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Le, T. N., Bregt, A. K., van Halsema, G. E., Hellegers, P. J. G. J., & Nguyen, L-D. (2018). Interplay between land-use dynamics and changes in hydrological regime in the Vietnamese Mekong Delta. Land Use Policy, 73, 269-280. DOI: 10.1016/j.landusepol.2018.01.030

# Interplay between land-use dynamics and changes in hydrological regime in the Vietnamese Mekong Delta

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## ABSTRACT

Policies supporting rice production and investments in water infrastructure enabled intensification and diversification of farming systems in the Vietnamese Mekong Delta (VMD) over the past 20 years. Yet, demands of food security, economic development, and climate change continue to pose diverging and often conflicting challenges for water resources management in the upper, central, and coastal zones of the delta. The major changes effected in the VMD's hydrological regime and land-use patterns are acknowledged in the literature, but few studies have examined the interplay between these dynamics at the delta scale. Based on time-series maps and statistical data on land-use, flooding, and salinity intrusion, we investigated the interrelations between land-use dynamics and changes in hydrological regime across the VMD in three representative periods. Land-use was found to be highly variable, changing by 14.94% annually between 2001 and 2012. Rice cropping underwent the greatest change, evolving from single cropping of traditional varieties towards double and triple cropping of high-yielding varieties. Aquaculture remained stable after rapid expansion in the 1990s and early 2000s.

Meanwhile, flooding and salinity intrusion were increasingly controlled by hydrological infrastructure erected to supply freshwater for agriculture. Effects of this infrastructure became particularly evident from 2001 to 2012. During this period, spatial and temporal impacts on flooding and salinity intrusion were found, which extended beyond the rice fields to affect adjacent lands and livelihood activities. Unforeseen effects will likely be aggravated by climate change, suggesting a need to rethink the scale of planning towards a more integrated hydrologic approach.

*Keywords: land-use change, hydrological regime, land-use planning, water resources management, Mekong Delta, Vietnam*

## 1. Introduction

Surface water, including reservoir water and stream flows, is essential for human activities, particularly for agriculture, forestry, and fisheries. Indeed, land-use and water resources are reciprocally related and mutually dependent. Water availability shapes land-use patterns; and the way that land is utilized affects water supplies and quality. As discussed by Calder (2005), afforestation, intensive agriculture, and urbanization have changed hydrological regime, leading to diminished water quality in developing countries. This has contributed to changes in the global hydrological cycle, which in turn are considered a main factor causing erosion and more than half of the world’s soil degradation – resulting in reduced agricultural land availability. Understanding how changes in land-use interrelate with changes in hydrological regime is therefore crucial, at the global and at the regional level.

The interplay between land-use patterns and water resources is particularly manifest in large deltas where agriculture is the dominant livelihood. In one such delta, the Vietnamese Mekong Delta (VMD), satellite observations from 2000 to 2007 suggest that particular farming systems have been employed to deal with seasonal variations in the water cycle (Sakamoto et al., 2009b, 2006). In the upper delta, before permanent dykes were built, farmers practised double rice cropping in the dry season to avoid the risks posed by flooding in the rainy season. In the central delta, farmers practised triple rice cropping, while also cultivating perennial crops taking advantage of the fertile alluvial soil and year-round availability of freshwater. In the coastal zone, farmers practised double and single rice cropping in the rainy season, as salinity intrusion and limited irrigation water constrained dry season cultivation. To adapt to the brackish conditions spanning six months of the year, many coastal farmers adopted rice-shrimp farming systems or converted their rice fields to shrimp ponds.

Over the last 20 years, seeking to increase rice production in the VMD, the Vietnamese government invested in new infrastructure to better manage the delta’s hydrological regime (Tri, 2012). By 2011, dykes and sluice gates offered flood protection to most of the rice fields in the upper and central zones (Duong et al., 2014; Kuenzer et al., 2013). Dykes, sluice gates, and water supply canals were also built in the coastal zone, to prevent salinity intrusion and facilitate rice cultivation (Hoanh et al., 2012; Toan, 2014).

This greater management of the hydrological regime, alongside increasingly intensive rice farming, has raised concerns, however, about impacts on the environment and livelihood activities. Indeed, dyke construction has reduced water retention capacity throughout the upper delta, while increasing the risk of flooding and erosion downstream (Käkönen, 2008). Furthermore, the large quantities of water abstracted from rivers for intensive rice farming have worsened salinity intrusion in the coastal zone, affecting fruit orchards and rice fields as far inland as the central delta (Hashimoto, 2001; Nhan et al. 2007). In the brackish areas, the prospect of high-value shrimp production has motivated farmers to try to retain saline water in their ponds. This, however, conflicts with the needs of rice farmers and the design of hydrological infrastructure (Hoanh et al., 2003)

Recognizing the consequences of its rice-oriented agricultural policy, the Vietnamese prime minister has sought to restructure the agriculture sector. With its Resolution 899, the government has aimed to raise the added value in agriculture while promoting sustainable development (Government of Vietnam, 2013). A planning exercise has also been completed, in which the Vietnamese government cooperated with the Dutch to develop a long-term vision for the VMD (Royal Haskoning DHV et al., 2013). Both the new policy and the development vision respond to challenges of economic development and climate change. Temperature and rainfall models suggest that flooding will become increasingly difficult to forecast in the upper delta, and that rising sea levels and more frequent severe droughts will cause salinity intrusion to occur for longer periods in the coastal zone and extend farther inland (Tri et al., 2013; Trung and Tri, 2014). Meanwhile, household surveys indicate that 65% of the region's farmers anticipate continuing their current livelihood practices, including their current land-use, even if sea levels were to rise by 30 cm (Smajgl et al., 2015). In this context, a better understanding of the factors driving changes in land-use, particularly changes in the hydrological regime, could help policymakers formulate effective management plans tailored to the different agro-ecological zones of the delta, while also mitigating water-related conflicts between delta regions.

Although the general mechanisms are understood, it remains difficult to specify exactly how changing land-use patterns interrelate with changes in hydrological regime, because these systems act at different spatial and temporal scales. Remote sensing has been widely used to monitor and investigate correlations between land-use patterns and flooding at the delta scale (Kuenzer et al., 2013; Sakamoto et al., 2007). Moreover, hydrological models and GIS analysis have been applied to explore the impacts of salinity intrusion on land-use patterns within a particular hydrological system (Hoanh et al., 2006; Tuong et al., 2003). While these techniques have proven useful for studying developments in land-use patterns and hydrological regime, as well as their interactions, little research has investigated the cross-boundary interplay between these variables at the delta scale. Previous studies have looked at how changing land-use interacts with the drivers of such change, including hydrological regime, at the household and community levels, using interview and statistical data to assess the role of the different drivers (Can et al., 2007; Ha et al., 2013; Hoang et al., 2008; Renaud et al., 2015). Such localized findings, however, fall short in representing the full spectrum of relations at the delta scale, particularly for a delta as complex as the VMD, with its range of agro-hydrological zones.

The current study sought to deepen insight on the land-water relationships throughout the VMD. Using secondary sources, such as scientific reports, statistical data, and maps, we systematically investigated the characteristics of land-use dynamics, hydrological regime, and the interactions between these in the VMD over three representative study periods extending from prior to 1995 to 2012.

## 2. Study area

The VMD spans 39,700 square km and is home to nearly 18 million people. This fertile delta produces more than half of Vietnam's rice output. Some 64% of the delta is devoted to agricultural purposes (GSO, 2012), and 69% of its labourers work in agriculture, forestry, or fisheries (Vormoor, 2010).

There are two main river systems in the VMD, the Mekong or 'Nine Dragons' and the Vam Co. We focused on the Mekong river system, as it is the delta's most dominant. The Mekong system flows from Cambodia to Vietnam in two main streams: the Bassac river and the Mekong river, which contribute, respectively, 17% and 87% of the total annual flow. The Mekong links to the Bassac via the Vam Nao river, eventually discharging from the Bassac into Vietnam's East Sea and West Sea (Tri, 2012). The Bassac has two tributaries, while the Mekong has six tributaries. These are interconnected via a dense network of natural streams and canals. In the rainy season, water-flows increase, causing prolonged inundation of the upper delta. In the dry season, low river flows and high tide events raise the salinity of the waters and soils along the coast, making water shortages and salinity intrusion serious problems.

