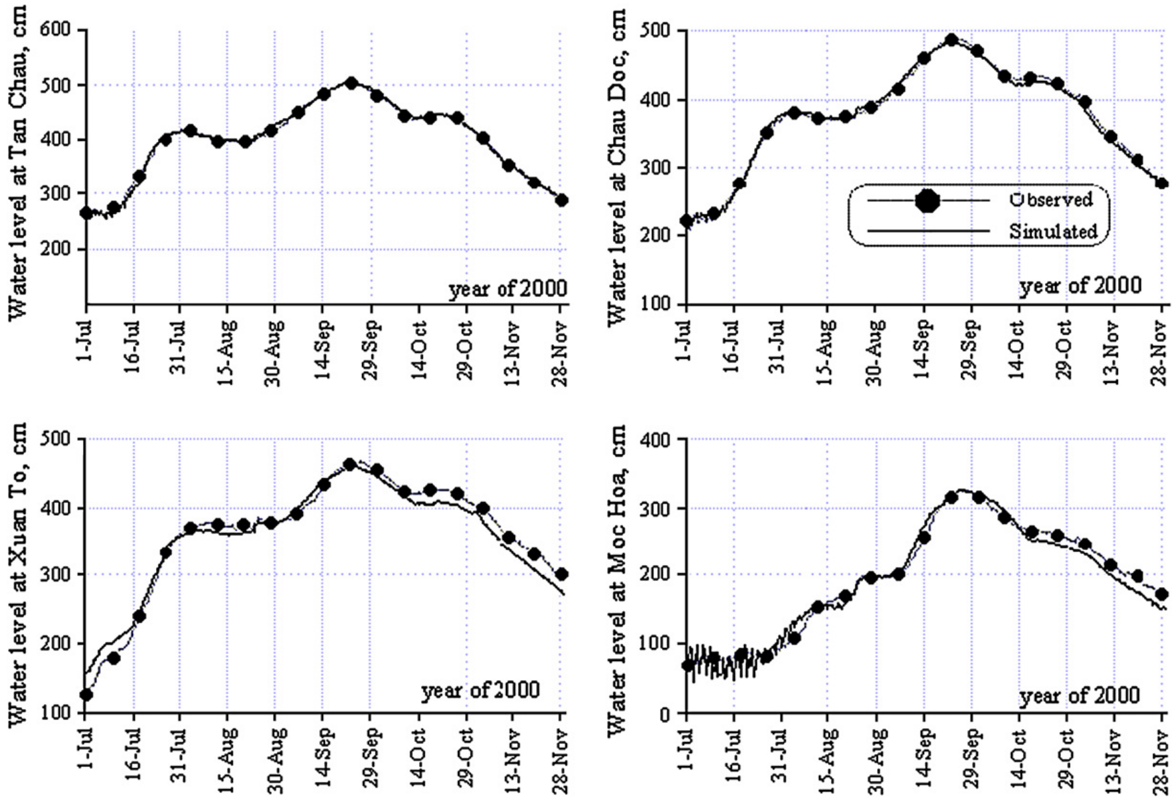

Fig. 2. Time series of observed and predicted water level at various locations in Vietnam Mekong River delta in 2000.

3.2. Model results

The year 2000 flood has a return period of 20 years. The model results for the year 2000 flood, using the year 2000 topography, are called scenario 1 and are used to test the response of the flood waves to five scenarios listed in Table 1. Scenario 2 corresponds to the year 2000 flood with the new topography corresponding of 2002 that includes the many embankments built in the period 2000–2002. Scenario 3 corresponds to scenario 2 where the topography is further

