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Floodplain hydrology of the Mekong Delta, Vietnam

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Abstract

The Mekong Delta is one of the largest and most intensively used estuaries in the world. Each year it witnesses widespread flooding which is both the basis of the livelihood for more than 17 Million people but also the major hazard. Therefore, a thorough understanding of the hydrologic and hydraulic features is urgently required for various planning purposes. While the general causes and characteristics of the annual floods are understood, the inundation dynamics in the floodplains in Vietnam which are highly controlled by dikes and other control structures have not been investigated in depth. Especially quantitative analyses are lacking, mainly due to scarce data about the inundation processes in the floodplains. Therefore, a comprehensive monitoring scheme for channel and floodplain inundation was established in a study area in the Plain of Reeds in the North-Eastern part of the Vietnamese Delta. This in-situ data collection was complemented by a series of high resolution inundation maps derived from the TerraSAR-X satellite for the flood seasons 2008 and 2009. Hence, the inundation dynamics in the channels and floodplains and the interaction between channels and floodplains could be quantified for the first time. The study identifies the strong human interference which is governed by flood protection levels, cropping patterns and communal water management. In addition, we examine the tidal influence on the inundation in various parts of the Delta, since it is expected that climate change induced sea level rise will increase the tidal contribution to floodplain inundation.

1. INTRODUCTION

The largest part of the Mekong Delta is located in Southern Vietnam, where the Mekong River drains into the South China Sea. The region encompasses an area of 39,000 km^2, and it is the homeland of 17 million people. The climate is influenced by two monsoon systems, the South-West Indian monsoon and the North-West Pacific monsoon, causing two distinct seasons; the dry season from December to the end of April and the flood season from May to November. During the flood season the Mekong Delta inundates about half of the area (19,000 km^2).

The man-made channel and dike systems have greatly altered the natural hydrodynamic conditions in the Vietnamese part of the Delta. The channel network consisted of only two canals in 1824 (Thoai Ha and Vinh Te), increased to 40 canals in 1934 (with a total length of about 1,375 km) and hundreds of canals in the 1980s (Dieu, 1999; Yasuyuki, 2001). Today, the channel network is more than 50,000 km long, and it is still increasing (Truong, 2006). In combination with the extensive development of dike systems in the last decades, especially after the devastating flood in 2000, the floodplains are increasingly cut off from the natural inundation regime.

In large parts of the Delta the floodplain inundation is controlled by sluice gates which are managed by local communities. On the one hand, the enclosure of natural inundation areas by flood protection dikes impedes the natural inundation processes and generates social and economic benefits; for example, a clear trend towards growing three crops per year is observed. On the other hand, water quality problems (MRC, 2007), riverbank erosion (Hung, 2004), and salt water intrusion (Sam, 2004; Nguyen and Savenije, 2006) were reported. Furthermore, on-going and expected changes like increasing flood variability (Delgado et al., 2010) and sea level rise (Doyle et al., 2010) are supposed to increase the frequency and intensity of flooding in the Delta.

The floodplains play an important role for the agro-ecosystem and the socio-economy of the Mekong Delta. They provide natural flood retention and reduce the discharge peaks in the flood season. Natural flood retention has been strongly altered by control structures and agriculture, especially by the popular cultivation of fruits and paddy rice. Traditionally, the inflow and outflow to the fields is controlled by cultivation activities during the rising and falling stage of the flood period, i.e. in July and December. These controls are required in order to harvest two rice crops per year. The controls are achieved by low ring dikes retaining the water from the floodplains until the crops are harvested in July. The surplus water is pumped out of the floodplains. The low ring dikes also ensure that substantial amounts of sediment and nutrients are deposited in the fields. These nutrients are the source of the very productive agricultural system in the Delta. In case of absolute flood protection, the annual sediment and nutrient source does not reach the fields. Hence, the benefits of flood protection are controversially discussed from the communal to the national level in Vietnam. However, no quantitative data exist to support either position in this debate.

The natural floodplains of the Mekong River in Cambodia have received some attention in this respect. Fujii et al. (2003) analysed the hydrological role of the Cambodian floodplains from Konpong Cham to the Vietnamese-Cambodian border. Their main finding is that the decreased overbank flow to the fields, as consequence of infrastructure development (roads and dikes), reduces the economic benefit of cultivation activities. Similar studies for the controlled part of the Vietnamese Delta are missing. There are a number of hydrodynamic modelling studies published since the 1960s, by e.g. UNESCO/ SOGREAH (1967), Zanobetti et al. (1970), Dac (1996) and Nien (1996), but none of them aimed at the quantification of floodplain sedimentation. This can partly be explained by the inability of 1D hydrodynamic models to simulate the floodplain sedimentation processes properly. A few recent publications using 2D and 3D hydrodynamic models studied floodplain sedimentation. However, they lacked sufficient calibration and validation data (Ngoc et al., 2007, MRCS/WUP-FIN, 2007).

This study, therefore, aims at understanding and quantifying typical floodplain processes in the Vietnamese Mekong Delta. In particular, it investigates:

- the spatial and temporal characteristics of the floodplain inundation processes,
- the influence of the operation of water resources infrastructure (sluice gates, water pumping) on the inundation of floodplain compartments,
- the effect of the tidal influence,
- the hydraulic linkage between channel network and floodplain compartments.

The study is performed in an area of about 15 km^2 in the Plain of Reeds, located in the Tam Nong District / Dong Thap province in the North-Eastern part of the Vietnamese Delta (Figure 1). The area is characteristic for the Delta: topography, man-made structures and the multiple land use (paddy rice, shrimp farming, fish farms, and vegetable crops) are typical for the intensively used floodplains in Vietnam (Figure 2a). The hydrology of the floodplains is controlled by the annual floods of the Mekong River and two different tidal systems from the Gulf of Thailand and the South China Sea, despite being about 180 km away from the coast.

The study presents, for the first time, a quantitative analysis of the floodplain processes in the Vietnamese part of the Mekong Delta. It is based on ground data with high temporal resolution and remote sensing data of inundation extents with high spatial resolution. Hence, the unique features of the Vietnamese floodplains including the anthropogenic influence could be quantified.

2. FLOOD CHARACTERISTICS, STUDY AREA AND MONITORING SYSTEM

2.1. Flood characteristics in the Mekong Delta

The annual flood volume of the Mekong River is about 475,000 million cubic metres. In a global comparison of large rivers, the Mekong River has the largest runoff per unit area, whereas it seems to be one of the large rivers with comparatively little anthropogenic interference (Adamson et al., 2009). However, this situation is likely to change in the future due to a number of dam projects along major tributaries and along the main river in Laos and Cambodia (Lu and Siew, 2006; Walling, 2008; Västilä et al., 2010; Xue et al., 2010).

The inundations in the Mekong Delta are dominated by three factors: (1) the flood hydrograph originating in the Mekong basin upstream of Kratie, (2) the buffering of the flood wave in the Tonle Sap lake system, and (3) the tides of the South China Sea and the Gulf of Thailand (Figure 1). The Tonle Sap plays the most important role with regard to the duration of the flood in the Delta. At the beginning of the flood season, the flow is divided into two parts: flow to the Tonle Sap Lake and water flowing into the Delta. The water in the Tonle Sap Lake is reversed back to the Mekong River when the water level in the Mekong River is lower than the lake water level. This natural system buffers the floods reaching the Delta, resulting in less severe but prolonged floods compared to the floods at Kratie. The flow into the Tonle Sap starts around middle of June, while the return flow to the Mekong River normally initiates in the beginning of October. The annual average inflow and outflow volume of the Tonle Sap Lake is about 79.0 km^3 and 78.6 km^3, respectively (Kummu and Sarkkula, 2008).