This seasonal regime has played a key role in the delta's agricultural development. Floods and water flows have been managed by water infrastructure since the early 19th century. The first canal network and waterways that shaped the VMD today were built under political efforts of the Vietnamese and French authorities as well as the American army. After the end of the Vietnam War in 1975, hydraulic works continued to be conducted by the government and locals (Biggs, 2011; Evers and Benedikter, 2009; Hoanh et al. 2010). To utilize and manage water flows, a huge infrastructure has been built, including 15,000 km of main canals, 27,000 km of secondary canals, 50,000 km of on-farm canals, 80 large sluice gates, 13,000 km of flood-prevention dykes, 1,290 km of salinization-prevention dykes, and 450 km of sea dykes (SIWRP, 2011).

The dominance of rice cultivation in the VMD nowadays is a product of explicit government policy to ensure food security, which was initiated after the 1980s, when the country became a net rice importer. Much of its current flood- and salinization-control infrastructure was completed or has been upgraded since 1990. The resulting improved water management has enabled triple rice cropping on the floodplains and in brackish zones of the delta. Moreover, enlargement of canals and drainage systems has allowed farmers to reclaim areas with acid sulphate soils for rice cultivation. These hydrological interventions, while expanding the region's agricultural potential and boosting rice output, have also led to natural resources degradation and affected farmers' livelihood options (Käkönen, 2008).

## 3. Materials and methods

We analysed changes in land-use patterns and the hydrological regime in the VMD based on three representative periods, which were derived from literature documenting historical events affecting these variables. The literature includes scientific articles and book chapters related to topics of 'land-use change', 'farming systems', 'water resources management', 'flood management', and 'salinity intrusion' in the VMD. Our review particularly explored reports of the Southern Institute of Water Resources Planning (SIWRP) and references used in the Germany-Vietnam WISDOM project (**W**ater-related **I**nformation **S**ystem for the Sustainable **D**evelopment **o**f the **M**ekong Delta in Vietnam). The study periods are as follows: (1) prior to 1995, (2) from 1995 to 2000, and (3) from 2001 to 2012 (Table 1).

**Table 1**
Three study periods identified based on historical events affecting land-use patterns and hydrological regime in the VMD.

| **Period and highlights** | **Historical events** |
|---|---|
| Prior to 1995<br>• Low rice production<br>• Food security crisis | 1967: Introduction of high-yielding rice varieties (HYVs) (Tanaka, 1995)<br>1975: End of the Vietnam War, start of land reform/collectivization<br>1986: Start of the *Doi Moi* economic reform<br>1988: De-collectivization of land/agricultural production (Pingali and Xuan, 1992) |
| 1995–2000<br>• Remarkable growth of rice production<br>• Vietnam joined the market-oriented economies | 1995–1997: Freshwater supply canals and high dykes reinforced or built throughout the delta (Can et al., 2007)<br>2000: Resolution 09 allowed high-value farming (fruit and shrimp) to replace low-value farming (rice) (Hoang et al., 2008)<br>2001: Boom in aquaculture in the coastal zone (Binh et al., 2005) |

| | |
|---|---|
| 2001–2012<br>• Dominance of market-oriented economics<br>• Increased impacts of intensive rice and fish farming | 2001: Water conflicts between shrimp farmers and rice farmers in the Quan Lo-Phung Hiep project (Hoanh et al., 2003)<br>2006: Rice output undermined by brown plant hopper outbreak (Sakamoto et al., 2009a)<br>2011: Master plans for water resources management in the VMD to deal with climate change and sea level rise (SIWRP, 2011) |

### 3.1. Characterization of land-use dynamics

Land-use dynamics can be spatially characterized in various ways, depending on the data available. For instance, official statistical data, such as area devoted to a particular land-use within a region, can indicate trends over time even when the exact location of farms is unknown (Vormoor, 2010). Another approach is use of satellite images and land-use maps to analyse land-use patterns and the sequence and frequency of changes over time (Sakamoto et al., 2009a). We adopted different land-use characterization methods for each of our study periods, as different types of data were obtainable. We furthermore examined changes in land-uses in three regions of the delta – the upper delta, the central delta, and the coastal zone – as each represents a different agro-ecological zone (Can et al., 2007) (Fig. 1).

As statistical data and digital land-use maps were unavailable for the first period, we synthesized information on land-use from the literature, focusing on the transition from the traditional rice monoculture farming system in use prior to the 1970s to the diversified farming systems of the early 1990s. For the second period, we used statistical data from the website of the General Statistical Office of Vietnam to identify trends in land-use. Nonetheless, limited availability of time series data meant that rice and inland aquaculture could only be analysed at the provincial level (GSO, 2012). For the third period, we utilized maps from the Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization, Japan (NIAES) (GAEN-View, 2013). Each map included 11 land-use types, classified based on Moderate Resolution Imaging Spectroradiometer (MODIS) (250 m x 250 m) (Sakamoto et al., 2009a). Overlaying land-use maps, we identified unchanged areas and calculated percentages of change in land-use throughout the delta. The dynamics of land-use was defined by the number of changes observed during the 11-year study period. We validated our spatial analysis using 2001–2012 statistical data.

The spatial and statistical data provided is rather precise in the distinction between the different types of rice cropping, but they are very limited in distinguishing different types of shrimp farming. In reality, shrimp farming has been practiced in various systems such as the extensive system, the improved extensive system, the rice-shrimp farming system, and the intensive shrimp farming system (Joffre and Bosma, 2009; Ha et al., 2013). Due to this limitation of data sources, we could not analyse the dynamics of the aquaculture land-use in details.

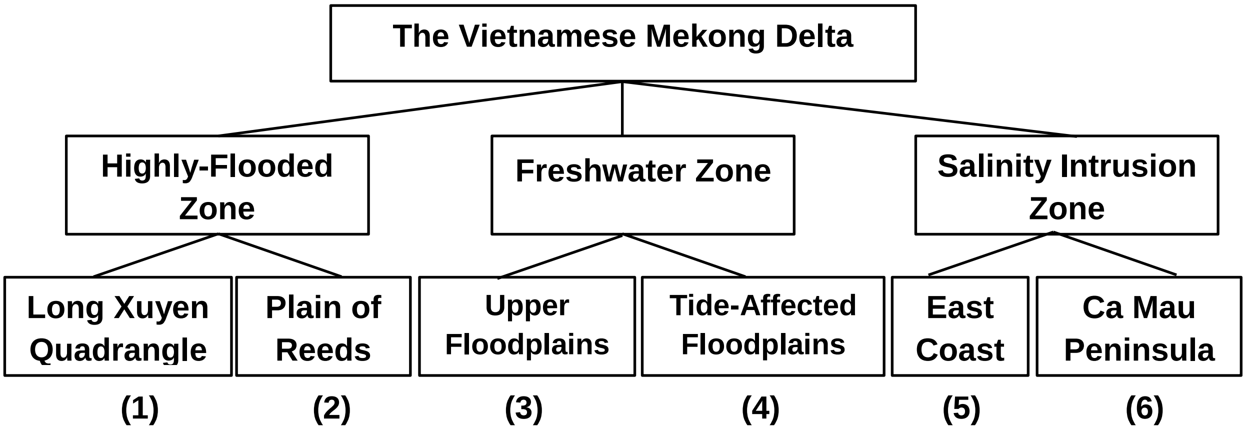
### 3.2. Characterization of hydrological regime

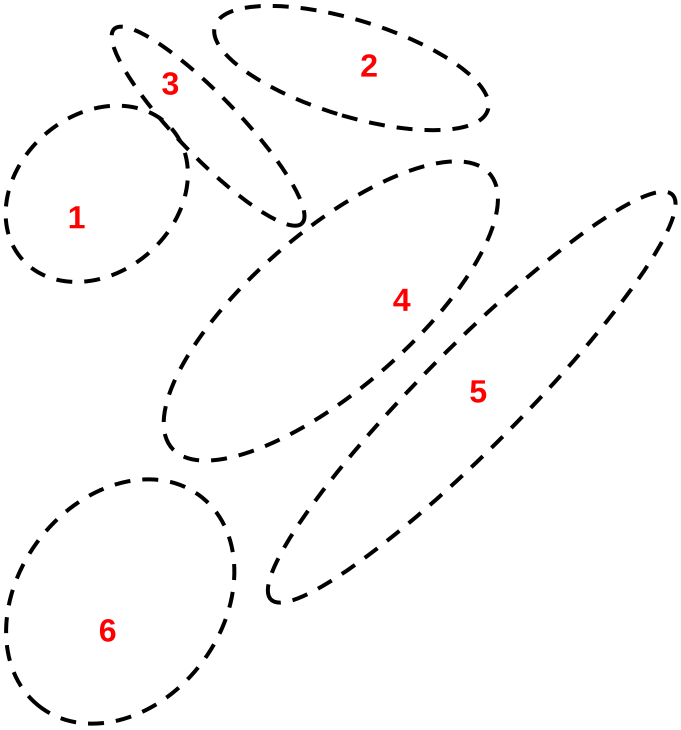
Hydrological and environmental studies typically represent hydrological regime using physical variables, such as rainfall, water discharge, water level, tidal range, and topography (Tri, 2012). However, aspects such as water quantity and quality are also important determinants of land-use and agricultural patterns. Flooding in the rainy season and salinity intrusion during the dry season are two manifestations of the hydrological regime that greatly influence land-use patterns in the VMD (Sakamoto et al., 2007; Smajgl et al., 2015). Similarly, human interventions impact the local effects of hydrological regime (Hoanh et al., 2012; Le et al., 2007). Our research therefore considered hydrological regime as a function of both physical variables and human interventions, the latter being mainly new water control infrastructure.