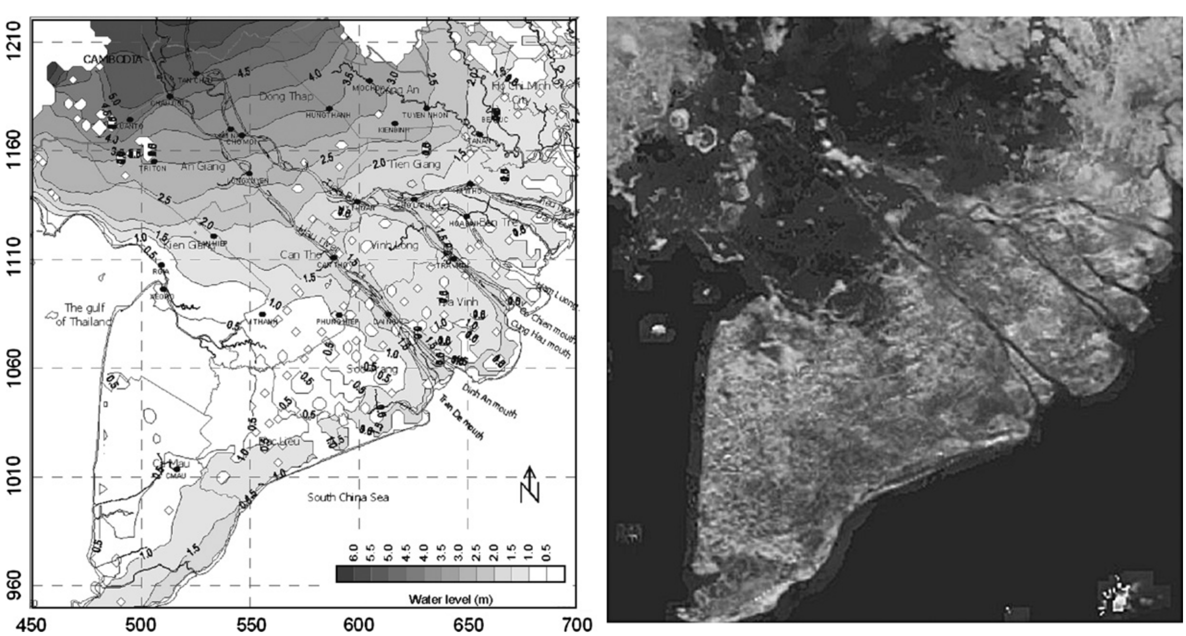

Fig. 3. (Left) Spatial distribution of water levels in October 2000 for the year 2000 topography (scenario 1) and (right) a simultaneous satellite view of the Mekong River delta showing the inundated areas.

Table 1
Description of model scenarios

Scenario No.	Description
1	Year 2000 topography + year 2000 flood
2	Year 2002 topography + year 2000 flood
3	Planned year 2010 topography + year 2000 flood
4	Scenario 3 + typhoon Linda
5	Scenario 4 + 0.5 m sea level rise

modified by the planned embankments to be built over the next 5 years (i.e. for the year 2010 topography). Scenario 4 corresponds to typhoon Linda occurring during the 2000 flood for the year 2010 topography. The typhoon is assumed to occur at the end of September when flooding in Vietnam's MRD is at its peak. Scenario 5 corresponds to scenario 4 for the year 2010 topography and a sea level rise of 0.5 m. This estimate by Titus and Narayanan (1995) is in the upper quartet of the IPCC (2001) predictions for the next 100 years.