The hydraulic gradient in the main river of the Mekong Delta is relatively small, about 2 to 5 cm/km. Data from 1978 to 2009 show that the travel time from Tan Chau to My Thuan (Figure 7) is about 7 to 22 days, corresponding to 5 km/day to 17 km/day. The flood hydrograph in the Mekong Delta has often two peaks, whereas the early peak arrives from mid-July to mid-August and the second peak from September to October. The second peak is associated with the landfall of typhoons from the South China Sea.

2.2. Study area

The study area encompasses five municipalities in the Tam Nong district, Vietnam (Figure 2a). About 30,000 people live along the channel and dike network and in a few scattered clusters. The area encompasses a number of man-made channels and 24 ring dikes in floodplains which are mainly used for growing paddy rice and for aquaculture (fish and shrimp farms). The dike system is comprised of low and high dikes for crop and flood protection, respectively, an intervention which is very common in the Mekong Delta in Vietnam.

The study area in Tam Nong was selected, since it is annually flooded and it has deep inundation depths. Further, its characteristics are typical for the Mekong Delta. The total area is about 11,500 ha, of which 4.5% is used for shrimp farming, 0.5% for fish farming, and 95.0% for paddy and vegetable cultivating. The channel density of 11.6 m/ha is somewhat below the average density in the whole Delta (14 m/ha, including river and natural channel network). 67% of the dikes are low dikes with average crest levels of about 2.5 m.a.s.l, and 33% are high dikes for flood protection with average crest levels of about 4.5 m.a.s.l. These fractions are representative for the whole Plain of Reeds.

Different land uses lead to different water demand and control schemes. The requirements for water for agriculture are different to those for aquaculture in terms of quantity, quality and regulation scheme. In the case of floodplain compartments fully protected by high ring dikes, the water flow is entirely controlled, enabling three crops per year. Consequently, the water management in these areas differs considerably from the areas under the natural inundation regime.

The combination of

- annual floods inundating the area directly from the Mekong River,
- flooding due to overland flow from the Cambodian-Vietnamese border (Dung et al., 2010),
- the bi-modal tidal influence,
- the low topography and hydraulic gradients,

- the diverse man-made channel system with its numerous control structures

creates a highly complex hydraulic scheme. The resulting inundation levels in the floodplains range from 1 to 3 m depending on topography, flood magnitude, tidal amplitude and control of sluice gates and pumps. In the case of completely controlled floodplain compartments, the control of the system may cause different water levels in adjacent compartments (Figure 2c).

2.3. Floodplain processes monitoring scheme

In order to understand and quantify the inundation processes, an extensive monitoring scheme was designed and installed in the study area. 21 pressure probes for water level monitoring were deployed to selected locations. For these water level stations (H-stations) we used absolute pressure probes, facilitating deployment at any location without the necessity of recording atmospheric pressure. Thus the probes could be submerged completely and they recorded autonomously for several months. The pressure readings were offline corrected for atmospheric pressure after retrieval. Figure 3 (top right) shows a typical floodplain station with its protecting steel box and warning sign for fishermen.

Additionally, seven water quality stations were designed for long-term operation and deployed to channels and floodplains. The water quality stations (T-stations) operate autonomously by solar power supply and are equipped with various sensors. Because the power supply and data loggers cannot be inundated, the T-stations contain a weather- and lightning-proof steel box hosting the solar panels, battery and the data loggers. The box is mounted either on a bridge or, in case of floodplain deployment, on a pylon 4 m high (Figure 3, top left and bottom).

The stations were strategically distributed in the investigation area in order to capture the important inundation processes (Figure 2a, 2b). By placing the probes in the channel, on low dikes and in the floodplains, we intended to quantify the different inundation controlling processes (dike overflow, sluice gate and pump operation, respectively). Four of the T-stations were placed in the floodplains, while three others were installed in channels. Besides the water level, the T-stations record turbidity, conductivity, water temperature and pH. However, in this publication only the water level data will be evaluated.

It has to be noted that the continuous monitoring of the inundation processes and of the water quality in floodplains is a novelty, not only for the Mekong Delta.

2.4. Additional data

A Digital Elevation Model (DEM) of 5 m resolution was supplied by the National Remote Sensing Centre, Ministry of National Resource and Environment, Vietnam. The DEM includes the dike topography. This dataset was enhanced by ground survey data from local authorities and field survey campaigns using differential GPS.

In addition, the German Remote Sensing Data Centre (DFD) of the German Aerospace Centre (DLR) provided a series of inundation maps, derived from TerraSAR-X Radar satellite images in high resolution (Gstaiger et al., submitted). Using different operation modes of TerraSAR-X (scan and strip mode), inundation maps with a resolution of 2.75x2.75 m and 8.25x8.25 m, respectively, could be produced with an approximate revisit cycle of 11 days in the two flood seasons 2008 and 2009. Using the inundation maps, also the spatial dynamics of the inundation could be assessed, in addition to the temporal dynamics derived from the gauge data.

Daily discharge measurements were provided by the Southern Regional Hydro-Meteorological Centre. The discharge was measured from bridges using wing flow velocity meters with a measurement range of 0.15 to 3.5m/s and an error of <1.5%. In order to get an overview of the influence of the ocean tides on the inundation processes, hourly water levels from the following stations were collected: Tan Chau, Chau Doc, Vam Nao, My Thuan, Can Tho, Cua Tieu, Ben Trai, My Thanh, Tan Hiep and Rach Gia (Figure 7). The water level time series cover different flood situations: a low flood (1998), an average flood (1999), and an extreme flood (2000).

3. RESULTS AND DISCUSSION

This section illustrates the results of the floodplain monitoring for two subsequent years, 2008 and 2009, as well as the evaluation of the additional data for different aspects of the flood regime in the Mekong Delta.

3.1. Flood hydrology and hydraulics

Figure 4 shows water level time series for two stations, representative for the main river (T1) and for a secondary channel in the floodplains (H11). It can be seen that the hydrograph characteristics in the channel and the floodplain are generally identical, except with regard to the tidal influence. The tidal influence is dampened in the floodplains due to the low momentum of the large inundation area.

The inter-annual comparison shows that in 2008 the first flood peak was more pronounced and the typhoon season increased the flood magnitude only slightly. In 2008 there was no major typhoon landfall in southern or middle Vietnam. In 2009, in contrast, there was a more distinct flood peak at the end of October indicating a more violent typhoon activity. On September 29th and 30th 2009 Typhoon Ketsana hit Central Vietnam, leading to heavy rainfall in the mountainous area along the border between Laos and Vietnam and to rapidly rising water levels in Laos between Pakse and Stung Treng. The resulting flood wave arrived in the investigation area around October 12th.

