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A study of the climate change impacts on fluvial flood propagation in the Vietnamese Mekong Delta

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Abstract

The present paper investigated what would be the flood propagation in the Vietnamese Mekong Delta (VMD), due to different projected climate change scenarios, if the 2000 flood event (the most recent highest flood in the history) was taken as a base for computation. The analysis herein was done to demonstrate the particular complexity of the flood dynamics. The future floods, on short term horizon, year 2050, were studied by considering the projected sea level rise (SLR) (+30 cm). At the same time, future flood hydrograph changes at Kratie, Cambodia were applied for the upstream boundary condition. In this study, the future flood hydrograph was separated into two scenarios in which: (i) Scenario 1 was projected in 2050 according to the adjusted regional climate model without any development in the Upper Mekong Basin; and, (ii) Scenario 2 was projected as in Scenario 1 but with the development of the Upper Mekong Basin after 2030. Analyses were done to identify the high sensitive areas in terms of flood conditions (i.e. with and without flood) according to the uncertainty of the projection of both the upstream and downstream boundary conditions. In addition, due to the rice-dominated culture in the VMD, possible impacts of flood on the rice-based farming systems were analysed.

1 Introduction

Climate change is an on-going and progressive process with notable impacts on the eco-hydrological environment (Black and Burns, 2002; Gupta et al., 2002; Prudhomme et al., 2003) leading to significant challenges to livelihood of local residents in different parts of the world (Lespinas et al., 2010; Muste et al., 2010; Quinn et al., 2010). Vietnam is projected to be one of the most vulnerable countries to global climate change and the Vietnamese Mekong Delta (VMD) (Fig. 1) is identified as particularly susceptible to the impacts of extreme climate events and climate variability (ADB, 2009; WWF, 2009). Possible changes of the hydrological conditions, (including: spatial and temporal distribution of floods, modification of wet and dry season precipitation and alteration of salinity intrusion pattern) as a consequence of the global climate change may present significant threats to the socio-economic and environmental systems (Quinn et al., 2010).

Hoanh et al. (2010) conducted a study to explore the possible impacts of climate change and development on the Mekong flow regimes. These authors concluded that there could be an increased possibility for flooding during wet season versus an expansion of water shortage in the dry season. It was projected that the maximum monthly flow will increase by about 35 to 41 % in the Mekong Basin and by 16 to 19 % in the delta, with lower and higher value estimated for the years 2010 to 2038 and 2070 to 2099, accordingly (Hoanh et al., 2010; Vastila et al., 2010); in contrast, the minimum monthly flows were estimated to decline by 17 to 24 % and 26 to 29 % in the basin and the delta, respectively (Hoanh et al., 2010). As a consequence, expansion of areas under severe water stress (flood and drought) would be one of the most pressing environmental problems in the area in the future as the number of people living under severe water stress would be likely to increase substantially in absolute terms. In the VMD, the future sea level rise might result in a large inundated area (mainly along the east and west coast; Fig. 1) (WWF, 2009) leading to the significant lost of mangrove forest and agricultural lands while the livelihoods of about 1.9 million local residents would be at risk and extended from 2000 to 2050 (Ericson et al., 2006).

Previous studies predicted that the modification of the water balance within the basin and sea level would result in great alteration of the eco-hydrological environment (Lu and Siew, 2005) and consequently adverse impacts on the socio-economic system would be felt in the VMD. In fact, the modification of the upstream discharge would be the main concern in the upstream section (Vastila et al., 2010; Dinh et al., 2012) while the rise of sea level resulting in wider (temporal) inundation along the coast was considered to be more important in the downstream section (Carew-Reid, 2008). Apart from the significant changes on the livelihood of the local residents (Nuorteva et al.,

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2010), the sea level rise would contribute to changes of the hydraulic nature along the river network (Dooge and Napiorkowski, 1987).

Different studies were done to project impacts of upstream discharge and sea level rise on the VMD with specific attention to the inundation in the upstream section of the VMD (e.g., Wassmann et al., 2004; Le et al., 2007, 2008; Dinh et al., 2012). It was found that the impacts of projected climate change would be an expansion of the inundation area, e.g. the flood contour lines, would be shifted towards the sea (Wassmann et al., 2004; Dinh et al., 2012), and the average and maximum water levels and flood duration increase in 2010–2049 (Vastila et al., 2010). However, these studies did not consider the short duration floods in the coastal area in the downstream section of the VMD. The mentioned studies left, however, a number of issues open, such as future changes in the upstream flows and the combined impacts of sea level change and upstream flows were not fully considered, and most importantly the detailed analysis of the inundation modelling and its impacts on the lower delta (coastal) zones were not conducted (Dinh et al., 2012).

The study presented herein aims therefore at addressing the following: (i) investigation of temporal and spatial dynamics of the fluvial flooding in the whole VMD (using a catastrophic flood of 2000 as an example); (ii) investigation of climate change impacts on flood dynamics and inundation extent taking into account changes in upstream flow as well as sea level rise; (iii) Sensitivity analysis of the flood model outputs to climate change characterization (model boundary conditions). More detailed uncertainty analysis of inundation model has been undertaken as well but will be reported in another paper.

It should be noted that in this study the focus is on fluvial floods only. Pluvial floods occur as well but local effects that are much less significance than the fluvial ones.

The paper is arranged as follows: brief characterization of the VMD is provided, followed by descriptions of methodology, set up of experiments, discussions and results; finally, conclusions are drawn and recommendations for further works are given.

1.1 The study area

According to the Mekong River Commission (MRC) (MRC, 2005), the Mekong Delta begins at Phnom Penh, Cambodia, where the river divides into two main branches, the Mekong and the Bassac (Fig. 1). In Vietnam, the Mekong Delta is generally lower than 5 m with reference to the mean sea level and the complex channel network had been modified over a long history for agricultural (i.e. irrigation and drainage systems) and residential purposes.

In the VMD, The Mekong River was characterized by fluvial-unstable network (Reichel and Nachtnebel, 1994; Neuhold et al., 2009; MRC, 2010a) and the hydraulic nature of river network is highly complex (Nguyen et al., 2006) and is impacted by both the upstream discharge and sea level along the East (semidiurnal tides) and West (diurnal tides) Sea (Nguyen and Savenije, 2006) (Fig. 2a, b). The tidal amplitude from the East Sea is between 3.0 and 3.5 m, resulting in typical measured stage differences during the dry season in a day at Can Tho (90 km from the sea) of about 1.5 to 2.0 m and at Tan Chau and Chau Doc (190 km from the coast) of about 1.0 m. Figure 2c presents the measured maximum daily discharge in 2000 at the two main upstream gauging stations in the VMD (Tan Chau and Chau Doc); in fact, discharge entering the VMD was routed mainly along Tan Chau and then along the Vam Nao canal, discharge was redistributed by routing water from the Mekong to Bassac. In general, the flood hydrology in the VMD is typically classified as relatively low peak with a high volume, the main reason being the effect of the Tonle Sap Lakethat reduces the intensity of the flood hydrograph and distributes the discharge over a longer period (MRC, 2005). The most recent severe floods were about several months of duration with discharges above critical threshold (A), causing bank and levee erosion and, consequently, infrastructure damage.

An important element in conducting a good study based on a flood modelling for the VMD and its vulnerability to floods (Delgado et al., 2010; Dinh et al., 2012), consists of the effects in the economies that are in relation to the land use og the agro-ecological zones that were derived from a land use map of the year 2006 (Fig. 3). Rice-based farming systems dominated and could be found in different parts of the VMD. Fruit gardens were mainly along the Mekong and to some extended along the Bassac. In the Ca Mau Peninsula, the main land cover types were single rice crop, double-crop of single rice crop in combination with a single upland crop and intensive shrimp farming. The land cover pattern in 2006 was used as a reference for further discussion about the impacts of future flooding on the agriculture in the VMD, and it could be stated that the analysis of flood inundation dynamics in this area is of the upmost importance (Dinh et al., 2012).