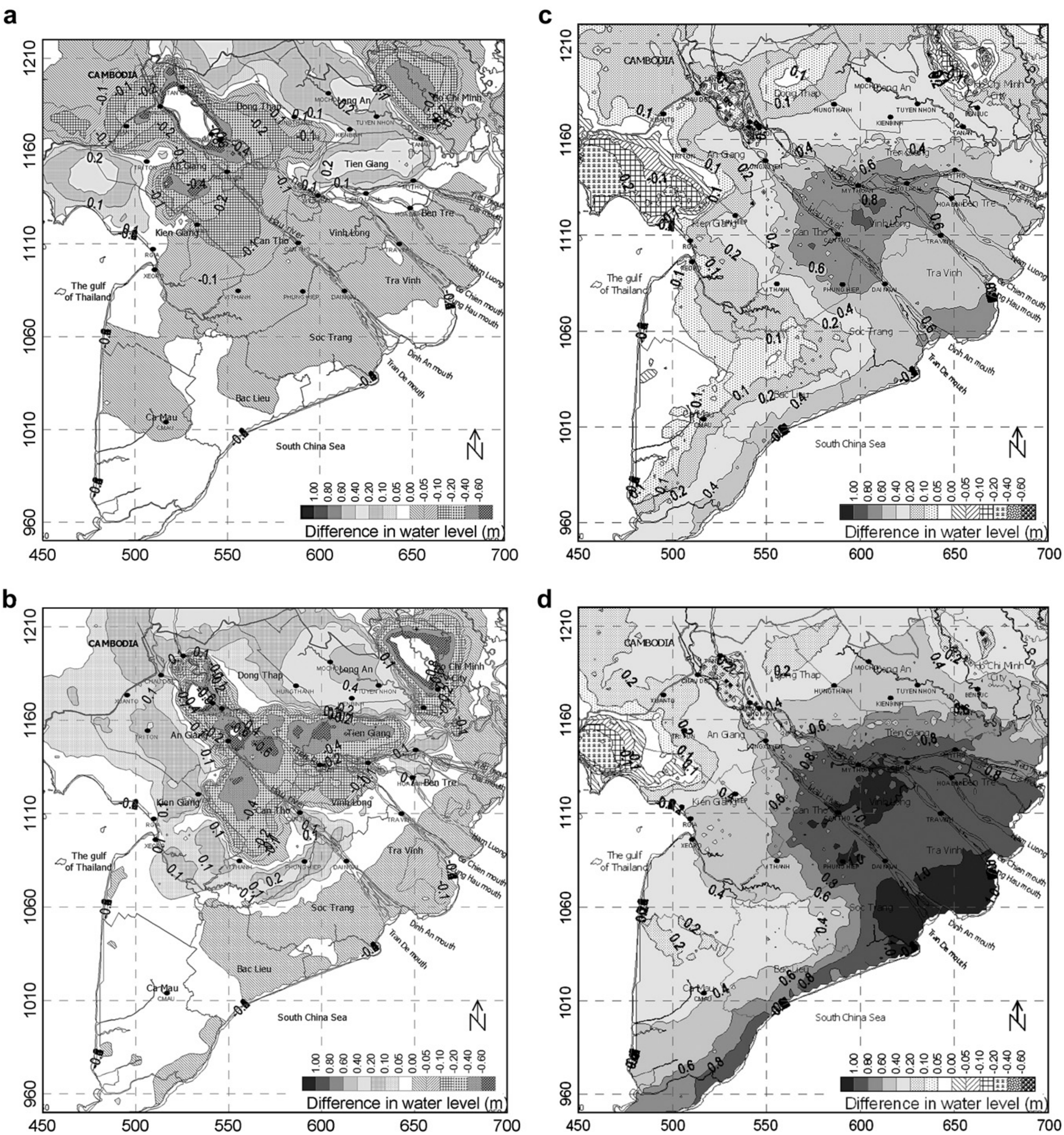

Fig. 4. Changes in water levels (>0 if flood levels increase) between scenario 1 and (a) scenario 2; (b) scenario 3; (c) scenario 4; and (d) scenario 5.

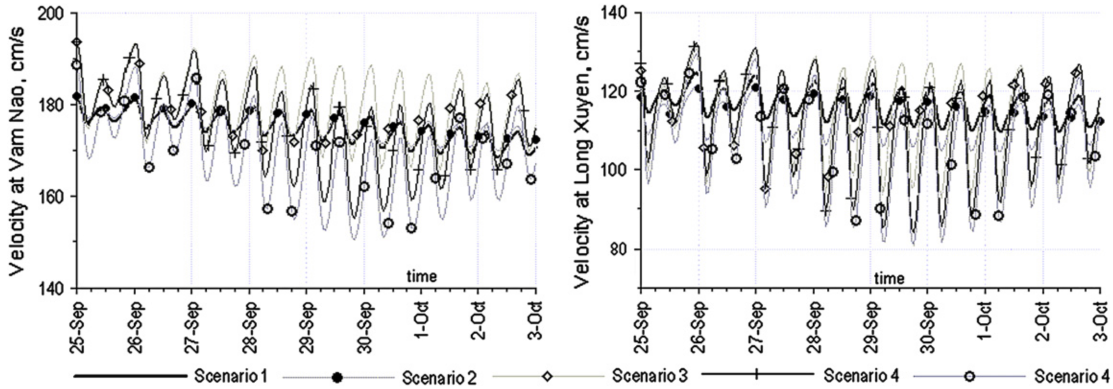

Fig. 5. Time series plot of the maximum velocities at two river sites in the Mekong River delta for the five scenarios.