In order to discuss the inundation dynamics in a more structured way, we divided the typical flood hydrograph in the Mekong Delta in three periods: “rising stage”, “high stage”, and “falling stage”.

a) “Rising stage”: In this stage the flood regime is controlled by the inflow into the Tonle Sap and by the tidal influence. Flood control in the Vietnamese part of the Delta serves mainly for the purpose of crop protection. The second rice crop is usually harvested in August and the low dikes protect the paddy fields from inundation until they are harvested. As shown in Figure 4, the tide plays an important role during this period. Tides may cause short-term floodplain inundation in the case of coincidence of spring tides and early small flood peaks coming from upstream. The higher the flood level, the more attenuated is the tidal effect. This is shown in the comparison of the hydrographs of 2008 and 2009 at station T1. The tidal influence is dampened with distance from the main river, as shown in Figure 6. H11 is located in a secondary channel at about 11 km distance from the Mekong River, resp. station T1.

b) “High stage”: With rising water levels, the hydrodynamic processes change. Floodplain inundation is initiated by overbank flow or sluice gate operation in case of closed ring dikes. The influence of the tides on the inundated progression is diminishing. At the upstream boundary, the Tonle Sap Lake releases water back into the Mekong River, while in the Plain of Reeds in the Delta the flood peaks from the Mekong and the overland flow from the Cambodian border coincide. Additionally, the hydraulic head created by the overland from North-East changes the stage-discharge relationship in the secondary channels: at the same river water level less water flows from the Mekong River into the channels (Fig. 5, green marked data). During this period, typhoons may hit the southern part of the Lower Mekong basin. Typhoon induced floods superimpose the normal flood hydrograph caused by the South-West monsoon which may cause high flood peaks.

c) "Falling stage": From mid-October the water levels fall gradually, and there are no further flood peaks caused by tropical typhoons. Water levels are characterized by rising tidal influence and widespread human activities to regulate the remaining inundation waters in the floodplains. Traditionally, water is pumped out from the floodplains when the water level in the channels falls below the elevation of the low dikes. This facilitates the timely planting of the first paddy crop of the new cropping season. A particular feature at the beginning of this stage, i.e. between mid-October and mid-November, are stagnant and even reversal flow conditions, mainly in East-West channels. This is caused by a phase shift between the second flood wave coming overland from the Cambodian -Vietnamese border and the flood wave in the Mekong River. This feature is visible in the stage-discharge plot in Figure 5 (red marked data).

In Figure 5, the blue marked data represent the "normal" relationship during low flow and the rising stage of the flood, which is dominated by the flood wave of the Mekong River. The scatter in the data has to be attributed to the tidal influence. The green data indicate the high stage of the flood, where the flood wave of the Mekong River and the overland flood from North-East coincide. The red data indicate stagnant or even reverse flow conditions in the first phase of the falling flood stage, where the hydraulic head of the Mekong is falling below or equal to that of the overland flood wave. Slightly rising water levels in the Mekong River by minor flood peaks alleviate this situation which is observable in 2009.

In order to separate the tidal influence from the flood hydrograph, the tide signal was extracted by a Butterworth band-pass digital frequency filter with a band pass period of [6, 24] hours. In Figure 6, three distinct features become obvious:

1. The tidal influence is generally dampened during high flows, resp. high water levels: The amplitude during low flow is in the range of 1 m in the channels, while it is reduced to below 15 cm during high flow.
2. The tidal amplitude is dampened with distance to the Mekong River (compare H11 to T1), especially during high flows: T1 close to the main river still shows an amplitude of 20 cm, whereas H11 at 11 km orthogonal distance from the Mekong exhibits hardly any tidal influence during high flows (< 3 cm). This is due to travel time in the

channel, but also due to the additional hydraulic head imposed by the overland flood from the Vietnamese-Cambodian border.

3. The tidal amplitudes in secondary channels and floodplains are generally lower than in the main river.

This means that the tidal influence is small during high flows in our study area. However, this is different in other parts of the Delta, especially those closer to the coastal line where high tides can trigger short-term inundations.

3.2. Tidal influences in the Mekong Delta

Tides represent an important contribution to short-term water level variations in the Mekong Delta. They have to be taken into account as boundary condition of any hydraulic model for any sub-region in the Delta. However, this contribution is both spatially and temporally variable. We characterize the tidal effects for different areas, and we estimate wave travel times for different points in the Delta without the help of a hydraulic model. The analysis is performed for a typical drought (1998), normal (1999), flood (2000) year, and in each year the flood hydrograph is divided into dry season and wet season, as characterised by MRC (2009). For that purpose, we use a time-frequency analysis based on the wavelet transform which is able to estimate the phase coherency over time and the correlation between two time series localized in time and frequency. This information is important for the estimation of tide induced floods which are expected to increase with rising sea levels.

The Mekong Delta is affected by two different tides: the Western coastline is dominated by a “mixed type – prevailing diurnal” tide, common to the Gulf of Thailand. The Southern Eastern coastline of the Delta is under a “mixed type – prevailing semi-diurnal” regime associated with the South China Sea (Wyrtki, 1961). The combination of these two tidal regimes and the inflow from upstream yields a mixture of effects on the Delta that invalidates the use of harmonic analysis (Flinchem, 2000).

Based on an adapted wavelet decomposition of the water level (Torrence and Compo, 1998), we were able to assign the fractions of variance to different tidal frequencies. The fraction of variance attributed to semi-diurnal and diurnal tides are given in Figure 7a for the flood year 2000. The results for the drought and normal years, as well as for tidal amplitudes, are given in Table I. At the South China Sea stations in Cua Tieu, Ben Trai and My Thanh, the fraction of variance due to the semi-diurnal tide is over 57% of the total variance of the signal.

Upstream in Can Tho and My Thuan, this component is still over 44% of the total variance. However, between these locations and Chau Doc/Tan Chau, both the diurnal and semi-diurnal components decay sharply until they account for no more than 2% of the total variance. On a drought year, these fractions can go up to 12% in Chau Doc/Tan Chau, while increasing less sharply downstream. Although the influence of the Gulf of Thailand tide is not detectable in the stations along the main Mekong River, its effect should not be dismissed in the Western area of the Delta as seen in the station Tan Hiep.

The amplitude of both tide components is given in Table I, divided into dry season and wet season (MRC, 2009). It is clear that the amplitude is greater than average in the dry season because less water from upstream arrives at the Delta. During the wet season, the tidal amplitude decreases to one third of the value in the dry season in upstream stations like Tan Chau. During some periods in the wet season, the tidal effects are even no longer measurable. The water level at which this occurs may be estimated based on the time-frequency analysis. When the power of the tidal signal was lower than the 95% confidence level of the spectrum of a background white noise process, we assumed that the tidal effects were no longer felt. For example, the water level threshold was achieved for Tan Chau at 1.61 m (filtered data). This value is only indicative, as it depends on the particular hydrodynamic condition of a given year (for example the upstream discharge). In downstream stations like My Thanh the tidal effects are permanently felt, because river flood induced water level variations have much smaller amplitudes.