Due to limited availability of spatial data prior to 2000, we characterized hydrological regime in our first two periods using evidence from the literature, supplemented by monthly average water levels at the Tan Chau monitoring station since 1976. This station is located in the upper delta and measures water levels where the Mekong river flows from Cambodia into the Bassac river. For our last period, we used remote sensing and GIS data to investigate spatial-temporal changes in hydrological regime. The highest flood-extent in 2000 and in 2007–2012 was detected by remote sensing instruments such as Envisat ASAR  (Kuenzer et al., 2013) and MODIS (Duong et al., 2014; Sakamoto et al., 2007). The boundaries of salinity intrusion were digitalized in 2000, 2005, 2008, and 2009 using maps provided by the Southern Institute of Water Resources Research. Because most paddy rice varieties require salt concentrations less than 4 g/l (Nhan et al., 2010), these maps trace the 4 g/l salinity contour in April, when salinity intrusion typically peaks (Tri, 2012). Maps showing the main water control infrastructure were developed using information from hydrological reports (SIWRP, 2011; Toan, 2014). Data on flooding and salinity intrusion enabled us to determine the natural boundaries of the different hydrological zones. The hydrological regime map was updated based on the years in which water control infrastructures were completed, thus reflecting spatial changes in the hydrological zones over time.

### 3.3. Interplay between land-use dynamics and hydrological regime

To investigate the interplay between land-use dynamics and changes in hydrological regime in our three representative periods, we identified and analysed land-use patterns in six agro-ecological zones. These reflect particular topographies, soils, water resources, and farming systems (shaded areas in Fig. 1). Thus, in the upper delta we focused on the Long Xuyen Quadrangle, the Plain of Reeds, and the upper part of the Freshwater Alluvial Zone. (The Hill and Mountainous Zone was not included in our analysis because of its small relative size.) In the central delta zone, we investigated the lower part of the Freshwater Alluvial Zone and the Trans-Bassac Depression. In the coastal zone, we examined the Ca Mau Peninsula and the East Coast, which consist of sand ridges unaffected by salinity intrusion, coastal flats, inter-ridges affected by salinity intrusion in the dry season, and mangroves highly affected by salinity intrusion (Can et al., 2007).





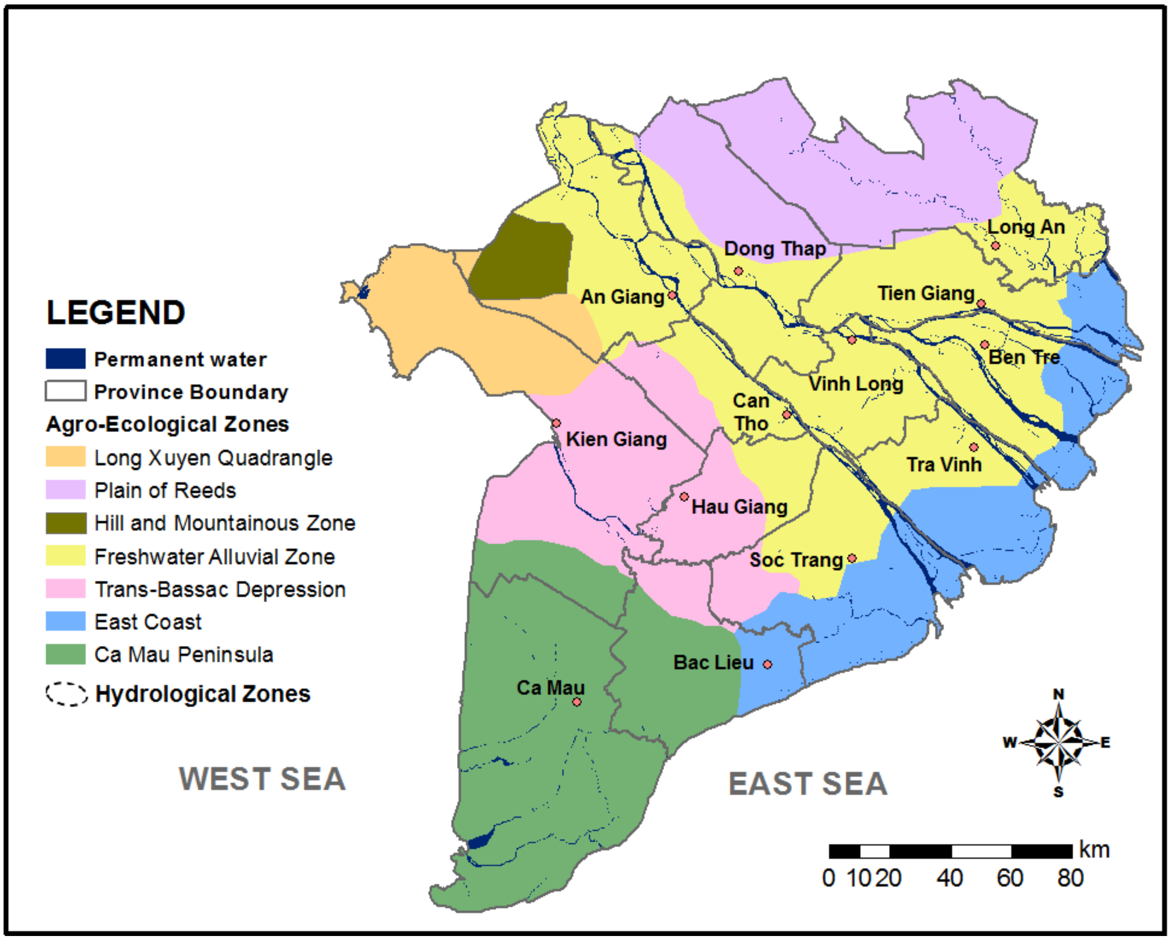


**Fig. 1**. Agro-ecological zones (shaded) and hydrological zones (circled) in the Vietnamese Mekong Delta. The upper panel describes the hydrological hierarchy.
*Source:* Can et al. (2007); Tuan et al. (2007); Vormoor (2010); created by the author.

For hydrological regime, six hydrological zones were identified (Tuan et al., 2007; Vormoor, 2010) (circled areas in Fig.1). Two zones, (1) the Long Xuyen Quadrangle and (2) the Plain of Reeds, were classified as highly flooded. Two zones were identified as freshwater: (3) the Upper Floodplains in the upper delta and (4) the Tide-Affected Floodplains in the central delta. Finally, two salinity intrusion zones were identified: (5) the East Coast and (6) the Ca Mau Peninsula (Tuan et al., 2007; Vormoor, 2010).

Finally, we synthesized our characterizations of land-use patterns and hydrological regime to distinguish different agro-hydrological zones (Appendix A). In these different zones, we qualitatively analysed the interplay between land-use dynamics and changes in the hydrological regime by looking at spatial and temporal changes in each representative period.

## 4. Results

### 4.1. Land-use dynamics

#### 4.1.1. Prior to 1995

Prior to 1995, land-use patterns in the VMD evolved towards more modern, diversified agricultural systems in three stages: (1) the traditional farming system practised prior to 1967, (2) the rice monoculture farming system of the 1970s and 1980s, and (3) the early diversified farming system from 1986 to 1995 (Tanaka, 1995).

In the traditional farming system, famers practised seasonal cropping of local rice varieties. Rice was grown six months of the year, during the rainy season, with only one crop produced annually. Thus, seasonal rice cropping is also called single crop rice. Rice was cultivated in areas with sufficient freshwater and favourable soils, mainly in the upper and central delta and in the higher-altitude alluvial lands of the coastal zone. Rice cultivation was very limited during this period in the Long Xuyen Quadrangle and the Plain of Reeds, due to the high acid sulphate content of soils and deep inundation during the flood season. Swamps and Melaleuca forests were dominant in these areas. Due to high salinity intrusion, mangroves covered much of the East Coast and the Ca Mau Peninsula.