According to the Research Institute for Climate Change (RICC) of Can Tho University (2009), the rice field with inundated level of 20 cm for 1 to 4 days continuously at the second half of the rice season would be seriously damaged (loss 80–100 % of yield); in this study, one day of continuous inundation was selected to project the areas where the rice farm could be endangered. However, the farmer could make temporary dikes (of about 20 cm height relatively to the field surface) to cope with the flood. If the stage went beyond 50 cm (above land surface), farmers could not make sufficient dykes to protect the rice field and hence the analyses were done to identify the areas which were harmed seriously by large floods. For the early stage of the rice season, even though the rice could stay for a longer inundated period (from 1 to 14 days) (DRAGON, Can Tho University, 2009), the continuous flood would delay the land preparation process; therefore, a single day of continuous inundation was assumed to cause delay for the coming season.

2 Model set up and data availability

In this study, we used the available ISIS model of the whole VMD developed by HR Wallingford and Halcrow, which is currently maintained by the Mekong River Commission (MRC, 2005). It includes 5002 nodes with 14 rainfall gauges; 25 upstream boundaries; 19 downstream boundaries; 3036 cross-sections; 193 spills; 528 junctions; 409 reservoirs; 749 floodplain units; and, 29 sluices. This model was applied to study the annual flood in the VMD. The model included also the Cambodian part of the Mekong Delta because of the complexity of the whole river network. In fact, during the peak flood period, apart from the flows entering the VMD from the main rivers (through Tan Chau and Chau Doc), the over-bank flows were especially an important source of inflows in the upstream sections of the VMD (Fujii et al., 2003; MRC, 2005). The ISIS model was developed to represent the complex interactions caused by tidal influences (along the East and West Sea), flow reversal in the Tonle Sap River and over-bank flow in the flood season with the varying inflows from upstream. Even though the ISIS model was considered to be able to provide a reasonable representation of the hydrodynamics of the Cambodian floodplain and VMD, MRC suggests that the model should not be used for design purposes (MRC, 2010b), but rather to estimate the trend of changes when the boundary conditions were modified.

The model was first set up to simulate the flood of 2000 (the 20-yr return period of the annual flood volumes; MRC, 2007), which had a big impact on the people in the VMD. The measured daily discharge at the Kratie gauging station was used as the upstream boundary condition. The downstream conditions were the hourly measured sea level along the East and West Sea.

For the simulation of future floods, the MRC's scenario of upstream discharge for 2050 and the projected sea level rise of up to 30 cm with reference to that in 2000 (Scenario B2) (MoNRE, 2009) had been used. Two scenarios were considered (Fig. 2d) (Hoanh et al., 2009). In Scenario 1, discharge was projected according to the adjusted regional climate model without any development in the Upper Mekong Basin, and in Scenario 2, discharge was projected as in Scenario 1 but with the development of the Upper Mekong Basin after 2030. In general, during the flood period, the projected discharge in Scenario 1 was greater than that in Scenario 2, which means that with future development in the upstream, less water would arrive in the VMD. The baseline for the climate change projection was the daily discharge from 1985 to 2000 (Hoanh et al., 2010). Analysis of available data allowed us to conclude that, in comparison to the historical mean daily discharge (1985–2000), the projected flood in 2050 would start and terminate later. With reference to the flood discharge (QKratie = 13 600 $m^3 s^{-1}$; MRC, 2007), the flood in 2050 would start between seven and fourteen days later for the Scenario 1 and 2, respectively and end about fourteen days late. In general, the projected daily discharge during the flood period in Scenario 1 would remain similar to the historical mean daily discharge while the projected discharge in Scenario 2 would be lower than the historical mean discharge (due to greater projected water demand in the future in the upstream Lower Mekong Basin). Different combinations of boundary conditions (upstream discharge and sea level) applied are presented in Table 1.

The sensitivity analysis was done with the modifications of the boundary conditions (i.e. ±30 % and ±15 % of the projected sea level in 2050 and between upstream discharges projected according to Scenario 1 and 2) to identify the sensitive areas in accordance with the changes of either the upstream or downstream boundary condition. For the changes of upstream conditions, inundated areas with the appearance (or not) of flood with stage of 20 cm were illustrated. For the changes of downstream conditions, analysis was done to identify the areas where the inundated condition was modified i.e. to identify the area turned from permanent dry condition on a selected date in 2000 to either partly or full inundated in 2050.

3 Modelling results

3.1 Model run no. 1: flooding of 2000

As a baseline case, the catastrophic flood of 2000 was simulated. The resulting flood maps are presented in Figs. 5 and 6. To understand the temporal distribution of the flood in the VMD, spatial distribution of the flood on four different days were analysed. The first selected day (4 July) was the early flood season when the flood started causing damage on rice farming systems. The second one (31 August) was the end of August when the rice crop was generally harvested. The third one was at the recorded peak of the flood (23 September) in 2000 (in Tan Chau). Finally, the fourth one was 1

November when the following rice season was coming. For each selected date, analyses were done to present the flood extent over both the upstream and downstream section (i.e. coastal areas) of the VMD.

3.1.1 Comparison to the results of other studies

Figure 4 presents the maximum measured and simulated stages for a day during the flood period at different gauging stations (Tan Chau, Chau Doc, Vam Nao, My Thuan and Can Tho) in the VMD. In general, the applied model overestimated the stage at all gauging stations. The maximum difference between the measured and simulated stage was 0.8, 0.5, 0.6, 0.5 and 0.6 m at Tan Chau, Chau Doc, Vam Nao, My Thuan and Can Tho, respectively. The observed model errors are comparable to those observed in other studies: 0.3 m (Le et al., 2008); 1.1 m (Vastila et al., 2010); and, 0.2 m (Dung et al., 2011) and within the limit of errors for hydraulic models, in case of severe floods (Hartanto et al., 2011; Gichamo et al., 2012; Quinn et al., 2010).

3.1.2 Flooding in the upstream section

Spatial distribution of the flood in the upstream section on 4 July, 30 August, 23 September and 1 November in 2000 are presented on Fig. 5, with the simulated stages higher than 20 and 50 cm shown. The flood extent became greater with the increase of the upstream discharge (from 4 July to 30 August and 23 September). Even though upstream discharge on 23 September was greater than that on 1 November, the flood extent on the later was greater than the earlier. It could be explained by backwater impacts (the higher sea level in the East Sea on the 1 November than that on 23 September; Fig. 2a, b). In addition, even though the high peaks in the East Sea were higher than those in the West Sea, the low peaks in the East Sea were also lower than those that in the West Sea. Therefore, the East Sea tidal regime could be considered as the main driving force for the flood dynamics (both in terms of spatial and temporal distribution) in the VMD.

3.1.3 Flooding in the coastal area

In this study, the area was considered inundated if the simulated stage was higher than the land surface of 20 cm. Figure 6 presents the inundated period (in hours) on the four different dates. One can say that the further inland, the longer inundation and the greater the upstream discharge, the further the flood extends towards the East Sea.

3.2 Model run no. 2: projected flooding

Figure 7 presents the differences between the inundated period (in hours) between the simulated flood in 2000 and the projected flood with the upstream discharge of the year 2000, measured at Kratie and sea level rise of +30 cm; the negative values illustrate longer flood in 2050 versus 2000. Actually, the upstream section of the VMD received minor impacts in comparison to the downstream section. Thus, the inundation period in the Ca Mau Peninsula (with influences of both the East and West Sea) were significantly prolonged. In addition, the flood duration in the area along the West Sea without any impact from the East Sea was slightly changed as the main river (i.e. the Mekong and Bassac) routed discharge from inland to the East Sea. Furthermore, the flood duration in the area along the East Sea without any impact from the West Sea (the coastal area) were changed but with smaller magnitude in comparison to that of the Ca Mau Peninsula.

3.3 Model run no. 3: projected flooding

3.3.1 Flooding in the upstream section

Figures 8 and 9 present the flood in the upstream section of the VMD on the same dates as for the year 2000, using as the simulated stage of 20 and 50 cm above the land surface according to the climate change Scenario 1 and 2, respectively. Similar to the simulated results of the flood extent in 2000, the flood extent in 2050 would increase on the considered four dates ranging from July to November. Apart from the backwater effects like it is the case in the year 2000, another discovered effect was that the upstream hydrograph changed its pattern (the later peak shifted towards the end of October, Fig. 2d). In comparison to the simulated results in 2000, the inundated area in 2050 would extend further to the East Sea with the increase of sea level.