Hourly data allows investigating the phase coherence between different gauges and deriving the variance of the most intense oscillatory mode. The latter helps to understand the dependency of tidal propagation on the different water levels. The phase coherence between different signals provides an estimate of the wave travel time between stations. The results for the high flood year can be seen in Figure 7a, where the numbers represent time in hours for the phase lag of semi-diurnal and diurnal modes, and arrows show the direction of progression of the tidal wave. These values are in agreement with the literature (e.g. Nguyen, 2008). The travel time is a function of the water level due to changing hydraulic conditions. The dependency can be seen in Figure 7b for the semi-diurnal tide between My Thuan and Tan Chau. The phase difference varies slightly, until the water level exceeds a certain threshold, after which the phase is overestimated because the tidal signal in Tan Chau is too weak. This part of the data is therefore not used for computing the travel time. This effect of overestimation was also observed for Chau Doc, Tan Chau and Vam Nao. In our study area the tidal signal, depicted in Figure 6, is more pronounced, both due to the fact that the year of field monitoring is not a high flow year and the resolution of the data of the own stations is greater than the resolution of the data collected from other stations.

3.3. Floodplain inundation – Spatial dynamics

Using a series of inundation maps derived from TerraSAR-X for the years 2008 and 2009, the impact of the dike systems and human control on the floodplain inundation could be assessed. Figure 8 shows inundation maps for the three flood stages “rising”, “high” and “falling” for comparable dates of both years.

a) “Rising stage”: Figure 8a shows that some floodplain compartments were flooded while others were not. Most of the dikes and channels are still continuously visible. This indicates that there was no or little overbank flow and that most of the floodplain inundation was triggered by sluice gates operation. Especially floodplains that are completely enclosed by ring dikes, e.g. the compartment in which station H6 is located, show a decoupling from the expected natural inundation dynamics triggered by overflow of low dikes. This is illustrated by the comparison of the water level at T1 and the inundation maps of 2008 and 2009. The water levels at T1 in the flood years 2008/2009 are 1.8/2.1m for Figure 8a, 2.7/3.3m for Figure 8b, and 2.2/2.0m for Figure 8c, respectively. In 2009, the water level was higher than that in 2008 at the time of image acquisition, but the compartment was not flooded which indicates a later opening of the sluice gates.

b) “High stage”: During the high stage in mid-October a number of smaller channels and dikes are no longer visible. That indicates dike overtopping and, consequently, a hydraulic connection between channels and floodplains as well as between individual floodplain compartments. At this stage the inundation is uncontrollable by sluice gates in low dike systems. The sluice gates of the high ring dike systems are opened for agricultural benefits (e.g. input of sediments and nutrients).

c) “Falling stage”: In this stage human interferences start again by pumping water out of the compartments with ring dike. In Figure 8c the compartment around H6 is already dry and the new cropping period is prepared. In compartments with low dikes the pumping cannot work before the water levels in the floodplains are below the dike levels. Inspection of the water masks in Figure 8b and 8c allows identifying the compartments fully protected by ring dikes.

3.4. Floodplain inundation – temporal dynamics

The particular features of the channel-floodplain interaction identified by the satellite images, i.e. hydraulic linkage and anthropogenic interference, can be quantified in terms of their timing and capacity by the ground based monitoring system described in section 2. Figure 9 shows the hydrographs for 2009 of gauging stations in neighbouring channels and floodplains for a ring dike with high dike levels in Figure 9a, and for a floodplain with low dike levels in Figure 9b. In case of compartments with high dikes, the floodplain inundation is completely controlled by sluice gates operation. This can be seen from the comparison of the hydrographs of station T7 in the channel and H6 in the floodplain along with the ground and dike levels of the floodplain compartments. The flood level is below the dike levels indicating the flood protection character of the ring dike. The first minor flood peak does not inundate the floodplain due to closed sluice gates. The opening of the sluice gates is recorded by H6. After the opening, the inundation in the floodplain follows the channel water level with a slight delay. This delay is partly attributed to the distance between the stations, but also to the limited discharge capacity of the sluice gates. This limits the reaction of the floodplain to water level changes in the channels, causing a weaker hydraulic connection compared to low dike compartments. This weak hydraulic connection is also responsible for the low tidal influence on the floodplain hydrograph compared to the channel. At the end of the flood season the closing of the sluice gates and the operation of the pumps are detectable by the divergence of the time series in the floodplains and the channels. The water level in the floodplain drops linearly without any visible tide influence, indicating the pumping operation and pumping capacity.

In contrast, the inundation of floodplain compartments with low dike levels is controlled by dike overflow. This is shown in Figure 9b by the comparison of the hydrographs of H11 in the channel and H3 in the floodplain. The onset of the floodplain inundation is clearly related to the lowest dike levels in the vicinity of H3. As soon as this level is exceeded, the floodplain inundation starts and quickly balances with the water level in the channel. The hydraulic connection between channel and floodplain is established over the entire length of low dikes and is thus more direct compared to ring dikes with high dike levels. Figure 9b illustrates the close match between floodplain and channel hydrographs including the tidal influence. The pumping in these compartments cannot start before the water level drops below the dike level. Figure 9b also shows this effect: The divergence of the floodplain and channel water levels starts as soon as the dike level is reached. Then, the floodplain water level decreases linearly, indicating the pumping operation.

Using the recorded time series and topographical information, the capacity of the sluice gates and the pumps could be quantified. Table II lists the maximum volume of different compartments and the time required to fill up the compartment until equilibrium level. From these values the average discharge of all sluice gates of the specific compartment or the combination of sluice gate discharge and dike overflow can be calculated. It can be seen that the sluice gates in the high ring dike of H6 have the lowest capacity which explains the weak hydraulic connection discussed above. This hydraulic link has direct implications for the sediment budget in the floodplains.

Similarly, the capacity of the pumps operated in the different floodplain compartments could also be estimated from the water level records. Table III shows that the high ring dike at H6 has a higher pump discharge and a higher volume. Since high ring dikes are intended to grow three crops per year, they are provided with higher pumping capacities compared to low ring dikes. This shows that if more high ring dike compartments are constructed, more water will be pumped out at the falling-flood stage, possibly leading to higher flood hazard downstream.

The analysis shows that human activities influence the floodplain inundation in two ways. First, the construction of dikes for different purposes and, hence, protection levels influence the flood propagation. Second, the floodplain inundation and the associated sediment budget are heavily influenced by the operation of sluice gates in the rising stage and pumps in the falling stage. Hence, the size of the sluice gates and the operation schemes are key factors in the hydraulic linkage between channel (high concentration of sediment) and ring dike compartment (low concentration of sediment). The development of new ring dike compartments in the next decades has to take into account both aspects, the sediment trapping and the water pumping induced flood hazard to downstream areas.

