AGRICULTURAL LAND-USE DYNAMICS IN THE FLOODPLAINS OF THE VIETNAMESE MEKONG DELTA
Hydrodynamic implications on flood regimes and adaptation options

Dung Duc Tran

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INVITATION

You are cordially invited to attend
the public defence of my PhD thesis entitled

AGRICULTURAL LAND-USE
DYNAMICS IN THE FLOODPLAINS
OF THE VIETNAMESE MEKONG DELTA

Hydrodynamic implications on flood regimes
and adaptation options

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On Thursday
29 November 2018, at 10:30 AM
in the Aula of Wageningen University,
Generaal Foulkesweg 1a, Wageningen.

PARANYMPHS

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Propositions

1. Floodplain communities only truly appreciate the benefits of floods once they are lost.
   (this thesis)
2. In assessing the impacts of floods, hydraulic modelling needs to be supplemented with socio-economic analysis.
   (this thesis)
3. In developing countries, preference for hard infrastructure in water management often undermines the benefits of communities.
4. Sustainable water management requires strategic planning.
5. Sandwich PhD programs offer a good mix of focus on working abroad and quality time at home.
6. Discussions among multiple supervisors help PhD students to develop scientific debating skills.

Propositions belonging to the thesis, entitled

"Agricultural land-use dynamics in the floodplains of the Vietnamese Mekong Delta: Hydrodynamic implications on flood regimes and adaptation options".

Dung Duc Tran

Wageningen, 29 November 2018.

AGRICULTURAL LAND-USE DYNAMICS IN THE FLOODPLAINS OF THE VIETNAMESE MEKONG DELTA

Hydrodynamic implications on flood regimes and adaptation options

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Dung Duc Tran

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Abstract

Due to intensified rice production, induced by national food security policy, the floodplains in the upper parts of the Vietnamese Mekong Delta have changed in agro-ecology from a seasonal floodplain into a highly intensified rice production area. To enable intensified rice production, large-scale flood-control infrastructure has been built, particularly low dikes and high dikes, to control the water entering agricultural fields. As a result, the delta has become a primary contributor to Vietnam's food security, and the delta's high production has made Vietnam one of the world's foremost rice exporters. However, this transformation has reduced the flood retention capacity of the delta, degraded land and water quality, and undermined delta ecosystem services.

The main aims of the research presented in this thesis were two: to identify the impacts of extensive construction of flood-control infrastructure on the flood dynamics of the delta and to explore adaptation options to maximize livelihood sustainability and ecological sustainability on the delta. An available 1D-quasi2D hydrodynamic model was developed for the delta system as a whole to simulate flood discharges and river water levels, considering four dike construction scenarios. Using a sustainable livelihood perspective, alternative farming systems were explored using multi-criteria analysis and cost-benefit analysis on the local scale, relying on multiple interviews with stakeholders operating under different types of dikes and at different locations on the floodplains. The next step was to elaborate on costs and benefits while shifting the focus to the delta scale, also considering various future flood-control scenarios.

As such, this study advances knowledge on the impacts of extensive flood-control infrastructure on hydrodynamic patterns and flood risk upstream and downstream in delta systems. The findings of this study suggest a need to develop flood-based land and water management strategies and farming systems, instead of continued expansion of high-dike infrastructure and related farming systems. Indeed, this study found higher economic and environmental returns to the low-dike farming systems in the long run. However, certain advantages of the high-dike systems must be recognized, such as their protection of built up areas and farmers' ready access to the stable market for rice.

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CHAPTER 1

Introduction

1.1. Background and problem statement

1.1.1. In a generic perspective

Different countries have different policies and goals to protect against and manage floods (Van Alphen and Lodder, 2006). Such policies and goals typically encompass two primary approaches to flood risk management: hard measures (also known as structural measures) and soft measures (also known as non-structural measures). Hard measures tend to be more expensive and have greater environmental impact, for example, on rivers and the surrounding areas (Temmerman et al., 2013). Soft measures tend to be more ecologically beneficial. Whether hard or soft measures are applied in any flood-affected country, their common objective is to contribute toward effective flood management strategies. These strategies must be economical as well as environmentally and socially sustainable; that is, they should not compromise the needs of future generations.

Agricultural intensification is considered a principal means of meeting the food demands of a growing global population (Rudel et al., 2009; Hongwei Pei et al., 2015). Worldwide, delta floodplains are among the most favored areas for concentration of intensive agriculture, due to the ideal conditions that delta floodplains offer for cultivation, such as fertile soils and abundant water. However, agricultural intensification influences the land and water management strategies that can be adopted on delta floodplains (Opperman et al., 2013). To prevent flooding from damaging residential areas and infrastructure for intensive agriculture, hard structures are usually the preferred means of floodwater management (Käkönen, 2008). Hard measures may indeed control extreme flooding better than soft measures, but the benefits of flooding are virtually foregone. In recent years, many studies have pointed to downsides of hard structures, while highlighting the benefits of soft measures in increasing floodwater retention capacity and conserving ecosystem services (Buijs, 2009, 2009; Temmerman et al., 2013; Van Staveren et al., 2014).