3.3.2 Flooding in the coastal area

Figures 10 to 13 present the flood (again, only flood depths greater than 20 cm are shown) in the coastal area in the VMD according to the two scenarios of future climate change. It can be seen that the changes of the future upstream discharge according to the CC Scenario 1 and 2 did not give significant influence on flooding in the coastal area, which would be mainly driven by the sea level along the East and West Sea. In comparison to the flood in 2000, the flood near in the coastal area would be greater in 2050 as the results of the sea level rise; however, further inland, the inundated area in 2050 would be smaller than that in 2000 as the upstream discharge in 2050 would be lower than that in 2000 (Figs. 8 and 9). In comparison to the flood in 2000, the flood in 2050 extended further to the East Sea due to the projected rise of sea level.

The flood was found to be extended longer along the coast but shorter in the upstream section of the VMD (Fig. 14; in which the negative and positive values represent the longer and shorter flood duration in the future, respectively). In both two climate change scenarios, the flood in the Ca Mau Peninsula would be prolonged while the inundation period in the upper part of the VMD would be shorter. In addition, along the coastal area the inundation period would be greater than that in 2000 but with smaller magnitude in comparison to that of the Ca Mau Peninsula. Figure 15 presents the differences between the simulated flood duration in 2050 according to the climate change Scenarios 1 and 2; the positive value represents the longer flood duration in Scenario 1 in comparison to Scenario 2. Without development in the upstream section of the Mekong (after 2030), the inundated period over the whole VMD could be extended from one day to about a month in total in which the majority of increase would be around four days.

The distinction between the floods in the upstream section simulated according to the different projected discharges at Kratie followed the climate change Scenario 1 and 2 are presented in Fig. 16. The analyses were done with the inundated depth of more than 50 cm meaning that only high damages to agriculture are considered. The common flooded areas according to the two scenarios are shown in red; the areas with flood in Scenario 1 but not in Scenario 2 are shown in yellow, and the green is by contrast. With the greater projected discharge, the climate change Scenario 1 would result in more flood in the upstream section of the VMD, especially in the beginning of the flood season (in July); one may see that in early July, the peak of discharge in Scenario1 was significantly higher than that in Scenario 2.

Distinctions between the floods along the coastal areas simulated according to the changes of the sea level (±30 % and 15 % of projected sea level in 2050) and the projected discharge in Kratie according to climate change Scenario 1 for the four selected dates are presented from Figs. 17 to 20. Because the flood in the coastal area was not affected strongly by the relative small modification of the upstream discharges, the findings were found similar between the simulations according to the projected discharges at Kratie according to Scenario 1 and 2. The obtained results show that in the early flood season (July), the flood which was affected by the tidal regime reach the upstream section of the VMD (up to Tan Chau and Chau Doc); however, with higher flood the inundated area with impacts of tidal regimes went gradually sea-wards (from July to November). In addition, due to the relatively poor drainage ability in the Ca Mau Peninsula, later in the flood season, more permanent flood whereas the spatial distribution of flood pattern in the area surrounding the main outlets of the river network remained quite similar over the whole flood period.

3.4 Concerned issues when studying the climate change and its impacts on the VMD

The impacts of climate change should not be considered by the impact of a single event only but the accumulative impacts should also be taken into account (Keskinen et al., 2010). In addition, to study the impacts of climate change on the VMD, it is important to study the impacts of such changes in different sections like the upstream vs. downstream section (Gichamo et al., 2012; Quinn et al., 2010), the Coastal zone vs. Ca Mau Peninsula and the east vs. west coast. In addition, it was found that in the Ca Mau Peninsula the flood was strongly influenced by both the East and West Sea; therefore, the modification in mechanism of tidal regime in each sea would change the future flood significantly. However, in this study, it was assumed that the rate of sea level rise would be similar between the East and West Sea; hence, further study on this issue should be done in order to make better projections for the future conditions.

Changes in the precipitation pattern in the Mekong Delta (including both the Cambodian and Vietnamese parts) were not considered in this research. Some studies were done to project future precipitation patterns in the area but with insignificant information about temporal distribution of such changes (i.e. only the changes in average annual rainfall were given) (WWF, 2009). In fact, the applied discharge in 2050 at Kratie considered the climate change impacts (and hence the precipitation) from Kratie further upstream already. In addition, due to the flat topography in the Mekong Delta, impacts of the accumulated discharge from the rainfall contributions to the flood along a certain river reach were actually lighter than that in the upstream section (Dinh et al., 2012).

Within a small floodplain, a 1-D hydrodynamic model could result in acceptable accuracy in terms of simulated inundation extent and floodwave travel times (Hartanto et al., 2011). However, for a large river network with extensive floodplain, 2-D hydrodynamic models were developed to study the detailed hydraulic nature, rather than the mean conditions in a 1-D hydrodynamic model (Gichamo et al., 2012). Even thought there were positive aspects of such 2-D hydrodynamic models, due to the requirements of intensive input data and powerful computers, 2-D hydrodynamic models were not very popular for large river networks like that in the VMD. In fact, the model complexity was constrained by the availability of data, and therefore, to model a complex river network was still a great challenge due to significant differences in the hydraulic nature along the river network (Costelloe et al., 2006; Dinh et al., 2012; Gichamo et al., 2012). It is suggested that a coupled 1-D/2-D or that a full 2-D hydrodynamic model should be developed to study the flows and its propagation along the floodplain for specific study purposes like flood risk assessment at a small scale (Dutta et al., 2007; Muste et al., 2010; Pender and Neelz, 2007).

The Mekong River in the VMD was characterized by fluvial-unstable network. With the applied one-dimensional hydrodynamic model, the changes of river morphology were not taken into account leading to a great doubt of the simulated future flood (in 2050). It was suggested that when the required data (e.g. sediment size) is sufficiently available, a more comprehensive hydrodynamic model should be applied to project the changes of the river morphology and then the hydraulic nature would be simulated based on such the morphological modification.

3.5 Impacts of the flood on the agriculture in the VMD

It is expected that the future climate changes would significantly impact the agricultural activities but it is difficult to quantitatively assess such influences (Schaefer, 2002; Dinh et al., 2012). Vastila et al. (2010) states that the damage to crops and infrastructure in the VMD would be serious as the average and maximum water stages and flood duration would increase in 2010–2049. The findings from this research also support the argument, and we provide a more detailed analysis to illustrate the changes in the extent of flooding. One may expext that with the rise of sea level only the agricultural system (including the rice-based farming systems and shrimp farming) in the Ca Mau Peninsula would be strongly affected, while the deep flood extent in the upstream section does not change significantly if compared to the 2000 flood (Fig. 13). However, if both boundary conditions are set to follow the CC scenarios (the upstream discharge and sea level), the flood in the Ca Mau Peninsula becomes longer but the flood duration in the upstream section of the VMD would be shorter (Fig. 14).

The effect of the possible temporal changes in annual hydrograph in the upstream section of the Mekong would result in considerable impacts on the flood extent and stage in the VMD and consequently lead to significant impacts on the agricultural system. With the shift of the flood season forward in time, the (rice) cropping system should be adjusted to avoid the damaging flood in November. The timing issue of flooding is critical for agriculture as can be concluded from the effects of the 2000 extreme flood which caused severe damage not only due to the high discharge and stage but also due to its early arrival (4 to 6 weeks earlier in comparison to the normal flood) (Le et al., 2007).

Simulated results show that the flood would extent further to the Ca Mau Peninsula with the sea level rise. In fact, with the dense river network in the coastal area and greater differences between the low and high peaks of the tidal regime in the East Sea (in comparison to the West Sea), the floods were routed to the East Sea faster than to the West Sea. In addition, the hydraulic regime in the Ca Mau Peninsula was complicated as it was influenced strongly by both the East and West Sea. Figure 21 presents the simulated stages on 30 August 2000 and 2050 with the CC Scenario 1 along the coastal area (Location 1), in the middle (Location 2) and far-west (Location 3) of the Ca Mau Peninsula (see Fig. 1). The simulated stages at Location 1 and 3 followed closely the tidal regime in the East and West Sea, respectively as they were near to the large river mouths, while the simulated stages at Location 2 (further inland) were influenced by the both the East and West Seas. The simulated stages in the Ca Mau Peninsula and coastal area for Scenarios 1 and 2 were similar (as the upstream discharge did not give significant differences in the simulated stage in those locations), so the results for Scenario 2 are not presented.

In specific consideration to agriculture during the flood period in the VMD, agricultural activities in the upstream section of the VMD will benefit as the physical conditions would be more favourable for agriculture (due to the “lower flood” condition). However, along the coastal area, especially in the Ca Mau Peninsula, the flood would be prolonged, which might cause changes in the structure of the current farming systems.