4. CONCLUSIONS

The annual floods are the basis of the livelihoods of about 17 Million people in the Mekong Delta, but they also pose a considerable hazard in case of extreme events exceeding the control levels. Therefore, a thorough understanding of the natural flood regime and of the interaction with the human control is vital for flood risk management, as well as for the economic development of the area. While the large-scale flood characteristics are quite well known, the influence of control measures on the local floodplain inundation has not been studied in detail. The dynamics of floodplain inundation in the Mekong Delta is practically unknown. This study quantified, for the first time, the dominant mechanisms, exemplarily for a typical area in the Plain of Reeds in the North-Eastern part of the Vietnamese Delta. Our main findings are:

- The flood season can be distinguished into three different phases with their own specific hydraulic features: A rising stage where the inundation start in the floodplains is controlled by dike elevation and control of sluice gates, a high stage where floodplains and channels are hydraulically linked and the inundation dynamics are governed by the natural flood regime, and finally a falling stage where human control of inundation levels is resumed by pumping water out of the floodplains which prematurely disconnects the floodplains from the channels.
- An important aspect of the hydrology in the Delta is the tidal influence. A wavelet analysis of water level time series from all over the Delta for representative low flow, average and high flow years identified the contribution of the two different tidal modes affecting the Delta differently in different locations. In addition, the travel time between the coast and the analysed stations could be quantified for the different flow conditions. This information is an important prerequisite to estimate the tidal contribution to floodplain inundation, in particular in relation to the expected sea level rise as consequence of climate change.
- The human impact on floodplain inundation through sluice gate operation and pumping could be quantitatively described. The hydraulic linkage between channels and floodplains differs between different types of floodplains. Floodplains in high ring dikes have a weaker hydraulic linkage; this link is governed by the capacity of the sluice gates. Other floodplains are more directly linked to the channels. Today’s inundation patterns are therefore patchy, compared to more continuous patterns which would result from pristine floodplain processes. Hydraulic models of floodplain processes often neglect these human controls. When implementing a hydraulic model, it is necessary to check if these human controls must be considered.
- Today, remote sensing data are extensively used for analysing hydrological and hydraulic systems. For the Mekong Delta, high resolution and high accuracy data are necessary, since the dike lines and channel network are very thin line object. However, they are key factors for flood inundation processes. The study used TerraSAR-X which is has the advantages of high accuracy and very high resolution (up to 3 m).

This data set proved to be a very valuable information source for the study. However, a problem of the X-band radar is that the short wave length cannot penetrate high and dense alto-cumulus clouds with high water contents which are typical for tropical convective thunderstorm in the Delta.

In summary, this study gave quantitative insights into the complex interaction caused by the natural flood regime and the human interference of channel-floodplain inundation in the Vietnamese Mekong Delta. The information gained serves as a basis for land development and flood management planning. In addition, the unique time series of floodplain inundation dynamics will serve as a valuable set for in-depth hydraulic model calibration.

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TABLES

Table I. Tide signal analysis using adapted wavelet decomposition of water level time series

	Fraction of variance due to type of tide (%)						Average tidal amplitude in Dry/Wet season (m)					
	Drought year (1998)		Normal year (1999)		Flood year (2000)		Drought year (1998)		Normal year (1999)		Flood year (2000)	
	Semi diurnal	Diurnal	Semi diurnal	Diurnal	Semi diurnal	Diurnal	Semi diurnal	Diurnal	Semi diurnal	Diurnal	Semi diurnal	Diurnal
Tan Chau	8.0	2.9	2.8	1.1	1.3	0.7	0.40/0.26	0.22/0.08	0.35/0.10	0.20/0.04	0.29/0.07	0.19/0.03
Chau Doc	11.6	4.0	3.8	1.5	1.7	0.8	0.42/0.28	0.22/0.09	0.37/0.11	0.21/0.04	0.31/0.08	0.20/0.03
Vam Nao	23.2	8.8	9.5	4.4	5.4	2.7	0.56/0.44	0.31/0.13	0.45/0.24	0.27/0.09	0.43/0.19	0.28/0.07
My Thuan	55.9	20.9	50.3	22.3	43.6	22.6	1.01/1.03	0.56/0.28	0.92/0.88	0.55/0.26	0.86/0.8	0.57/0.25
Can Tho	61.3	20.7	57.5	22.1	53.5	23.5	1.26/1.21	0.65/0.33	1.17/1.08	0.65/0.32	1.10/0.99	0.66/0.30
Rach Gia	30.4	42.6	31.3	41.3	25.1	40.2	0.34/0.29	0.36/0.19	0.33/0.28	0.34/0.18	0.31/0.26	0.35/0.18
My Thanh	66.7	23.8	63.1	26.7	60.3	29.3	1.93/1.97	1.06/0.54	1.91/1.92	1.15/0.58	1.85/1.91	1.20/0.60
Ben Trai	63.6	28.4	60.4	30.7	57.8	32.8	1.78/1.82	1.07/0.56	1.73/1.88	1.13/0.61	1.69/1.83	1.16/0.63
Vam Kenh	62.6	28.7	59.7	30.8	57.4	33.1	1.69/1.69	1.03/0.53	1.64/1.70	1.08/0.56	1.59/1.66	1.11/0.56

Table II. Sluice gate control and discharge, calculated from the recorded floodplain water level time series (T_1 is the initial time of flooding in the compartment, T_2 is the time when the water level inside the compartment equals the outside water level, $Q=V/\Delta T$, V is fill volume, $\Delta T=T_2-T_1$); at H3 the fill discharge is a combination of sluice gate and over-dike flow.

Station	Sluice opening time (T_1)	Levelled time (T_2)	Fill volume V [m^3]	Fill discharge Q [m^3/s]	Notes
H6	23/08/2009 22:15	26/08/2009 14:00	678,243	**2.95**	High dike
H12	14/08/2009 18:15	23/08/2009 12:30	2,997,487	**3.96**	Low dike
H14	13/08/2009 08:45	17/08/2009 22:15	1,890,895	**4.80**	Low dike
H3	17/08/2009 06:15	22/08/2009 08:30	3,325,825	**7.56**	Low dike

Table III. Floodplain pump volume and discharge, calculated from recorded floodplain water level time series (T_1 is start of pumping, T_2 is end of pumping, $Q=V/\Delta T$, V is pump volume, $\Delta T=T_2-T_1$)

Station	Start pumping time (T_1)	End pumping time (T_2)	Pump volume V[m^3]	Pump discharge Q [m^3/s]	Notes
H6	21/10/2009 10:30	30/10/2009 23:00	6,182,167	**7.5**	High dike
H12	10/11/2009 13:45	20/11/2009 13:00	3,164,104	**4.1**	Low dike
H14	10/11/2009 14:30	19/11/2009 24:00	2,513,140	**3.1**	Low dike
H3	11/11/2009 08:45	20/11/2009 23:15	3,336,112	**4.0**	Low dike
T3	16/11/2009 10:15	21/11/2009 05:45	1,465,617	**3.5**	Low dike

FIGURES

Figure 1. The Mekong Delta, including the major rivers and channels and the location of the study area Tam Nong