When high-yielding rice varieties (HYVs) were introduced in 1967, most VMD farmers switched from local varieties to HYVs, which took only three months to harvest. This meant that farmers could grow two crops each year. At first, double cropping consisted of seasonal rice and HYVs. Then, double cropping shifted to only HYVs, with cultivation planned to avoid peak flooding. In the upper delta, besides growing HYVs, some farmers kept growing ‘floating rice’, a local variety that could withstand even deep inundation (Chiem, 1994; Tanaka, 1995). After the Vietnam War ended in 1975, rice production throughout the country and in the VMD declined notably due to changes in economic policy and land ownership – though farmers still grew HYVs. Drops in production forced Vietnam to import rice in the 1980s (Pingali and Xuan, 1992). To ensure sufficient food supply, the government initiated a rice-production stimulation policy. Canals were enlarged to reclaim land for rice cultivation, and farmers were encouraged to relocate to areas with acid sulphate soils and more saline waters, to bring these lands into cultivation too. Large expanses of fallow lands and forests in the Long Xuyen Quadrangle, the Plain of Reeds, and the Ca Mau Peninsula were converted into rice fields. However, the unfavourable soil and water conditions there meant that farmers could produce only a single rice crop. In the whole of the delta, rice monoculture was the dominant land-use at this stage.

After the economic reforms began in 1986, farmers became more active in managing their lands and agricultural production. Triple rice cropping, which had not been allowed previously due to the greater risk of pest outbreaks, became widely practised in favourable areas, particularly in the central delta. Moreover, stimulated by new market opportunities and the potential to earn additional income from other high-value products, farmers in the central delta began to diversify, integrating double rice cropping with cash crops, fruit tree cultivation, fish farming, and freshwater shrimp production. In the upper delta, the area devoted to double rice cropping quickly expanded, and this farming system became dominant in the early 1990s (Chiem, 1994). Areas where triple rice cropping was possible were still limited, however, due to flooding. While farmers in the upper delta practised double rice cropping with cash crops, or rotated ‘floating rice’ with cash crops, diversification in this region was less pronounced than in the central delta. In the Plain of Reeds, single rice cropping continued on favourable lands, while other lands were converted back to forest for conservation purposes. In the coastal zone, farmers tried to integrate single rice cropping with shrimp or fish farming, or alternated rice cropping in the rainy season with brackish shrimp farming in the dry season. This is the original practice of the rice-shrimp farming system. Besides, the extensive system which was the brackish aquaculture availing of naturally occurring species had begun its expansion along the coast by the end of this period, (Tanaka, 1995).

Two decades after the war, notable land-use changes could be observed in the VMD. In the upper and central delta, the rice cropping pattern had changed significantly, particularly from single cropping to double cropping. The dominant trend was towards more intensive rice cultivation, stimulated by the availability of HYVs and government policy to boost food security. Diversification of farming systems was also observed in some villages, led by innovative farmers. Another change was in the acid sulphate soil areas, where fallow lands, swamps, and Melaleuca forests made way for single cropping rice fields. In the brackish areas, large expanses of mangrove were replaced by rice-shrimp farming systems, and some brackish aquaculture emerged (Tanaka, 1995).

#### 4.1.2. From 1995 to 2000

From 1995 to 2000, land-use in the VMD evolved towards intensive rice farming. Descriptive statistics at the delta level show that the area under seasonal rice diminished by 28%, while the total area planted to rice increased by 24% (Table 2). The total area planted to rice represents the sum of seasonal rice, summer-autumn rice, and winter-spring rice. In the double rice cropping system, winter-spring rice was cultivated from November/December to February/March, and summer-autumn rice was cultivated from May/June to August/September

(GSO, 2012). Thus, the area under seasonal rice diminished whereas the area of the other two rice cropping systems substantially increased.

At the provincial level, the total area planted to rice in the central and upper provinces was consistently larger than in the coastal provinces. In 1995, Can Tho province, in the central delta, had the largest area devoted to rice cultivation, occupying 401,800 ha. Five years later, that distinction had shifted to Kien Giang (541,000 ha) and An Giang provinces (464,400 ha) in the Long Xuyen Quadrangle. Meanwhile, Ben Tre province, in the coastal zone, had the smallest area devoted to rice cultivation, occupying 92,700 ha in 1995 and 101,600 ha in 2000. Seasonal rice was grown mostly in the coastal provinces while the smallest areas under seasonal rice were found in the central delta. In 1995, the three coastal provinces with the largest area under seasonal rice were Ca Mau (169,500 ha), Soc Trang (132,600 ha), and Bac Lieu (111,600 ha). Though this area had decreased five years later, Ca Mau (147,000 ha) and Bac Lieu (98,300 ha) remained in the top three. (GSO, 2012)

The total area planted to rice increased sharply from 1995 to 2000 in coastal provinces such as Ca Mau, Bac Lieu, Soc Trang, and Tra Vinh. Among them, Bac Lieu showed the greatest change, at 67% (Table 2). Overall, the coastal zone recorded the highest percentage of change in rice cropping, while the largest areas planted to rice were found in the upper and central delta. This trend is explained by the fact that many farmers in the upper and central delta already practised double rice cropping prior to 1995. Thus, their change in the ensuing five years was less marked than in the coastal zone, where the government stepped up water management measures to reclaim acid sulphate soils and transform lands from brackish to freshwater conditions.

**Table 2**

Changes in area devoted to rice cultivation and aquaculture in the Vietnamese Mekong Delta (1995–2000).

| Zone | Provinces | Change in area from 1995 to 2000 (%) | | |
|---|---|---|---|---|
| | | **Seasonal rice** | **Total rice** | **Aquaculture** |
| Upper delta | An Giang | –61.1 | 18.5 | 35.4 |
| | Dong Thap | Ceased in 1996 | 13.1 | –40.6 |
| | Long An | –47.7 | 39.1 | 87.9 |
| Central delta | Can Tho | Ceased in 1998 | 2.9 | 52.5 |
| | Vinh Long | –59.1 | 1.3 | 20.7 |
| | Tien Giang | –75.4 | 4.9 | –12.4 |
| Coastal zone | Ben Tre | –1.4 | 9.6 | 18.5 |
| | Tra Vinh | 15.1 | 40.0 | 132.4 |
| | Soc Trang | –49.4 | 34.4 | 1280.0 |
| | Bac Lieu | –11.9 | 67.2 | 30.3 |
| | Ca Mau | –13.3 | 32.7 | 27.7 |
| | Kien Giang | –59.8 | 42.3 | 176.0 |
| Vietnamese Mekong Delta | | –28.2 | 23.7 | 53.9 |

*Source:* GSO (2012).

The other major change was the sudden rise of aquaculture. From 1995 to 1999, the total area devoted to inland aquaculture increased by 15%. In the next year, however, the sector took off, with the area of aquaculture increasing by 34% in 2000. Statistical data show that this increase was mainly attributable to a boom in aquaculture in the coastal provinces. Ca Mau, Bac Lieu, and Tra Vinh were the three provinces with the largest area devoted to aquaculture, followed by Kien Giang and Ben Tre. Compared with the situation in 1995, the greatest changes were experienced in Soc Trang, Kien Giang, and Tra Vinh (Table 2). However, the sudden rise of aquaculture in one year might be due to limited data sources. The rise of aquaculture is a reflection of a trend towards diversification and was driven mainly by the high price of shrimp on the export market (Binh et al., 2005). The rise probably happened in many coastal provinces years before the large area of aquaculture farming was reported in official statistical data. Indeed, previous studies using satellite images to detect changes overtime of land-use in Bac Lieu and Ca

Mau provinces showed that shrimp farming has been practised progressively since 1995 (Binh et al., 2005; Tuong et al., 2003).

### 4.1.3. From 2001 to 2012

We explored land-use dynamics from 2001 to 2012 using statistical and spatial analysis. According to GSO data, the total area planted to rice continued to expand. From 2000 to 2012, it increased by 238,200 ha within the delta as a whole, with particular growth in the upper delta provinces. In 2012, 55.9% of the total area planted to rice was in the upper delta (the provinces of Long An, Dong Thap, An Giang, and Kien Giang). Meanwhile, the area devoted to inland aquaculture increased as well, by nearly 288,800 ha, particularly in the coastal provinces. In 2012, 93% of the inland aquaculture area was in the coastal zone (the provinces of Ben Tre, Tra Vinh, Soc Trang, Bac Lieu, Ca Mau, and Kien Giang) (GSO, 2012).