Potential adaptation measures in the VMD, agriculture was the main economic sector of development; consequently, climate change adaptation in agriculture was a priority (Boer and Tirpak, 2010). With different policies to ensure the rice-based farming systems, permanent dykes along the upstream section of the VMD were raised to protect effectively the rice-based farming systems from the annual floods (Nguyen et al., 2007). However, with the drawbacks of such permanent dyke system (e.g. environmental pollution and degradation of soil fertility) (Nguyen et al., 2007), semi-dyke systems (MRC/WUP-FIN, 2006) in combination with water retention (Buijse et al., 2002; Hartanto et al., 2011; Hooijer et al., 2004; Meire et al., 2010; Platteeuw, 2010; Popescu et al., 2010) could be considered as a suitable solution to maintain the agricultural production in the VMD. Actually, in the past (decades ago), floods were kept in backswamp areas in order to not only supply freshwater flow in main canals during the early dry season (Dang et al., 2007) but also to eliminate the flood over the peak periods. For the irrigated rice-based farming systems, the possible adaptation measures might be applied in the VMD, including (i) adjusting the cropping seasons could be a suitable adaptation measure to avoid the peaks of the flood (ADB, 2010; Mainuddin, 2010); (ii) Shifting from rice intensification systems into livelihood diversification (Nguyen et al., 2006); (iii) Alternating wetting and drying irrigation methods (Belder et al., 2004); and, (iv) diversifying cropping patterns (Hoanh et al., 2003). Moreover, to study the nature of the future flood in the VMD, climate change aspects (upstream discharge changes and sea level rise) should not be considered separately from other factors (e.g. economic and social environment) (Keskinen et al., 2010). It is important to notice that the physical changes would not be happening suddenly (e.g. sea level would rise gradually over several decades; Wassmann et al., 2004). However, the anthropological factors would contribute significantly to dramatic changes like the dam construction along the upstream section of the Mekong (Yang et al., 2006; Kummu et al., 2007, 2010) and those should be considered carefully and seriously before any action would be turned into practice. In fact, “adaptation to climate change should be integrated in social economic planning at all scales” (Popescu et al., 2010).

4 Conclusions

Fluvial floods in the VMD were characterized by two types: (i) floods in the upstream section mainly affected by the upstream discharge; and, (ii) floods in the coastal area strongly influenced by the East and West Sea tidal regimes. Therefore, the floods in the VMD were highly dynamics both in terms of spatial and temporal distribution and were not only driven by the upstream discharge but also the East and West Sea level.

Flood maps (in the upstream section and coastal areas in the VMD) were made with four critical dates in a flood season. For the highest recent flood in 2000, the affected areas were mainly upstream in the delta. For the year 2050 which was a fairly normal hydrograph for the Mekong River discharge and well below the peak river hydrograph of 2000, the flood hazards were more severe along the coastal area, according to the higher sea level leading to diminished drainage capacity. In fact, the fluvial flood hazards in the coastal area were determined by the tidal regime (e.g. high tides induced fluvial floods, low tides permit drainage).

In general, with impacts of the climate change and upstream development, the upstream discharge in Kratie would be modified significantly resulting in great changes in the flood duration and stage in the VMD. The findings were that the future floods would be lower (in simulated stages) but last longer in the upstream section of the VMD. However, due to the change of the downstream boundary conditions (sea level rise), the inundated area along the eastern and western coast in the VMD, especially the Ca Mau Peninsula, would be greater than that in the present. Moreover, with the impact of upstream development (Scenario 2), the flood duration would be shorter (in comparison to that of Scenario 1). Due to a dense river network in the coastal area and low sea level during the low tides, the flood duration in coastal area would not be long (often less than 24 h per day even in the sea level rise scenario).

The agriculture in the upstream section of the VMD would have more favoured environment as the fluvial flood would be in the lower part in the future than the one in 2000. In the downstream section (along the coastal zone and the Ca Mau Peninsula), longer inundation length during the flood period might be also a good environment for rice cultivation. In fact, the high stage would be higher due to the projected increase of sea level but such floods would not last for long due to the impacts of the tidal regime. However, with the study on the flood merely, conclusions on the impacts of climate change and upstream development on rice cultivation could not be withdrawn thoroughly as changes in available water in the dry season were not studied yet.

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Table 1. The set-up of the boundary conditions of the model runs.

Model run	Upstream boundary	Downstream boundary
Model run No. 1	Discharge in year 2000	Water level in year 2000
Model run No. 2	Discharge in year 2000	Water level in year 2050 (SL2000 + 30 cm)
Model run No. 3a	Discharge in year 2050 (Scenario 1)	Water level in year 2050 (SL2000 + 30 cm)
Model run No. 3b	Discharge in year 2050 (Scenario 2)	Water level in year 2050 (SL2000 + 30 cm)

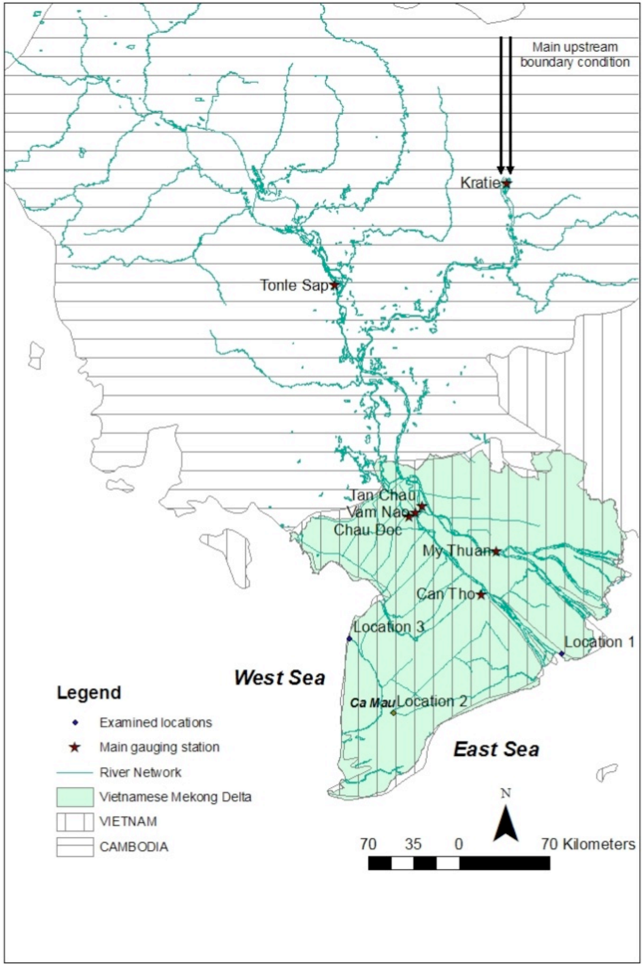

Fig. 1. The studied river network and the Vietnamese Mekong Delta.

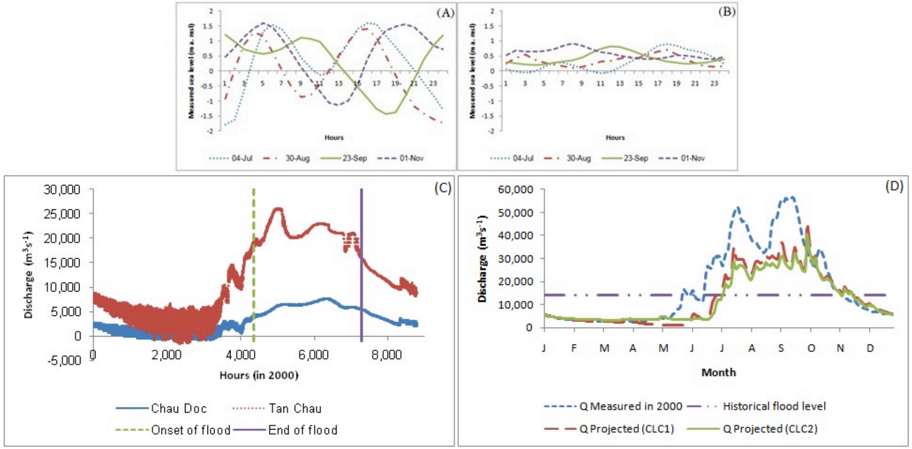

Fig. 2. Measured sea levels in the East **(A)** and West **(B)** Sea on selected dates; Measured hourly discharge in 2000 at the Tan Chau and Chau Doc gauging stations **(C)**; and, the annual hydrograph measured in 2000, historical mean daily discharge (1985–2000) and projected annual hydrograph in 2050 (Scenario 1 and 2) **(D)**.