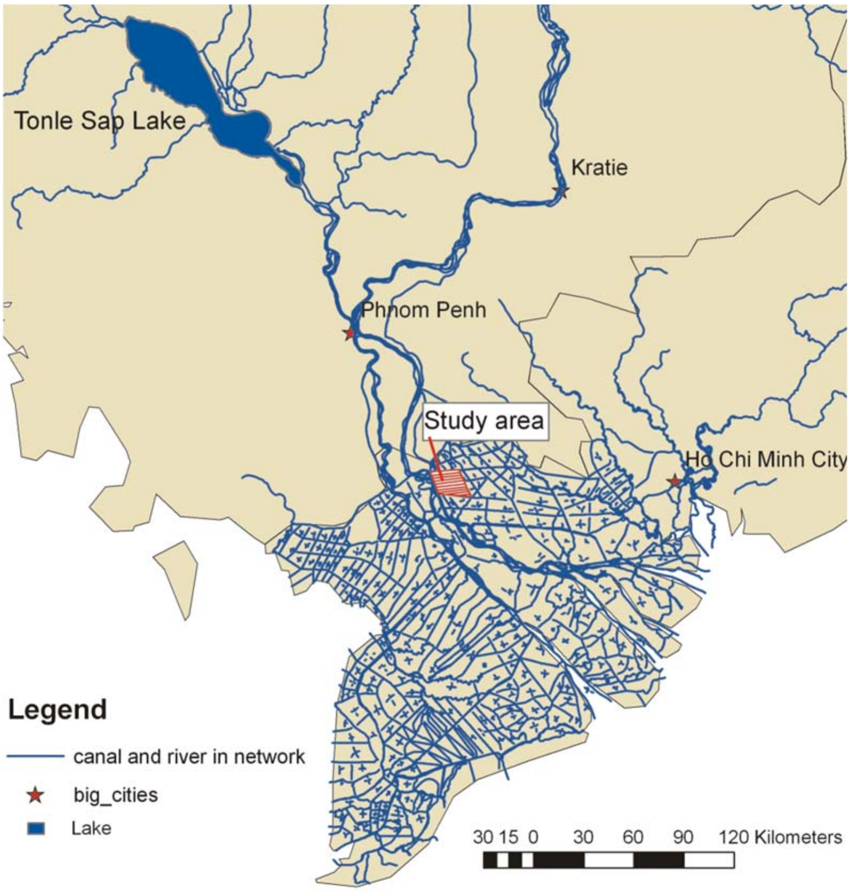

Figure 2. (a) Study area, dikes, elevation and monitoring stations, (b) Scheme of deployment of the water level probes in channels, floodplains and on low dikes, (c) Cross-section profile with schematic flood water levels due to different dike elevations, structures and control schemes.

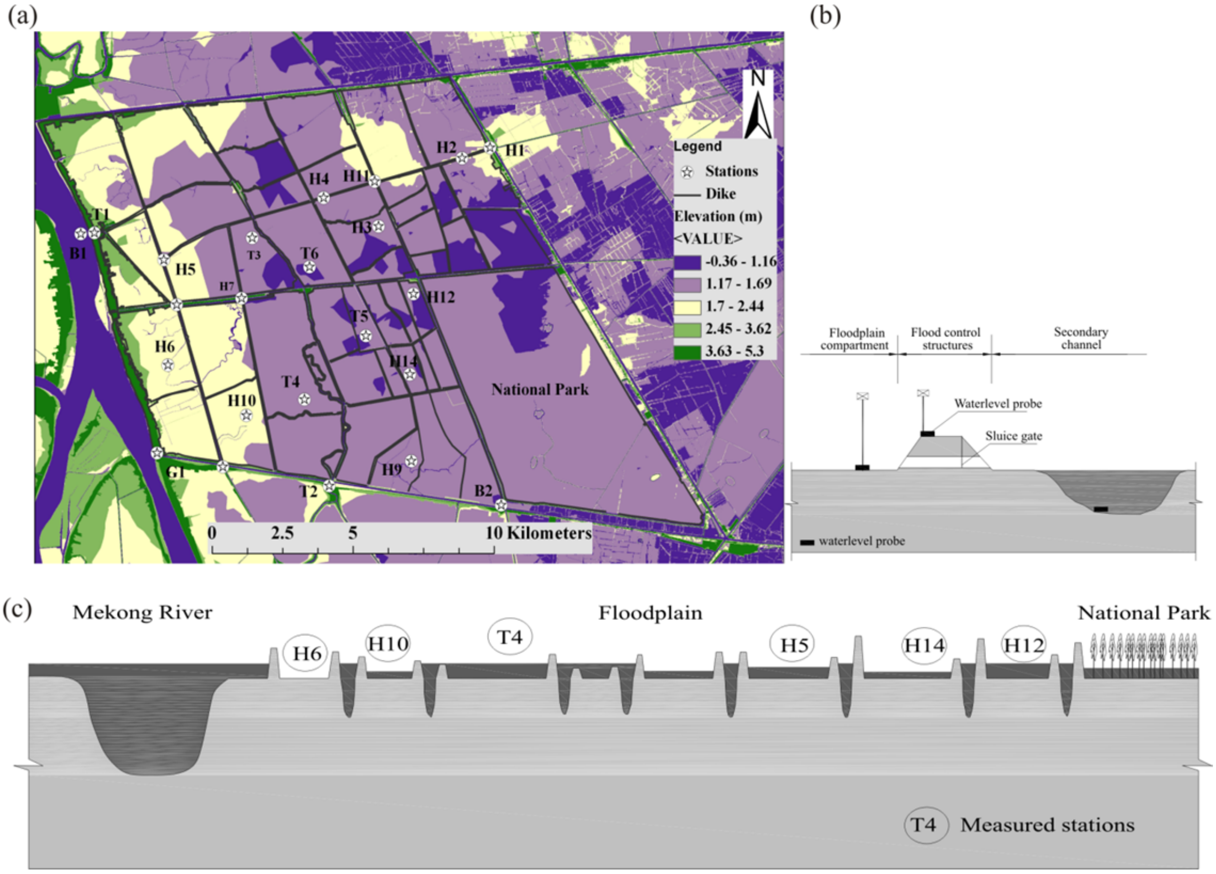

Figure 3: Water quality monitoring stations in channels (top left); water level stations in floodplains (top right), and water quality stations (bottom) in floodplains (dry and flood season).

Figure 4. Water elevation at station T1 (2008, 2009) and H11 (2009). The coloured boxes in the lower panel indicate the stage of the flood (blue = rising, green = high, red = falling).

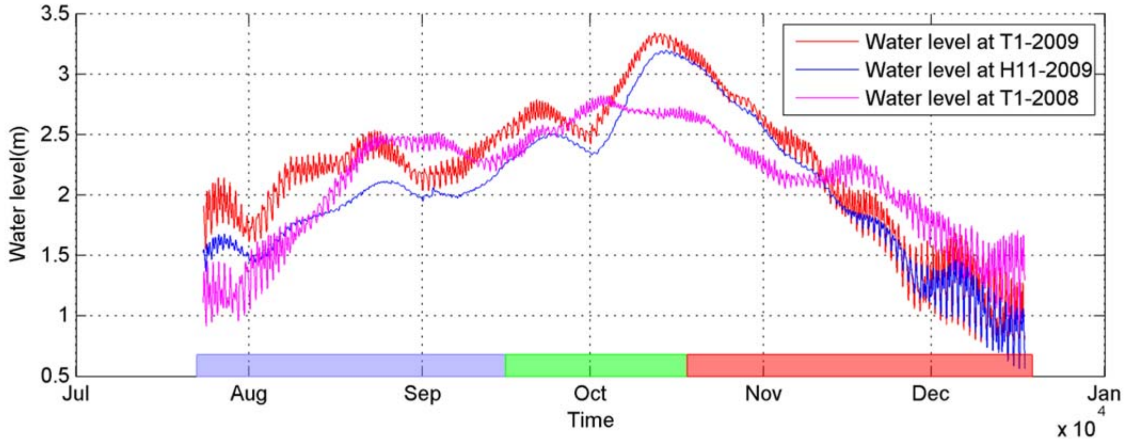

Figure 5: Stage-discharge relationships at station G1 (cf. Fig. 2) for the flood seasons 2008 and 2009. The colours indicate the stage of the flood 1) blue = rising, 2) green= high and 3) red= falling.