For our spatial analysis, we concentrated firstly on areas that had changed land-use at least once between 2001 and 2012. Fig. 2 shows the overlay results. The percentage of changed areas was 44.9%. Most of the changes were in the rice cropping areas. Calculating the percentage of changed areas in each year, we found an average percentage of change of 14.9% for the VMD as a whole, which can be considered highly dynamic (Fig. 4).

The areas that remained unchanged during the 11 years occupied 55.1% of the VMD. Although the highest percentage of unchanged area showed in Fig.2 was assigned to the ‘other’ land-use or land-cover types, representing forest, orchard, urban, and unused lands, our analysis excluded it because this land-use type was not result of the satellite observation. It did not show changes over time from our original data (Sakamoto et al., 2009a). Least changed therefore was the area devoted to inland aquaculture, which occupied 13.0% of the total area of the VMD. Since our spatial data did not provide a detailed classification of aquaculture system types, the change toward intensive shrimp farming system in this period is not visible in our mapping results. This trend, however, was significantly acknowledged in literature (Can et al., 2007; Ha et al., 2013)

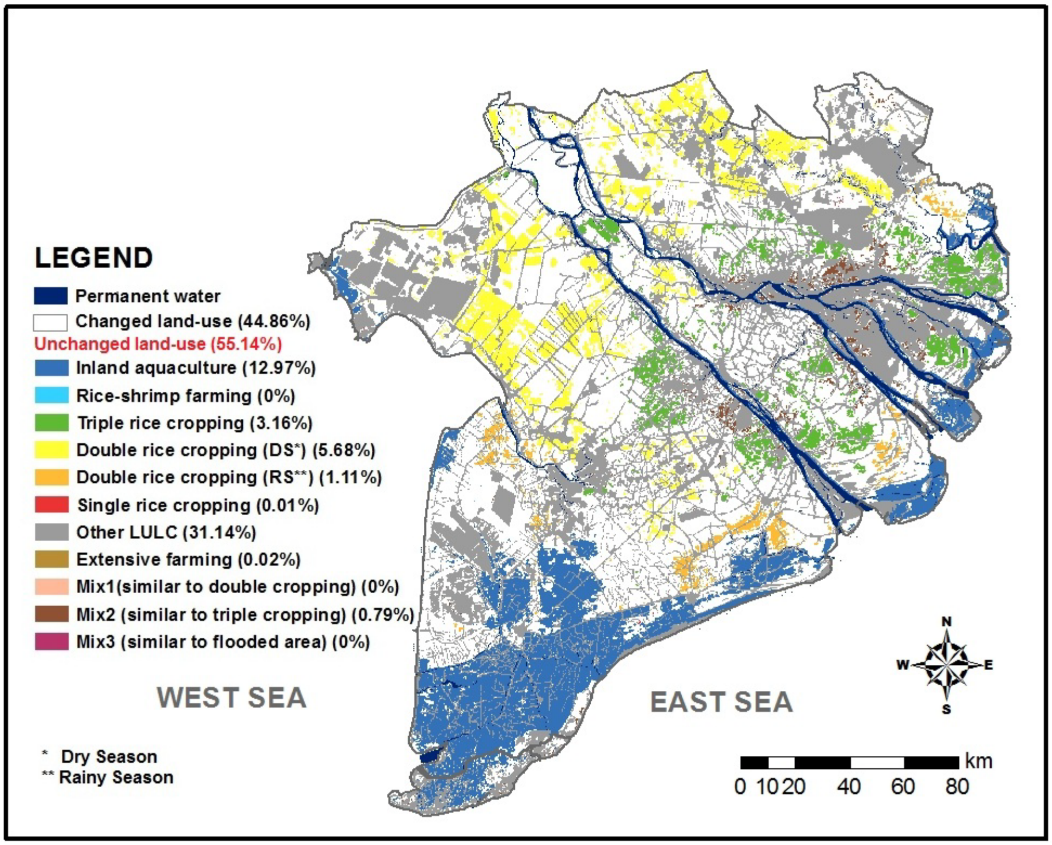


**Fig.2**. Distribution of stable (unchanged) and changed land-use in the Vietnamese Mekong Delta (2001-2012). With stable land-use demarcated in colours (percentages between bracket indicating occupied area); and changed land-use in white.

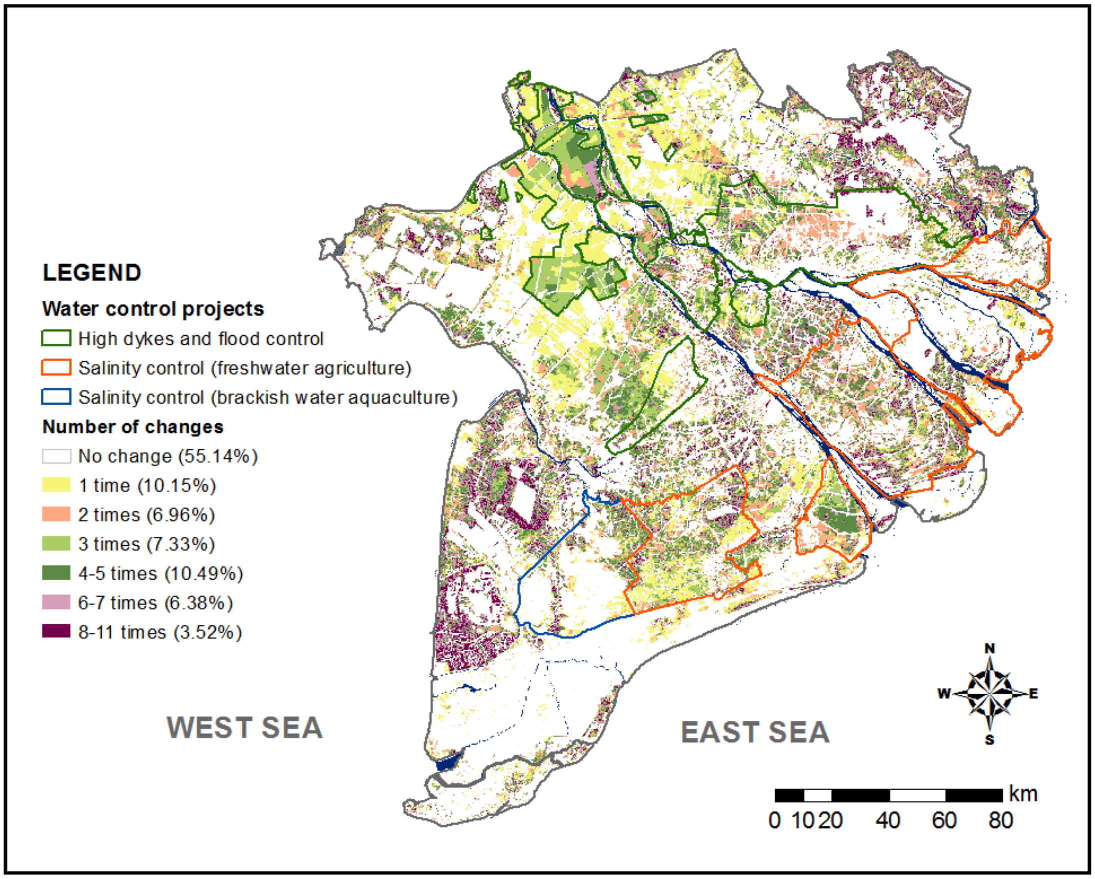


**Fig. 3.** Frequency of land-use change in the Vietnamese Mekong Delta (2001–2012). The percentages between brackets present the occupied area of each land-use frequency. Frequency ranging from unchanged (white) to more than 8 changes (purple) for the reported period.

To quantify land-use dynamics, we looked at the numbers of changes observed in the various zones over the 11 years (Fig. 3). In the VMD, 55% of the area did not change during the 11 years, while 45% changed at least once. The least dynamic areas that changed only once during the 11-year period occupied 10% of the VMD and occurred mainly in the Long Xuyen Quadrangle and the Plain of Reeds. The Upper Floodplains in the upper delta show a more dynamic land-use with the number of changes up to six and seven times. A clear pattern of large land-use changes can be observed in the upper delta, especially within the dyke systems. Changes in land-use were also observed in the central delta and coastal zone, but here the patterns are more fragmented. Besides, we have to note that the highest values for land-use change, ranging from 8 to 11 times, are probably due to ‘noise’ or data processing errors. For example, land-use types classified as ‘mixed’ in the original maps due to unrecognized patterns (Sakamoto et al., 2009a) resulted in quite dynamic areas in the analysis.