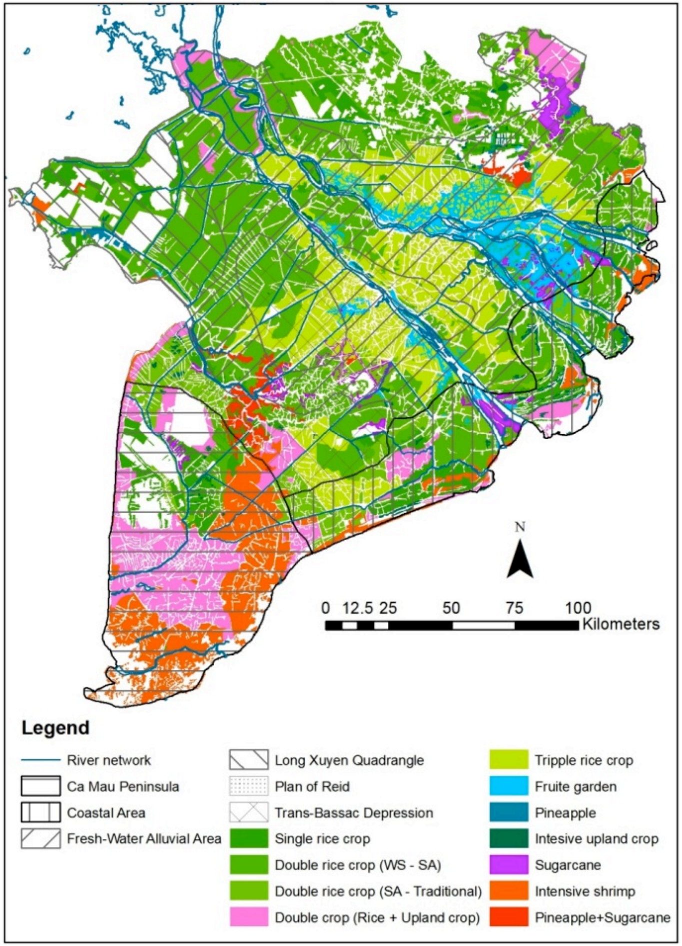

Fig. 3. Agro-ecological zones and land use map in the VMD in 2006.

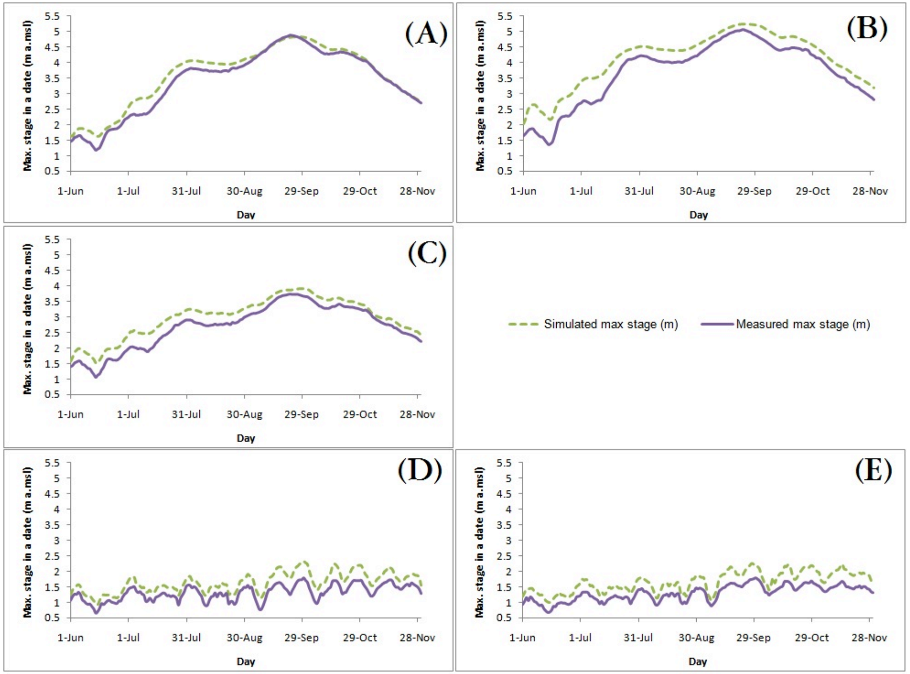

Fig. 4. Daily measured and simulated maximum stages during the flood period in 2000 at different gauging stations, **(A)** Chau Doc; **(B)** Tan Chau; **(C)** Vam Nao; **(D)** Can Tho; and, **(E)** My Thuan.

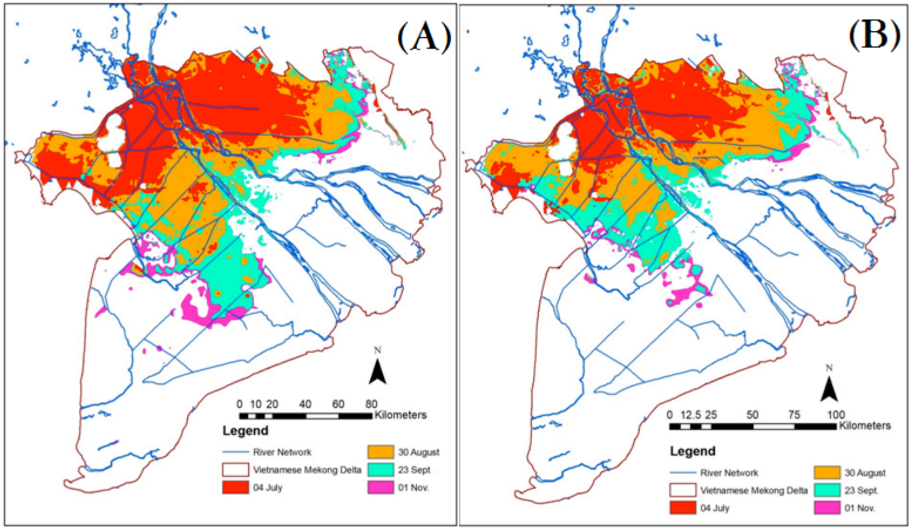

Fig. 5. The inundated area on 4 July, 31 August, 23 September and 1 November in 2000 with the simulated stage of 20 cm **(A)** and 50 cm **(B)** above the land surface.

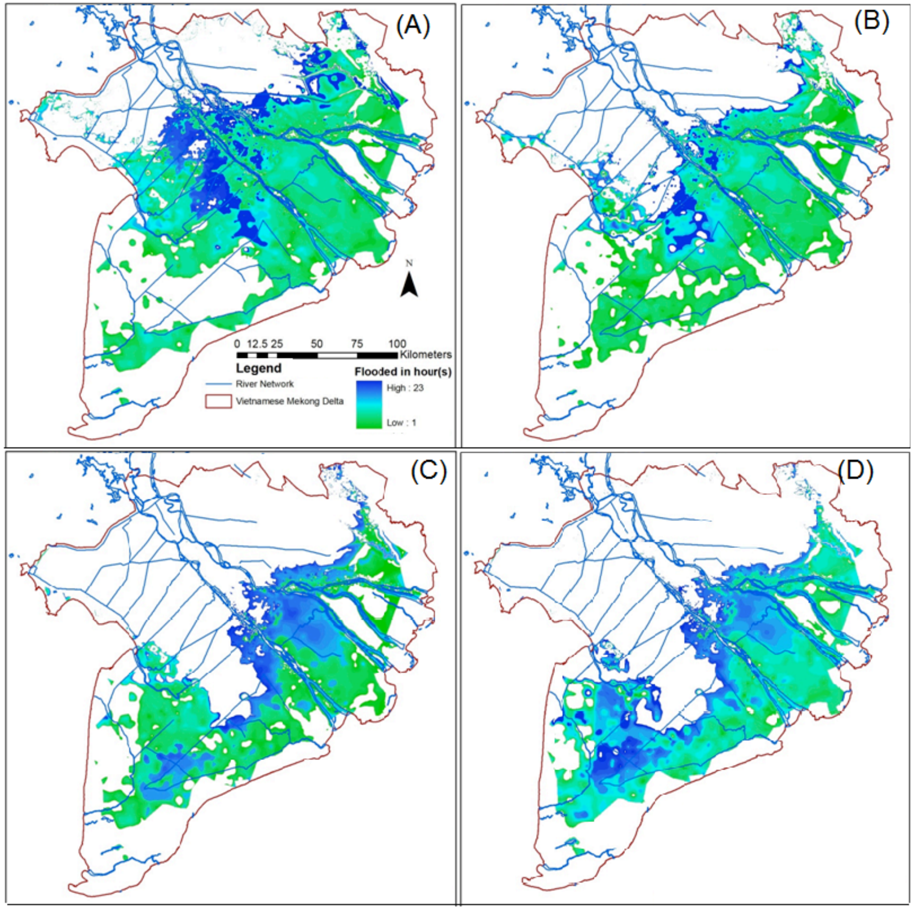

Fig. 6. The inundated period (in hours) on 4 July **(A)**, 30 August **(B)**, 23 September **(C)** and 1 November **(D)** 2000.