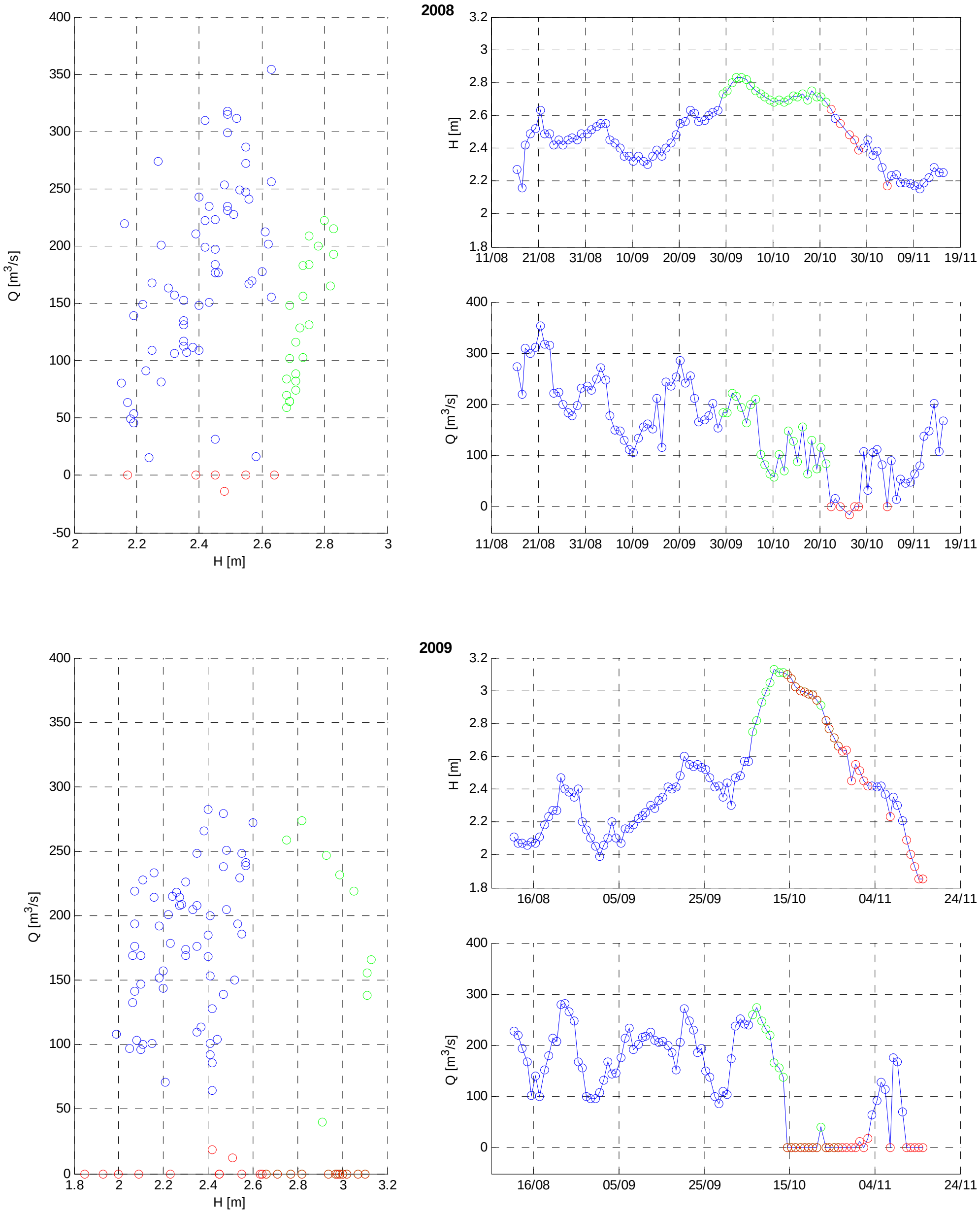

Figure 6. The tide signal of the water elevation, extracted by a Butterworth band-pass digital frequency filter with a band pass period of [low, high]=[6, 24] hours. The colour indicates different flood stages (blue = rising, green = high, red = falling).

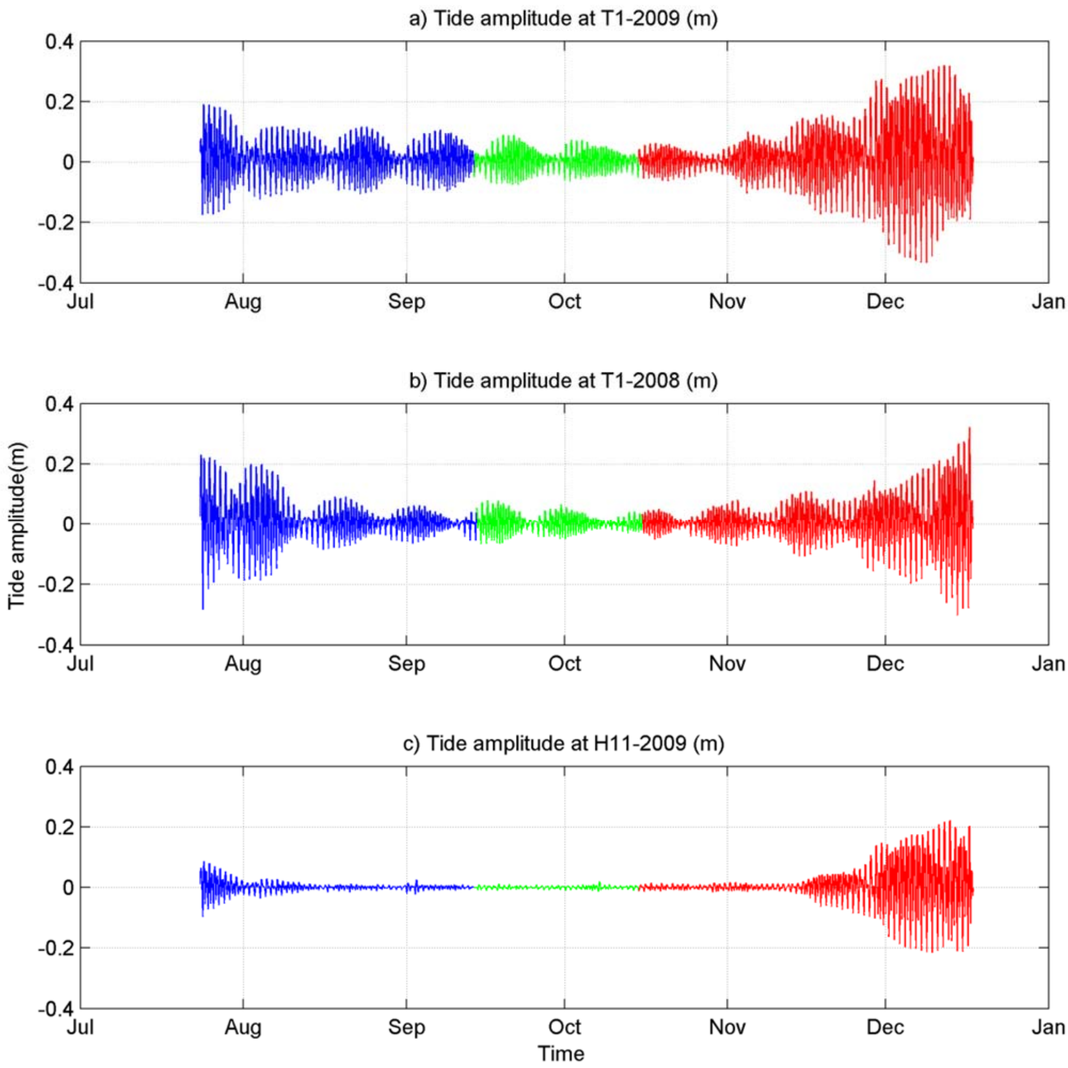

Figure 7. a) Fraction of variance attributed to semi-diurnal and diurnal tides at different locations, and time in hours for the phase lag of semi-diurnal (dark grey) and diurnal modes (light grey) for a flood year; b) travel time of tidal wave or phase difference between My Thuan and Tan Chau (black) for a flood year; water level at Tan Chau is also given (gray). The shaded area was not used for calculating the average travel time because the tidal signal at Tan Chau was close to zero during this phase.