Although hard structures locally protect residential areas and agricultural activities against flooding, extensive development of hard structures typically increases the flood risk elsewhere (Winsemius et al., 2013). In addition, hard measures have numerous economic, ecological and environmental repercussions in the longer term. Economically speaking, water management infrastructures require high up-front investment, and they bring substantial operation and maintenance costs (Temmerman et al., 2013). Ecologically, these structures typically disconnect rivers from their floodplains, diminishing the many ecosystem services found in more natural river-floodplain systems (Opperman et al., 2013; Kousky and Walls, 2014). In environmental terms, floodplain soils and water may be degraded by overuse of agrochemicals and the loss of the erstwhile benefits of floodwaters, such as fertile sediment inflows and wild fish stocks (Tsujimoto et al., 2017). Intensive agricultural systems are rendered unsustainable if land and water become degraded (Pretty and Bharucha, 2014). Hard structures may therefore locally protect agricultural areas for food productivity, but the trade-off is high in terms of economic, ecological and environmental aspects in the long run.

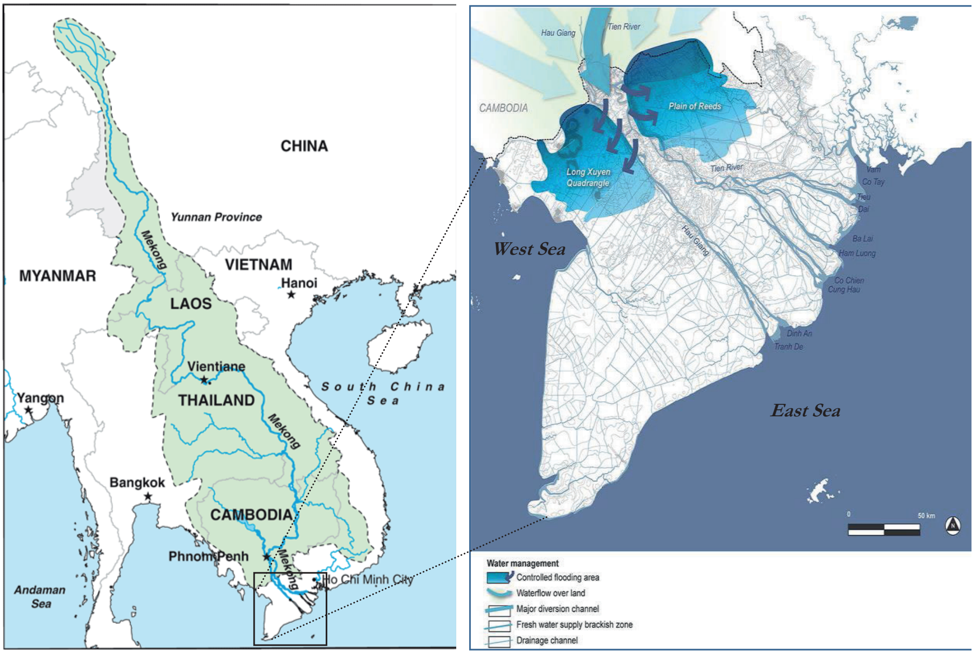
Many countries have shifted their emphasis in flood protection from hard measures to soft measures geared toward maintaining natural ecosystems and increasing capacity to adapt to the impacts of global environmental change (Opperman et al., 2013; Bubeck et al., 2015). Indeed, due to the negative impacts of hard measures on the environment, soft measures have been strongly recommended in recent decades as a more effective approach to maintaining ecological systems (Samuels et al., 2006; Wesselink et al., 2015). In particular, the Netherlands and Germany have invested in various soft measures as part of their "Room for the River" flood safety program, which was initiated following severe flooding in those countries in 1993 and 1995. Room for the River seeks to increase the space available for water storage and to restore flood-based ecosystems (Bubeck et al., 2015; Van Herk et al., 2015).

Room for the River can be considered an especially innovative approach for addressing the threat of flooding, as the Netherlands, at the time of the program's conception, had just completed its vast hard "delta works" infrastructure for flood risk management in response to the flood disaster in 1953 (Van Staveren et al., 2014; van Wesenbeeck et al., 2014; Wesselink et al., 2015). In the United Kingdom, soft measures such as insurance, private precautions and spatial planning have played an important role in flood risk management. Yet, Temmerman et al. (2013) concluded that hard measures such as sea walls are being increasingly challenged by the effects of climate change. Particularly, due to sea level rise and changing sediment supplies, maintenance of hard infrastructures is thought likely to become unsustainable. These authors suggest that soft measures should be implemented globally and on a large scale. Therefore, in many developed countries, restoration of natural water systems through soft measures that enhance the flood retention capacity of river floodplains is nowadays considered the preferred approach to sustainable development (Hein et al., 2016).