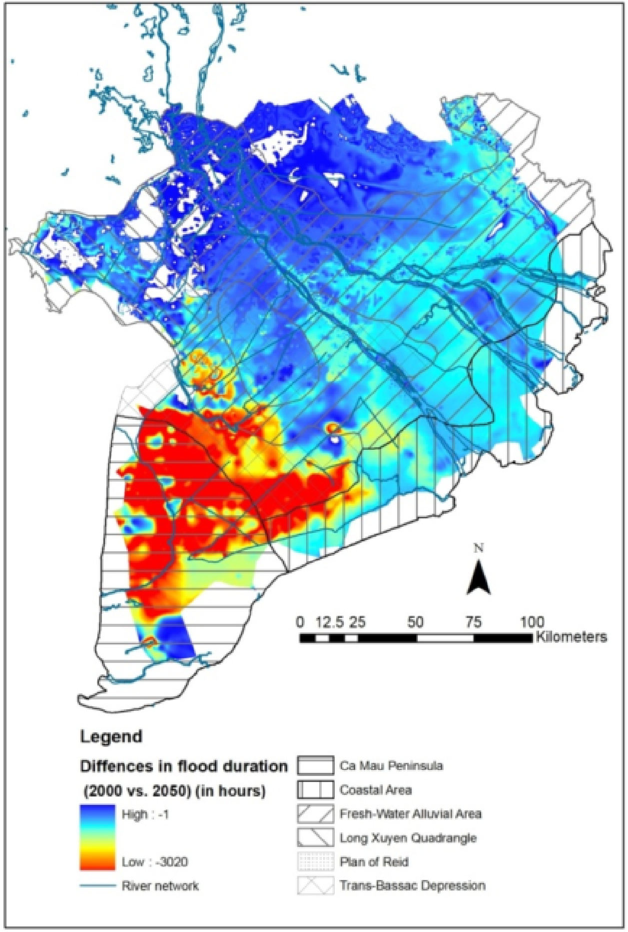

Fig. 7. Differences between the flood duration in 2000 and 2050 (with the sea level rise only).

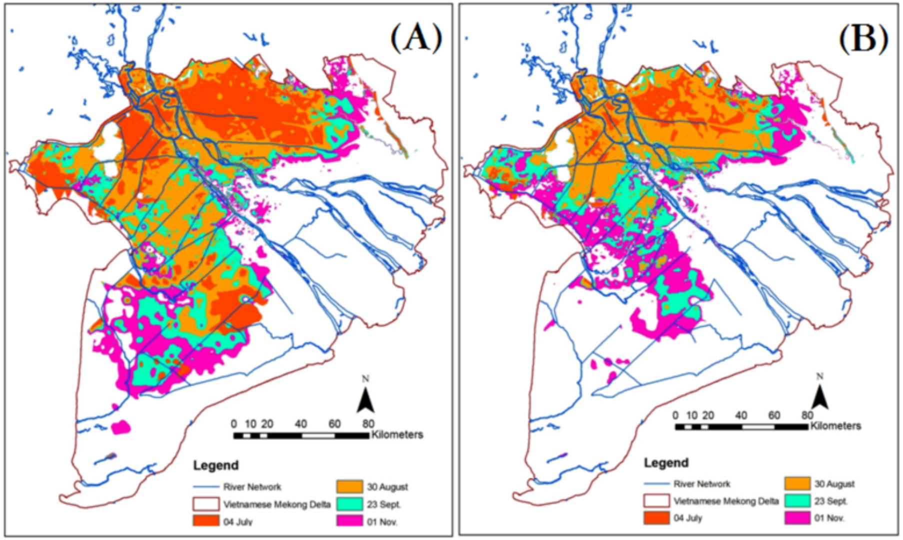

Fig. 8. The inundated area on 4 July, 31 August, 23 September and 1 November in 2050 according to the climate change Scenario 1 with the stage of 20 cm **(A)** and 50 cm **(B)** above the land surface.

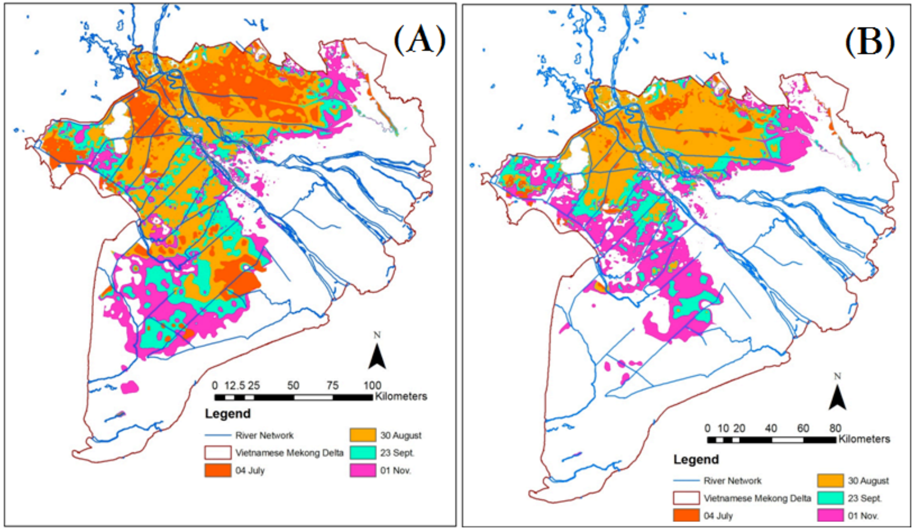

Fig. 9. The inundated area on 4 July, 31 August, 23 September and 1 November in 2050 according to the climate change Scenario 2 with the stage of 20 cm **(A)** and 50 cm **(B)** above the land surface.

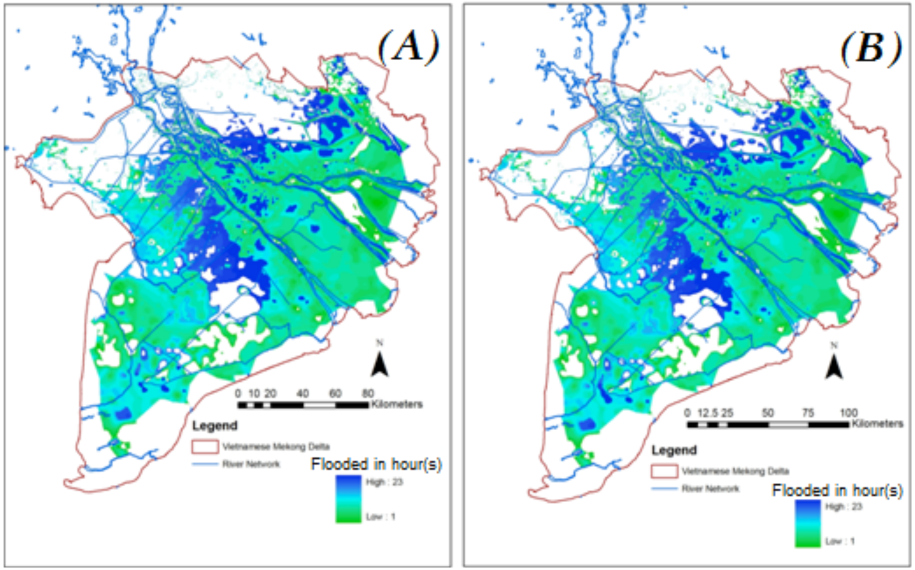

Fig. 10. The inundated period (in hours) on 4 July, 2050 according to Scenario 1 **(A)** and 2 **(B)**.