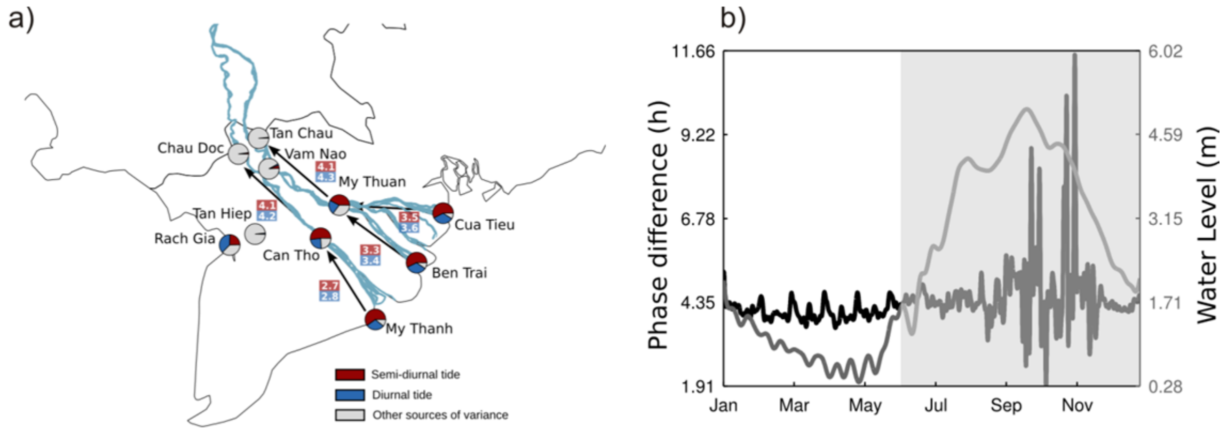

Figure 8. Inundation maps of the study area derived from TerraSAR-X satellite images during the flood seasons 2008 and 2009 (blue = water, light yellow = no water, green = low dike, red = high dike); a) the “rising” stage, where the influence of flood control structures can be inferred comparing 2008 and 2009 in the surrounding area of station H6 and east of H11 and H3, b) the “high” stage features complete inundation of the area with flow over low dikes, c) in the “falling” stage the effect of the water pumping is visible, again most pronounced in the enclosed ring dike of station T6. The red circle shows high convective alto-cumulous clouds with high water contents which are typical for tropical thunderstorms. These clouds cannot be penetrated by the X-band radar and the diffuse scattering from the clouds is interpreted as dry surface area.

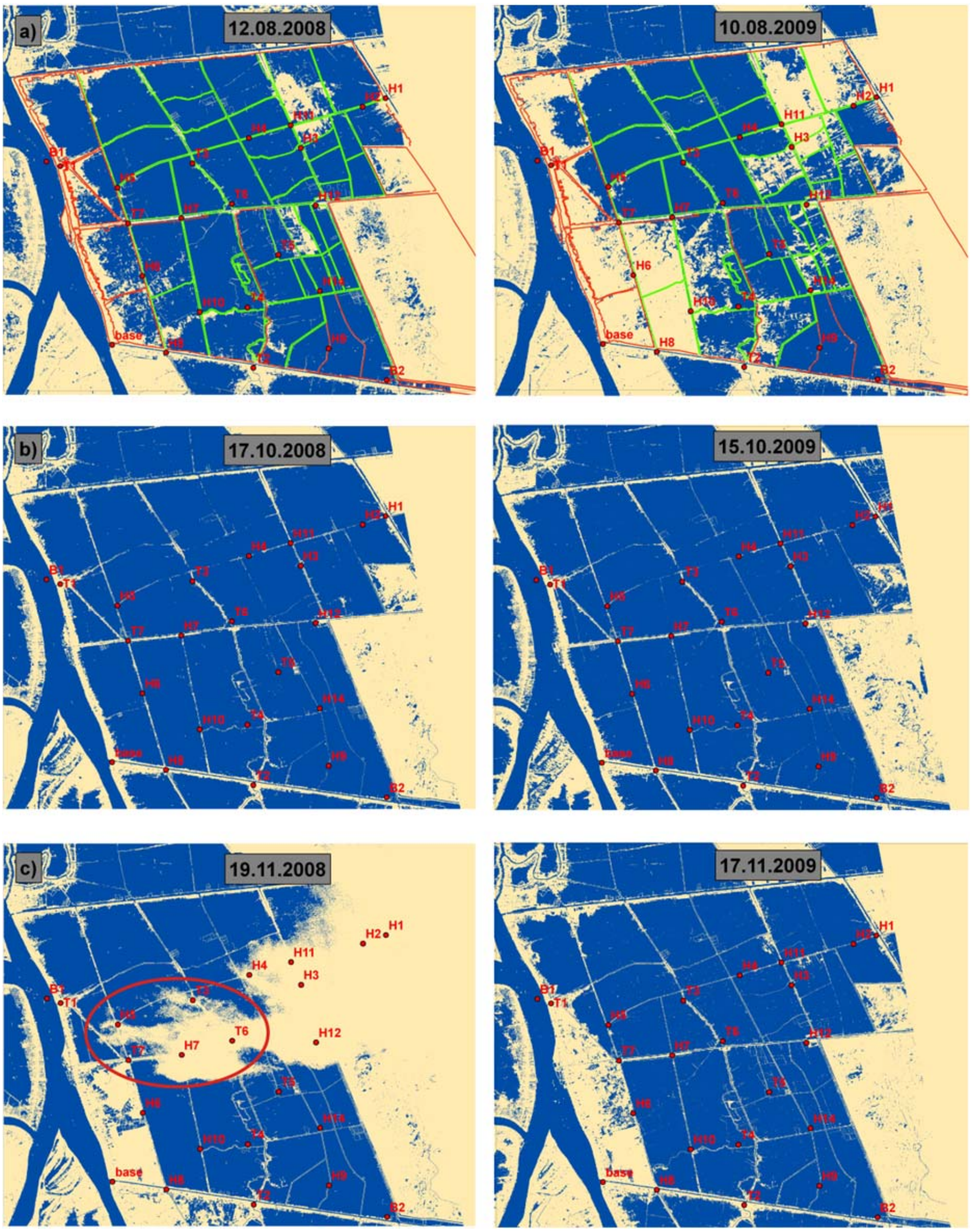

Figure 9. Comparison of channel and floodplain hydrographs in a ring dike with high flood protection dikes (a) and a floodplain compartment with low dikes (b) for the flood season 2009.