For scenario 2 (Fig. 4a) the predicted water levels in the rivers and canals increase by about 5–20 cm, at some points up to 50 cm, in the northeastern and westernmost MRD, i.e. in the Long An province, downstream of Dong Thap Muoi toward the Vam Co River. In the region between two Mekong tributaries, southwestern Dong Thap and southeastern An Giang and northeastern Kien Giang provinces, where the embankments were raised to protect crops, the predicted water levels decrease by up to 20 cm. This is due to these embankments causing the flood wave to be directed towards the northeastern and westernmost MRD. In that region the predicted duration of the flood increases from about 5 days to 10 days, while elsewhere the flood duration remains at about 5 days. Predicted peak water speeds in the estuary increase only slightly compared to that in scenario 1 (Fig. 5).

In scenario 3 (Fig. 4b) the predicted flood wave is steered towards the north near the border, delaying the propagation of the flood wave in the MRD. Especially downstream Dong Thap Muoi toward Vam Co River, and in the Long An province, the predicted peak flood level increases by about 20–40 cm. The flooding duration is predicted to decrease in the fully flood protected area between the two Mekong tributaries, especially in the Tien Giang, Vinh Long, Can Tho and Kien Giang provinces it decreases to about 5–10 days, while it remains largely unchanged at about 5 days elsewhere. Because of the high embankments, the predicted tidal effect propagates further inland and the peak flow velocities increase throughout the river. For example, the peak velocity in the Vam Nao River that connects two Mekong tributaries increases by 0.2–0.25 m s^{-1} (Fig. 5). This enhances the risk of erosion and ultimately may lead to the failure of the high embankments.

In scenario 4 (Fig. 4c) the area inundated by 0.6 to 0.8 m covers a wide area along the coast and along all the MRD estuaries as far as 70 km inland. The storm surge introduces backwater effects that reduce peak velocities in the coastal rivers and up to 200 km inland (Fig. 5). The area inundated to a depth larger than 2.5 m increases by 700 km^2 to reach 3200 km^2.

In scenario 5 (Fig. 4d) a significant increase in maximum water level of about 1 to 2 m is found in coastal areas. All the provinces along the Mekong tributary estuaries as far as 85 km inland would be submerged to about 0.6 to 0.8 m. The water level in the Bassac River at Can Tho would increase by about 1 m while the backwater effect of sea level rise on the flood wave is predicted to be felt over half of Vietnam's MRD. The area inundated to depths of at least 2.5 m would reach 4300 km^2.

Construction of the dams on the Mekong River upstream of Vietnam is predicted to silt the Basaac River estuary. In particular between Can Tho and the mouth the thalweg width is