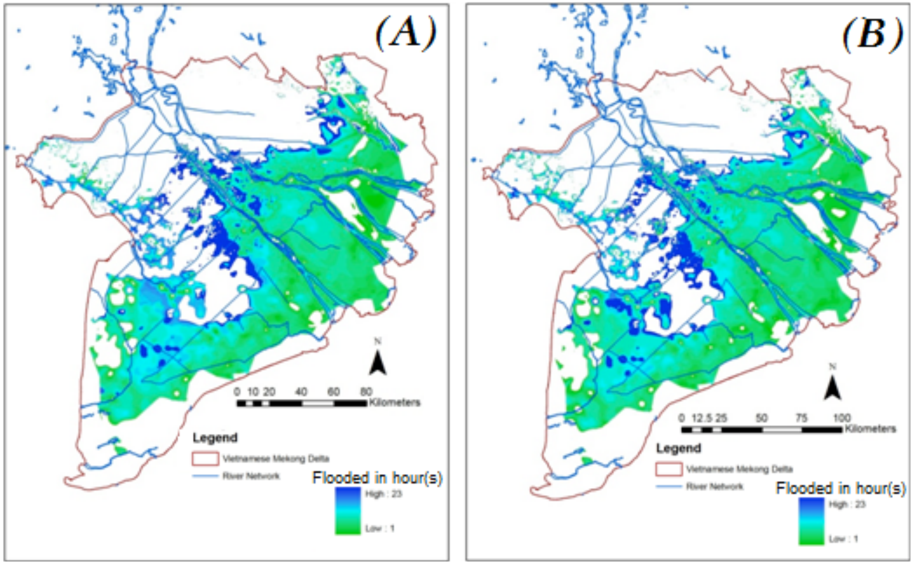

Fig. 11. The inundated period (in hours) on 30 August, 2050 according to Scenario 1 **(A)** and 2 **(B)**.

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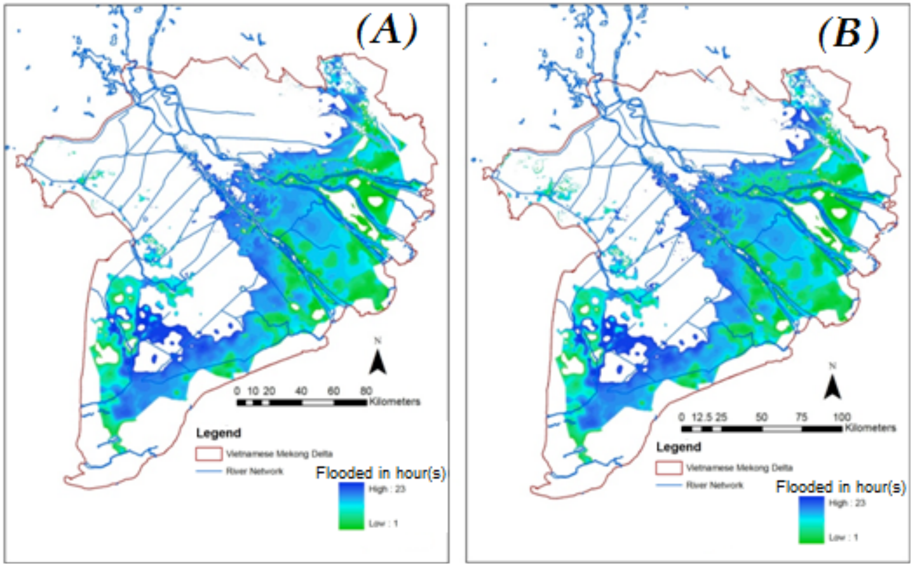

Fig. 12. The inundated period (in hours) on 23 September, 2050 according to Scenario 1 **(A)** and 2 **(B)**.

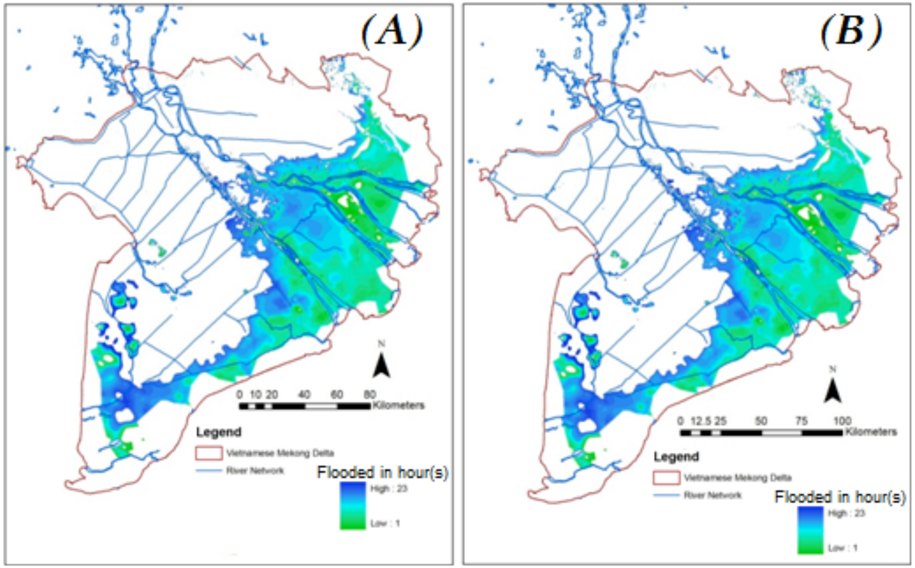

Fig. 13. The inundated period (in hours) on 1 November, 2050 according to Scenario 1 **(A)** and 2 **(B)**.

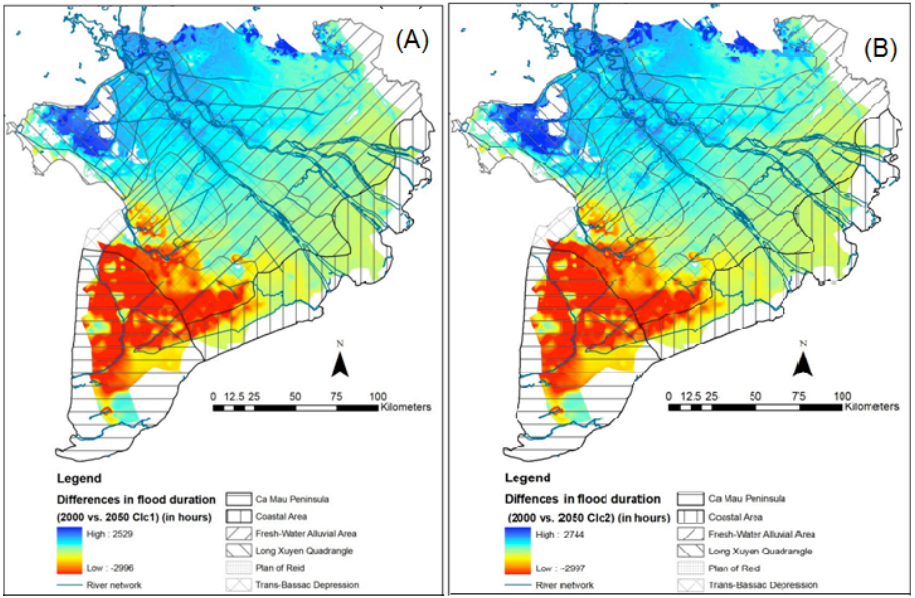

Fig. 14. Differences between the flood duration in 2000 and 2050 with the climate change Scenario 1 **(A)** and Scenario 2 **(B)**.