1.1.2. Flood management in the Vietnamese Mekong Delta: From hard to soft?

The Mekong is one of the largest international rivers in the world (Hiroaki et al., 1995). Its delta, located largely in Vietnam, covers a region of 3.9 million hectares, equivalent to 5% of the total area of the river basin (Figure 1.1). The delta plays an important role in

Vietnam's national food security. Agriculture there contributes 70% of rice exports and 51% of the national rice production, making Vietnam one of the world's foremost rice exporters (Kakonen, 2008).



Source: www.schillerinstitute.org and Mekong Delta Plan (2013).

Figure 1.1 Location of Vietnamese Mekong Delta and flooded areas

The Vietnamese Mekong Delta (VMD) is currently at a crossroads in development of a sustainable strategy for land and floodwater management (Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013). It is still implementing extensive hard measures, such as high dikes, sluice gates and pumps, to protect triple rice farming against flooding and increase rice productivity. However, there is a growing realization that this development trajectory could transform the delta to a collapsed state (Renaud et al., 2013). Soft measures are therefore increasingly being prioritized, in an effort to ensure that sufficient space is available for floodwater storage on the floodplains and to exploit the benefits of the annual floodwaters, including their introduction of new wild fish stocks and fertile sediments. However, it is recognized that this might reduce agricultural production capacity to some extent. Indeed, a trade-off is said to exist between agricultural intensification to increase food production, though coupled with land and water degradation, and less intensive agricultural practices that could increase delta sustainability and ecosystem services derived from flood-based farming systems.

In development of the Mekong Delta Plan (2013), the most promising option was sought for a sustainable VMD future. The solution proposed was an agricultural system that exploited the flood season for cultivation high-value crops paired with reduced flood protection infrastructure in the middle of the delta (Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013).

Climate change and hydropower dam developments upstream are two major factors impacting downstream river water regimes and livelihood sustainability on the delta. Due to climate change, both the severity and the frequency of high-flood years are predicted to rise, while water shortages are also set to occur more often in the dry season (Tri et al., 2012a). Many studies have used climate models to simulate annual upstream water flows on the VMD. The water flows simulated vary from -6.9%–8.1% for a low emission scenario to -10.6%–13.4% for a high emission scenario (Hoang et al., 2016; Lauri et al., 2012; Thompson et al., 2013). Kingdom of the Netherlands and The Socialist Republic of Vietnam, (2013) highlighted the increase of 10%–50% in flood-season flows and the decrease of 15%–60% in dry-season flows in 2100 for both moderate and high emission scenarios of climate change. Hydropower dams, for their part, trap fertile sediment upstream in the flood season, stopping the usual provision of this common pool resource to the lower delta floodplains. This has affected the livelihoods of local inhabitants, especially poor farmers (Nguyen and James, 2013). Therefore, an effective strategy is needed for land and water management, alongside alternative farming systems, to adapt to the new reality posed by the changing climate and hydropower dam development for agricultural production and livelihoods, particularly, to help local farmers increase their livelihood sustainability.

1.2. Research objective and questions

On the VMD floodplains agricultural land-use dynamics are tightly interwoven with land and water management strategies which often feature hard infrastructure, particularly dikes, to regulate water flows for cultivation and to protect built up areas against flooding. Indeed, extensive dike construction on the VMD has spurred rapid agricultural intensification based on a rice monocrop, while also changing flood regimes and influencing livelihood sustainability locally, regionally and on the delta scale. Prolific dike construction has affected various aspects of the delta environment, in particular changing the distribution and severity of the annual floods. It has therefore become essential to understand the fuller effects of extensive construction of dikes on the delta environment, in the long term as well as at the current time. In addition, exploration and analysis of alternative farming systems is called for, to determine what land-use trajectories could be suitable for the delta and to inform strategies for maximizing livelihood sustainability.

In this context, and considering the problems facing the VMD, two objectives were defined for this research:

(1) to identify the hydrodynamic impacts of agricultural land-use dynamics on flood regimes on the delta, regional and local scale; and

(2) to explore and analyze the potential of adaptation measures, in both farming systems and agricultural land use, to contribute to a sustainable delta.