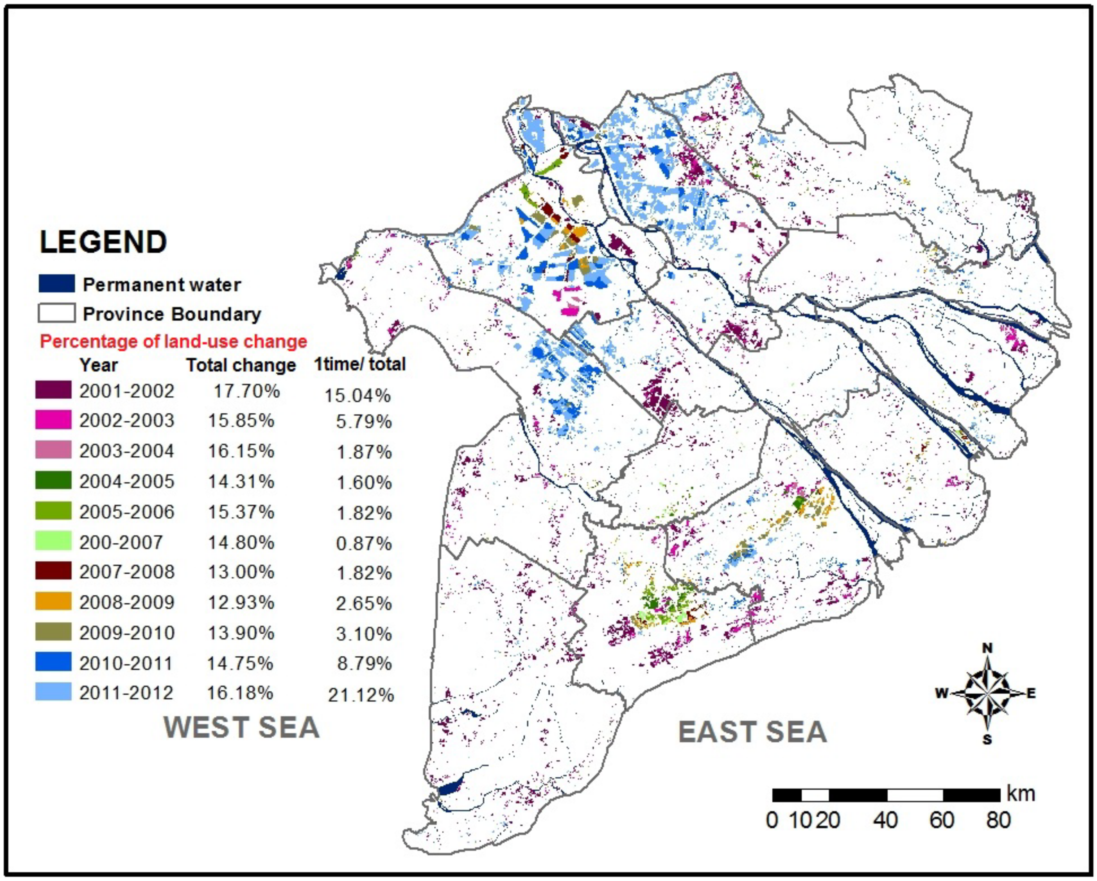


**Fig.4:** Areas where land-use changed only once during the 2001–2011 period in the Vietnamese Mekong Delta.

Fig. 4 presents our results for areas that changed only once during the period under study. In the majority of instances, this occurred in the Long Xuyen Quadrangle and the Plain of Reeds from 2010 to 2012. The change was from double rice cropping to triple rice cropping, meaning that these lands were stable under double rice cropping from 2001 to 2010. In the eastern Plain of Reeds, farmers continued double rice cropping, having switched from single rice cropping in 2001–2002. Some smaller areas in the central delta switched from double rice cropping to triple rice cropping in 2001–2002. Those lands were still devoted to triple rice cropping 10 years later.

In the coastal zone, changes that occurred before 2004 were from single rice cropping or from a rice-shrimp farming system to inland aquaculture, while changes occurring after 2004 were from double rice cropping to triple rice cropping.

## 4.2.Changes in hydrological regime

### 4.2.1. Flooding

Flooding in the VMD is an annual event occurring in the rainy season, from July to December. Overflow waters come from two directions. At the beginning of the flood season, discharge from the Bassac and Mekong rivers rapidly increases, inundating the floodplains of the upper delta. Later, floodwaters from Cambodia cross the border into the Long Xuyen Quadrangle and the Plain of Reeds. Normally, water levels in the rivers rise slowly, about 10–15 cm per day. Floodwaters peak in late September, or early October, at levels of 3–4 m height. At this point, inundation is widest, affecting some half of the total area of the delta (Tri, 2012).

We determined the extent of flooding by the water levels measured at Tan Chau station in the Mekong river, or at Chau Doc station in the Bassac river. According to the General Department of Meteorology and Hydrometeorology of Vietnam, water levels greater than 2.5 m at Chau Doc, are classified as dangerous flooding. An emergency is declared when water levels surpass 3.5 m (Tuan et al., 2007). Most flooding in the VMD is considered gentle. Due to the delta's flat topography, water expands slowly, with inundation often taking four to six months. Prolonged inundation does induce some difficulties in transportation and agriculture. However, serious damage to life and property are rare, excluding in exceptional flooding events in wet years such as 1961, 1978, 1996, 2000, 2001, 2002, and 2011 (SIWRP, 2011).

Before construction of the present dykes and sluice gates, the highly-flooded zone was affected by 3–4 m inundation for six months of the year. The Upper Floodplains were less affected, due to their higher elevation, but floods here nonetheless measured some 2–3 m deep. Inundation of the Tide-Affected Floodplains was some 0.5–1 m in late September or early October. Although the first hydraulic works in the VMD were conducted in the early 19th century, the Vinh Te Canal was built in 1818 (Biggs, 2011). The old canal networks were mainly used for transportation and authority establishment (Brocheux, 1995; Evers and Benedikter, 2009). Until the late 1930s, the colonial government started following the “Dutch dyke strategy” to control flood by building dykes and using water pumps. These flood control measures have a long-term impact on hydrological regime in the delta (Biggs et al., 2009). From 1975 to 1995, efforts to reclaim acid sulphate soils for agriculture led to increased construction of canals and drainage systems in the upper delta. These systems helped release floodwaters faster and conveyed freshwater farther into the highly-flooded zone (Biggs et al., 2009; Tanaka, 1995). To protect rice fields from early floods in August, farmers in the upper delta built temporary embankments, called ‘August dykes’. In 1996, the Vietnamese government started constructing and enlarging the canal system toward the West of the delta, aiming to facilitate land reclamation and improve flood management in the VMD (Government of Vietnam, 1996). In 1999, the Tha La and Tra Su rubber dams were built in the northern Long Xuyen Quadrangle to control overflow from across the Cambodian border. After the destructive flood in 2000, high dykes were built to provide year-round protection for agriculture in the freshwater zones of both the upper and central delta (Triet et al. 2017). Since 2002, the government has upgraded the dyke systems and increased the number of high dykes in the VMD to facilitate triple rice cropping (Käkönen, 2008; Sakamoto et al., 2006). Large areas in the upper and central deltas are now fully protected by these dykes (Fig. 5).

As noted, however, development of flood control infrastructure has increased concern about effects, particularly regarding the duration and level of flooding in unprotected areas and downstream. For example, Triet et al. (2017) applied hydraulic model stimulations to analyse the role of high dyke development in upper delta (An Giang province) and other relevant factors on flooding regime in central delta (Can Tho province) in two particularly wet years, 2000 and 2011. They found that peak levels in 2011 had increased 9-13 cm and occurred 15 days longer in the downstream area due to the existence of upstream high dykes. Also, increasing tidal levels and land subsidence had a considerable impact on the change of flooding regime here.

#### 4.2.2. Salinity intrusion

Salinity intrusion is an annual occurrence in the VMD during the dry season, from January to June. Saline waters from the East Sea and West Sea of Vietnam intrude inland via river mouths and canal networks when water discharge from upstream rivers is low and tidal effects are high, particularly in March and April. Depending on river flows and local topography, saline water can penetrate 20 to 65 km inland (Tuan et al., 2007). Salinity intrusion is greatest in particularly dry years, as in 1998, 2004, 2005, 2006, 2007, 2008, 2010, and 2011 (SIWRP, 2011).

Before the current dykes and sluice gates were constructed, salinity intrusion affected the whole coastal zone during the dry season, lasting more than six months every year (Tri, 2012). Consequences were particularly serious in the Ca Mau Peninsula, where the effects of salinity intrusion were compounded by the tidal regime of both the East Sea and West Sea. Elsewhere, farmers adapted to a seasonal regime of six months of freshwater and six months of brackish water.