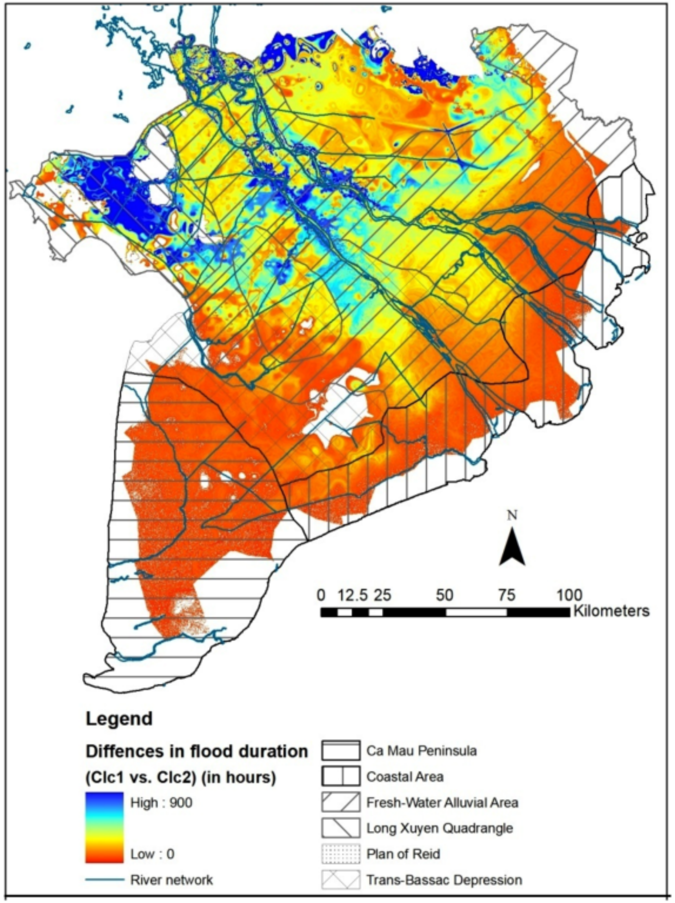

Fig. 15. Differences between the flood duration in 2050 according to the climate change Scenarios 1 and 2.

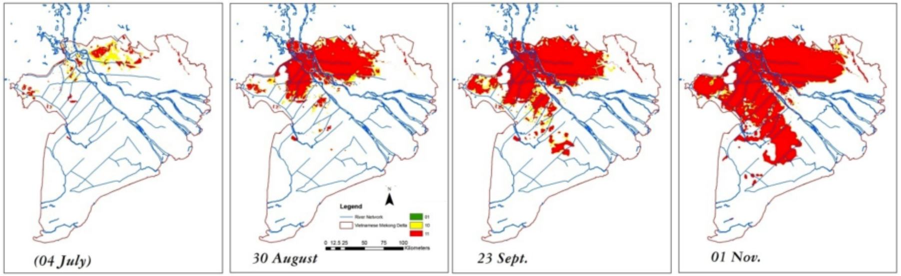

Fig. 16. Upstream floods simulated according to changes of the discharge projected at Kratie following the climate change Scenario 1 and 2 (with the sea level projected for 2050).

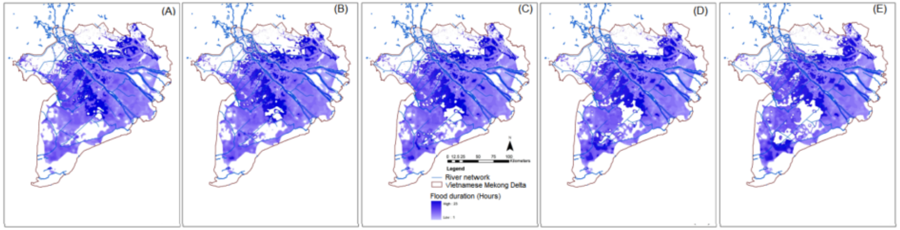

Fig. 17. Flooding along the coast simulated according to changes of the sea level (in 2050) and the discharge projected at Kratie according to the climate change Scenario 1 (4 July) (**A** – SL in 2050 −30 %; **B** – SL in 2050 −15 %; **C** – SL in 2050; **D** – SL in 2050 +15 %; **E** – SL in 2050 +30 %).

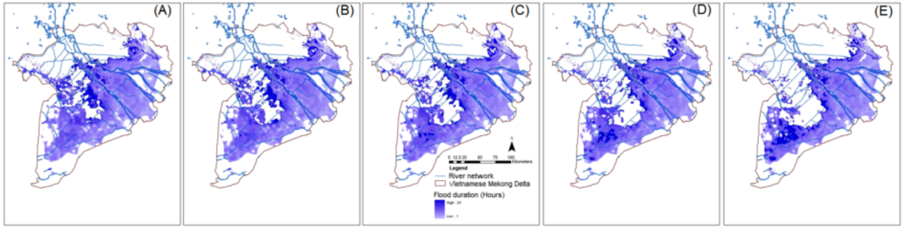

Fig. 18. Floods along the coast simulated according to changes of the sea level (in 2050) and the discharge projected at Kratie according to the climate change Scenario 1 (30 August) (**A** – SL in 2050 −30 %; **B** – SL in 2050 −15 %; **C** – SL in 2050; **D** – SL in 2050 +15 %; **E** – SL in 2050 +30 %).

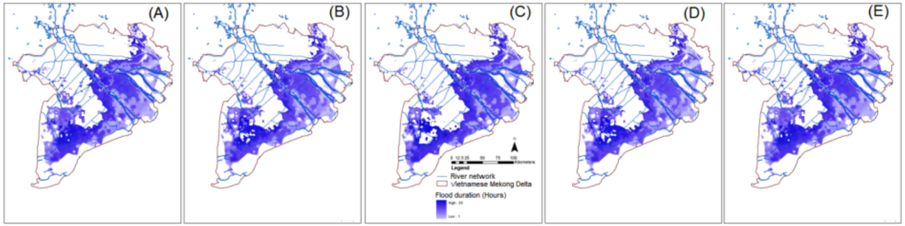

Fig. 19. Floods along the coast simulated according to changes of the sea level (in 2050) and the discharge projected at Kratie according to the climate change Scenario 1 (23 September) (**A** – SL in 2050 −30 %; **B** – SL in 2050 −15 %; **C** – SL in 2050; **D** – SL in 2050 +15 %; **E** – SL in 2050 +30 %).

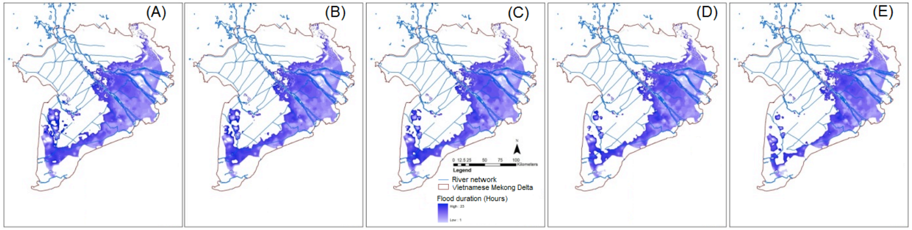

Fig. 20. Floods along the coast simulated according to changes of the sea level (in 2050) and the discharge projected at Kratie according to the climate change Scenario 1 (1 November) (**A** – SL in 2050 −30 %; **B** – SL in 2050 −15 %; **C** – SL in 2050; **D** – SL in 2050 +15 %; **E** – SL in 2050 +30 %).

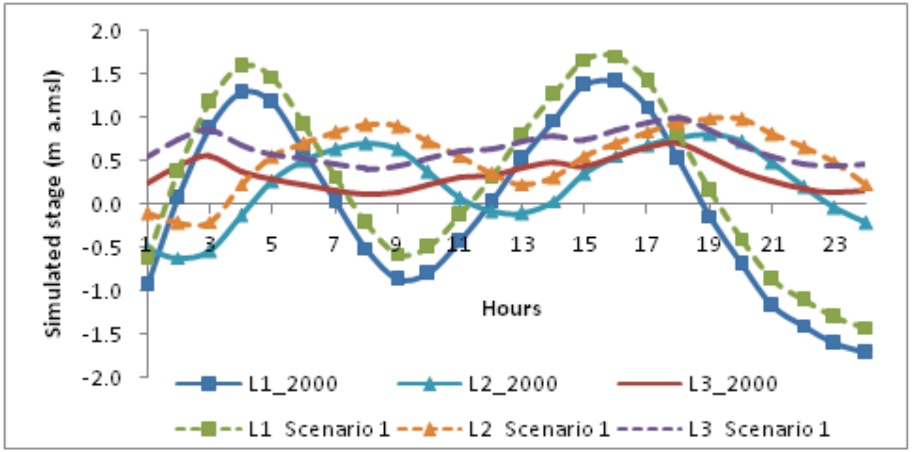

Fig. 21. Simulated stages in 2000 and 2050 with the climate change Scenario 1 in different locations on 30 August.