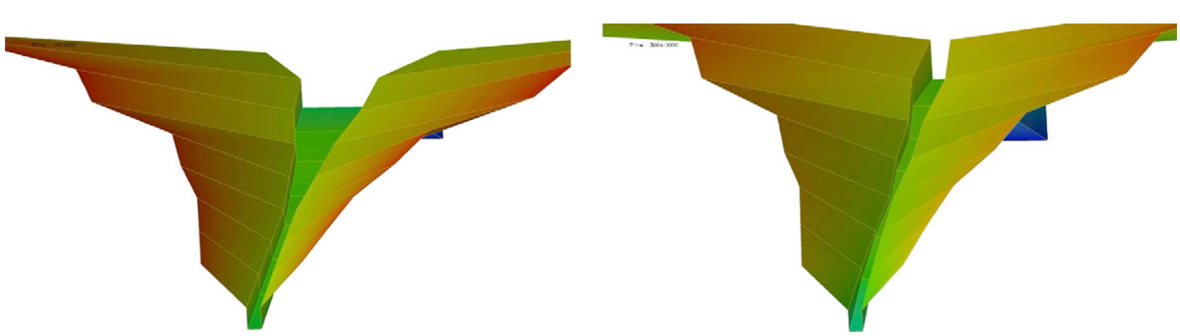

Fig. 6. Three-dimensional rendering of the bathymetry of the lower 35 km of the Basaac River estuary (see a location map in Fig. 1c). The view is from upstream looking towards the mouth at (left) time 0 (present bathymetry) and (right) 32 years following construction of the proposed dams in the Mekong River upstream of Vietnam. The maximum width is at the mouth and is about 18 km. The maximum depth at time 0 is located at the upstream boundary and is 4 m. The channel has a thalweg fringed by shallower areas. The two views are shown on the same datum; the model predicts that after about 30 years siltation will halve the width of the thalweg and raise the river bed by about 2 m.

predicted to halve in about 30 years and the channel bed to rise by about 2 m (Fig. 6). This siltation will further raise peak flood levels locally in the MRD by up to 2 m and this effect will be felt further upstream in the MRD as a result of backwater effects.

4. Discussion

Under scenarios 2–5, the predicted maximum elevation for the year 2000 flood would increase in the Mekong River delta (MRD). The model suggests that the structures constructed after the year 2000 flood decrease inundation in those regions where the embankments are raised, and cause the flood wave to propagate to other regions where flooding is worsened in peak flood height and duration. The future flood control works planned to be completed by 2010 will cause an increase in runoff peaks and prolong the duration of the flood recession. To decrease the risk of catastrophic dyke failure, conduits and ditches are necessary to lessen waterlogging in flood plains protected by high embankments.

The combined impact of storm surges and of a sea level rise may increase the area inundated to a depth of 2.5 m for the 20-year flood to 4300 km^2 for the worst-case scenario (scenario 5).

While comprehensive flood control measures will reduce flooding, the high embankments will be more prone to catastrophic failures that are made more likely by increased flow speeds in the rivers as a result of these embankments. Also, the high embankments obstruct the fine-sediment flow into agricultural lands. Historically these sediments deposited in, and enriched, agricultural land; this soil fertilization will stop. Further, the lack of flooding of agricultural lands will mean that acidic waters in these former mangrove soils will not be washed out at the beginning of the flood season. This may lead to soil acidification and the loss of crops (Pho and Tuan, 1995). To maintain the soils for agriculture requires flooding 3×10^4 km^2 of farmed land to a depth of about 20 cm; this uses about 6×10^9 m^3 of water, i.e. about 1.5% of the Mekong River discharge in the wet season. At the very least, conduits and ditches are necessary to mitigate these problems and to lessen water-logging in the high embankments.

Thus overall the flood control structures may alleviate human suffering in the MRD. There are however increased risk of flooding from storm surges as well as catastrophes as a result of failure of dykes. Environmental degradation may result with possible huge socio-economic consequences particularly if agricultural productivity is decreased by flood prevention generating acidification of farmed, former mangrove soils in the delta and preventing the annual fertilization of agricultural land by riverine fine sediment (Pho and Tuan, 1995).

As in numerous other cases worldwide (see a review in Syvitski et al., 2005), extensive estuarine siltation and increased flooding, together with increased coastal erosion and the loss of coastal wetlands, are likely to occur in Vietnam's MRD if the riverine sediment inflow to the sea is decreased by the construction of dams upstream in the Mekong River catchment.

Detailed studies of the Mekong River delta are needed in order to provide the science needed to develop an integrated land and water management plan. The successful management of the Mekong River delta requires an ecohydrology-based, basin-wide, transboundary approach. At the basin scale, a Mekong water resources management plan is needed that includes the hydrological needs of the delta. At the delta scale, a compromise is needed between allowing some flooding for agriculture and preventing catastrophic flooding to alleviate human suffering.

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