The first salinity control project in the VMD was the Tiep Nhat system developed in Soc Trang province in the 1960s and 1970s. This consisted of sluice gates and dykes preventing saline water from flowing into the river mouth, alongside canals to provide freshwater to the protected area (Biggs et al., 2009). The second project began in the late 1980s and was completed in 1996 in Go Cong, a coastal district of Tien Giang province. This is considered the VMD’s most successful infrastructure system for transforming a saline-affected zone into a freshwater area. Following this success, the Quan Lo-Phung Hiep project was initiated to convert a large northern area of the Ca Mau Peninsula into a freshwater zone. That project was implemented from 1992 to 2001. However, in 2000 conflicts between shrimp farmers and rice farmers obliged the government to make some adjustments to the infrastructure. Since 2001, the north-eastern project area has become suitable for freshwater agriculture whereas the south-western area has become favourable for brackish aquaculture (Hoanh et al., 2003). Another initiative, the South Mang Thit project, constructed from 1993 to 2004, protects three quarters of Tra Vinh province from salinity intrusion. Finally, the latest salinity control project, involving construction of a large sluice gate in the Ba Lai river, in Ben Tre province, began in 2005 but was not yet completed (Tri, 2012; Toan, 2014) (Fig. 5).

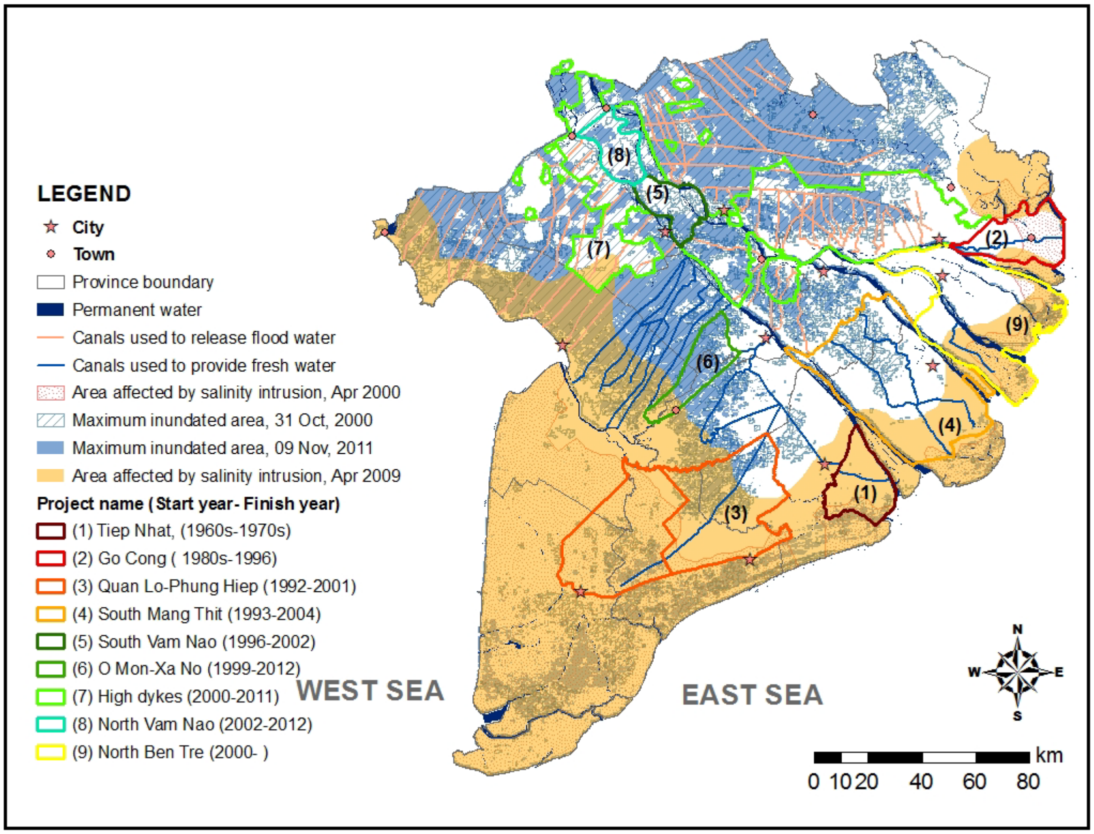


**Fig. 5.** Hydrological regime and water infrastructure in the Vietnamese Mekong Delta.

*Sources:* Duong et al. (2014); Tri (2012); Toan (2014); created by the author.

These dykes and sluice gates have facilitated freshwater agriculture, but by reducing access to brackish water, they have also induced difficulties for farmers wanting to continue aquaculture. Moreover, the water management infrastructure cannot fully protect the whole salinity intrusion zone. Outside the systems, saltwater has continued to intrude into freshwater areas via the labyrinth of canals. Moreover, climate change models suggest that salinity intrusion would become more serious if the scale of dykes was increased, in combination with the expected rise in sea levels and changes in rainfall patterns (Smajgl et al., 2015).

### 4.3. Interplay between land-use dynamics and changes in hydrological regime

Our analysis of changes in the different agro-hydrological zones of the VMD showed that natural flooding and salinity intrusion strongly affected farming systems prior to 1995. Rice cultivation in the highly-flooded zone was limited not only by the impacts of flooding during the rainy season, but also by the release of sulphate acid in the dry season. In the Upper Floodplains, farmers practised double cropping mostly in the dry season, avoiding rice cultivation in the flood season. In contrast, in the salinity intrusion zone, farmers practised double rice cropping during the rainy season. In the Ca Mau Peninsula, single rice cropping was practised, though only in small areas, due to the high and prolonged salinity of the water as well as the presence of acid sulphate soil constraining rice cultivation.

The subsequent introduction of water management infrastructure played a key role in maximizing cropping areas. The delta development is characterized by its transformation from an area dominated by swamps and marshes into valuable agricultural land. This is strongly associated with the hydraulic works aimed to expand rice cropping areas and give access to pioneer for rice cultivation, from the French colonization era to the present day. For example, *"From 1890 to 1930, more than 165 million cubic meters of earth were dredged and the total area put under cultivation rose fourfold to over 2 million hectares"* (Hoanh et al., 2010). After the country was reunited in 1975, large canals were built to contain floodwaters and sulphate acid, allowing double rice cropping in the Plain of Reeds and creating large double rice cropping areas in the Long Xuyen Quadrangle. Meanwhile, dykes were built in the Upper Floodplains to facilitate an additional rice crop in the flood season. In the salinity intrusion zone, dykes and sluice gates were built to prevent saltwater intrusion in the dry season, and canals were built and connected to main rivers in the upper delta to provide freshwater for agricultural lands. Consequently, double rice cropping rapidly expanded, replacing single rice cropping in the coastal provinces. In other words, construction of the water management infrastructure meant that flooding and salinity intrusion patterns were no longer determinative for land-use.

Moreover, water control infrastructure delineated boundaries between different farming systems. Satellite observation data show that farmers in the upper delta began to practise triple rice cropping once dykes were built (Sakamoto et al., 2006). Double and triple rice cropping were detected within the boundaries of salinity control projects, such as the Tiep Nhat, Go Cong, and South Mang Thit. Nonetheless, salinity intrusion proved difficult to control, due to the interconnectivity of the delta waters. In the Ca Mau Peninsula, efforts to optimize rice production faced many obstacles. First, although the government built sluice gates and canals to reclaim land for agriculture, the impacts of salinity intrusion and the presence of acid sulphate soil in the peninsula were still too serious for rice cultivation, even for the single rice cropping. Farmers therefore had to find another livelihood, such as trying aquaculture in mangrove forests. Satellite observation data from 1968 to 2003 show intensive shrimp ponds or shrimp-mangrove production systems came to dominate large expanses of this province (Binh et al., 2005; Tuong et al., 2003). Second, many farmers preferred brackish water conditions, due to the high prices paid for shrimp on the export market. They therefore sought to continue shrimp farming within the zone designed as freshwater. This created a fragmented land-use pattern in the buffer zone between freshwater and saltwater (Hoanh et al., 2012).

The interplay between land-use dynamics and hydrological regime became more complex as the full impacts of water control infrastructure and market reforms began to emerge. The 2001–2012 period witnessed completion of many water management projects in the VMD. Optimization of the hydrological regime for rice production induced a demand for expansion of triple rice cropping, which required enlargement of dyke systems to fully protect the upper delta from flooding. High dykes prevented flooding, but also blocked sediment flows into the fields. Rice fields within the dyke rings therefore lost the benefits of flooding, such as controlling populations of rats and insects, limiting the spread of diseases, soil fertility and provision of nutritious food in the from native fish species. Thus, farmers had to increase their use of agrochemicals to maintain high production. Hihg dyke systems, furthermore, reduced overflow and increased water velocity, exacerbating bank erosion (Hashimoto, 2001; Käkönen, 2008; Tri, 2012; Tuan et al., 2007). The impacts of the flood control systems in the upper delta extended into the central delta, as observed by the increase of water levels and prolonged flood peak in Can Tho province (Triet et al, 2017). Triple rice cultivation fields, fruit orchards and urban areas in the central delta became increasingly reliant on the protection of infrastructure. For example, the O Mon-Xa No project in the northern city of Can Tho was initiated to protect agricultural lands from upstream floods (Tri, 2012). In the coastal zone, the boom in aquaculture led to water-use conflicts involving freshwater systems already built. In 2001, farmers in Bac Lieu province opened sluice gates, damaging dykes in order to access saltwater for continued shrimp production (Hoanh et al., 2003). The dominance of shrimp farming also reduced the effectiveness of freshwater infrastructure in Ca Mau province. Thus, while the hydrological regime was changed by the water control infrastructure designed to facilitate rice-oriented farming systems, those changes also induced side effects, impacting lands and livelihoods in adjacent zones (Käkönen, 2008; Nhan et al., 2007).

Another interplay was the reduced availability of fresh water for downstream areas due to construction works upstream, such as interventions for irrigation and hydropower in the Mekong Basin (Hashimoto, 2001; Nhan et al. 2007). Although fresh water shortage and salinity intrusion are likely to happen in during the dry season, those hydrological problems have the tendency to increase in both time and space, due to the combined effect of sea level rise and changes in river discharge (Dat et al., 2011; Khang et al. 2008). A study in Ben Tre province showed that farmers were nowadays changing their land-use to adapt to the both saline and fresh water environments (Renaud et al., 2015). Also, increasing urbanisation and industrialisation along the river bank caused high demand for water abstraction and also resulted in water pollution which would threaten irrigation and land-use in downstream areas (Hashimoto, 2001; Marchand et al., 2014).

In sum, prior to 1995, flooding and salinity intrusion limited opportunities for freshwater agriculture in the VMD. From 1995 to 2000, water management infrastructure was constructed to facilitate intensive rice cropping, effecting changes in the spatial and temporal characteristics of the hydrological regime. From 2001 to 2012, effects of this infrastructure became particularly evident. During this period, spatial and temporal impacts on flooding and salinity intrusion were observed not only within but also beyond the rice fields to impact lands and livelihoods in adjacent zones.

## 5. Discussion

The annual percentage of change in land-use in the VMD was 14.94% from 2001 to 2012, with most change occurring in cropping patterns. Compared to regions elsewhere, this meant that land-use in the VMD was very dynamic. Abd El-Kawy et al. (2011) found agricultural land in the Western Nile Delta of Egypt changed 2.2% per year in the 1999–2005 period, and 2.3% per year over 2005–2009. In Southeast Asia, Goldewijk (2001) found that use of croplands changed by 1.45% annually over the twentieth century. These considerable differences between our findings and those of other authors can be partially attributed to the different land-use categories applied in each study. Abd El-Kawy et al. (2011) examined changes in agricultural lands and four non-agricultural land types. Goldewijk (2001) focused only on croplands and pasture, whereas our research used maps from Sakamoto (2009a) that distinguished three different cropping patterns and 11 land-use types.

In terms of land and water management at the delta scale, this detailed information on cropping patterns enabled us to conduct a refined investigation of the relationship between land-use dynamics and changes in hydrological regime. We found changes in cropping patterns to be closely related to the water control measures implemented throughout the delta. However, our research was unable to analyse changes in inland aquaculture as well as ‘other’ land-use or land-cover types, such as fruit orchards and urban areas, due to the broad scale of our analysis and the limited spatial data available. Another issue was the limited data availability on aquaculture practices during the 3 studied periods. Only statistical data were available for every province in the period of 1995-2000. It was therefore difficult to elaborate the concern about the sudden rise of aquaculture practice in the late 1990s and its expansion afterwards. The data gap could be improved by using remote sensing data to detect land-use change in the coastal zone, or by conducting interviews with farmers on the history of land-use change.

We derived characteristics of the VMD hydrological regime from the literature, particularly reports of SIWRP (2011) and the WISDOM project (Tri, 2012). Moreover, we investigated hydrological regime in relation to agricultural transformation. For instance, we examined and visualized flooding, salinity intrusion, and water infrastructure interventions, alongside changes in land-use patterns over space and time. However, due to the fragmented nature of historical and spatial data our analyses are limited to descriptive statistics and overlay analyses.

Land-use dynamics in the various regions of the delta appeared to interplay in different ways with changes in the hydrological regime. According to our spatial analysis, land-use patterns in the upper and central delta evolved in line with trends at the delta scale. The local government has availed hydrological interventions to enforce their land-use planning in the VMD for years. Construction of flood control infrastructure was associated with expansion of intensive rice fields, in line with the government's food security policy aims (Biggs, 2009; Evers and Benedikter, 2009; Vormoor, 2010). However, trends were less clear in the coastal zone, where aquaculture was found to be practised within the boundaries of the salinity control systems. Thus, water infrastructure interventions were not the only factor driving changes in land-use, though they did propel the overall landscape of the delta away from domination by natural systems into a policy-oriented development direction. Other studies found a variety of factors to influence land-use decisions at the farm and community level. For example, using statistical analysis, Vormoor (2010) found that increased availability of pumps and threshing machines was a larger factor in the growth of agricultural output than the network density of canals. Moreover, Sakamoto (2009b) concluded that, in reality, land-use decisions were made by famers considering mainly market price fluctuations and the experiences of neighbours. The boom in aquaculture in the VMD in the late 1990s bears out the strong influence of market trends in determining land-use (Hoanh et al., 2003). This suggests that study of land-use dynamics and hydrological regime could be improved by looking at finer scale interrelations and by considering the impacts of other driving factors.

## 6. Conclusions

To investigate the interplay between land-use dynamics and hydrological regime at the delta scale, our research analysed spatial and temporal changes in different agro-hydrological zones in the VMD. We found substantial evolution in land-use, towards more intensive rice cropping in line with the government's policy to stimulate rice cultivation – and thus food security – and the erection of water control infrastructure. We calculated a rather high annual rate of change in land-use on the delta, at 14.9% from 2001 to 2012. This was mainly due to the frequent changes observed in cropping systems. Meanwhile, spatial distribution of aquaculture remained stable after its initial rapid expansion in the 1990s and early 2000s. To facilitate intensive agriculture, water infrastructure was built or expanded from the upper delta to the coastal zone, initiating tighter control of the hydrological regime. At the delta scale, clear interplay was found between land-use dynamics and changes in hydrological regime. In the three periods investigated, construction of water infrastructure particularly influenced the way land was used. Prior to 1995, land-use patterns appeared to be shaped by the natural processes. From 1995 to 2000, land-use patterns were increasingly human-induced, shaped by interventions in the hydrological system. Effects of infrastructure were particularly evident from 2001 to 2012. During this period, spatial and temporal impacts on flooding and salinity intrusion extended beyond the rice fields, affecting adjacent lands and livelihood options. Unforeseen effects will likely be aggravated by climate change in the near future, suggesting a need to rethink the scale of planning towards a more integrated hydrologic approach. Finally, we found evidence that land-use changes at the farm level were driven by factors other than changes in hydrological regime and operation of water infrastructure. Indeed, the different land-use pattern dynamics in the upper delta and the coastal zone suggest a need for more detailed exploration of the way land-use decisions are actually made by farmers and communities.

## Acknowledgements

This research was a part of the Nuffic/Niche/104/VNM collaboration between Wageningen UR of the Netherlands and the Centre of Water Resources Management and Climate Change, Vietnam National University (WACC-VNU) in Ho Chi Minh City, Vietnam. We extend our special thanks to Dr. Toshihiro Sakamoto at Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization, Japan (NIAES), Vu Hoang Thai Duong, PhD student at Karlsruhe Institute of Technology, Germany (KIT), the German-Vietnamese

WISDOM project, and the research “Integrated system of remote sensing, GIS and mathematical model for assessing climate change in Southern Vietnam” which is funded partial by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number ĐT.NCCB-ĐHƯD.2012-G/03 for sharing data used to conduct this research.

The digital land-use maps of the Mekong Delta from 2000 to 2012 were officially provided by Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization, Japan (NIAES) under the Material Transfer Agreement.

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