Based on these research objectives, four research questions were formulated:

(1) How do agricultural land-use dynamics impact floodwater regimes across the delta? (Chapter 2)

(2) What alternative farming systems are assessed most favorably by stakeholders, adopting a sustainable livelihood perspective? (Chapter 3)

(3) What is the profitability of alternative farming systems compared to intensive rice production according to environmental and economic analyses? (Chapter 4)

(4) What are sustainable agricultural land-use management strategies for the delta according to an economic assessment? (Chapter 5)

1.3. Conceptual framework

This research formulated a conceptual framework that integrates the hydro-environmental, social and economic dimensions of floodwater management on the VMD (Figure 1.2). Strategies for floodwater management involve soft and hard measures, with the latter being specifically dike construction. These measures are recognized to produce particular agricultural land-use dynamics. To better understand these dynamics and their repercussions, the current research used a multidisciplinary method consisting primarily of modeling techniques and socio-economic assessment tools (multi-criteria analysis and cost-benefit analysis). The aim was to investigate the influence of the extensive dike construction on the VMD on delta agricultural land-use dynamics and floodwater regimes, alongside livelihood and delta sustainability. Alternative trajectories were explored and assessed, based on three dimensions of sustainability: hydro-environmental, social and economic. These were, furthermore, evaluated across spatial and temporal scales.

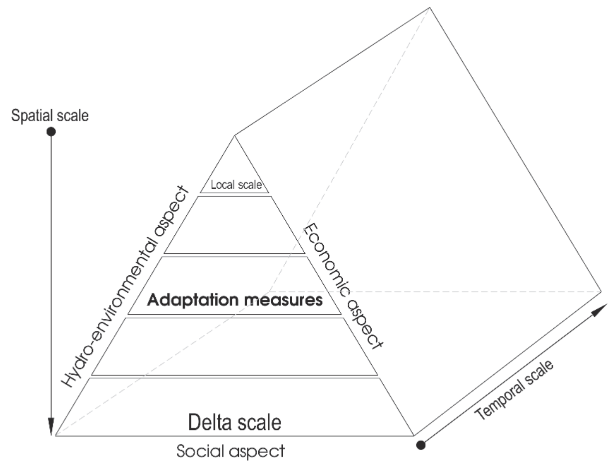


Figure 1.2 Conceptual framework

The core of my study is thus an assessment of adaption measures across spatial and temporal scales considering the hydro-environmental, social and economic dimensions. Adaptation measures will be required to counter the impacts of current agricultural land uses and water management infrastructure. Furthermore, using the conceptual framework, this research assessed potential adaptation measures to estimate their performance in the face of the hydrodynamic changes emanating from other impact factors, such as climate change and hydropower dam development.

1.3.1. The hydro-environmental module

This research used a hydro-environmental module to evaluate the hydrodynamic and environmental impacts of land-use changes associated with dike construction over the years. From a hydrological perspective, changes in floodwater regimes were quantified on the local, regional and delta scales. From an environmental perspective, farming systems and potential adaptation measures were evaluated quantitatively, mainly based on the increase or decrease in pesticide and fertilizer use that they entailed. These are important factors in assessing trade-offs across the delta scales, as local flood protection measures may imply a heightened flood risk upstream and downstream on the delta, alongside greater or reduced environmental degradation.

Indeed, recent decades have witnessed extensive dike construction for triple rice production on the VMD floodplains (Kien, 2014). My interest in the land-use dynamics associated with this development stemmed from the coincidence of this intensified agriculture with observations of increased flooding downstream on the delta, around the city of Can Tho. Comparing observations in 2011 with those in 2000, lower water levels were observed upstream in the more recent year, with higher levels measured downstream. At the upstream station of Tan Chau, for example, water levels in 2011 were 0.63 m lower than in 2000 (4.27 m vs. 4.90 m), whereas water levels downstream at the Can Tho station were 0.36 m higher in 2011 than in 2000 (2.15 m vs 1.79 m). These findings led me to explore possible associations between land-use changes and increased water levels, implying greater flood risk, due to the construction of the now vast network of dikes.

A hydrodynamic model was used to assess floodwater levels in rivers impacted by extensive dike construction on the VMD. Mike 11 is a popular one-dimensional (1D) hydraulic model that employs an implicit, finite difference scheme for computation of unsteady flows in rivers and estuaries (DHI, 2011). According to Soumendra et al. (2010), 1D models have long been used because of their speed of calculation, ease of parameterization and easy representation of hydraulic structures in the flow domain. To understand the interactions of dike construction on the floodplains, however, a quasi2D approach had to be embedded into the 1D models, as these latter neglected key spatial variability features of floodplain hydraulics and oversimplified floodplain flows. Nonetheless, two-dimensional (2D) and three-dimensional (3D) hydrodynamic models are deemed unfeasible for simulating hydraulic details for a river network as immense and complex as that of the VMD. Prohibitively large computational power and terrain data would be required for use of a 2D or 3D approach on such a large domain (Soumendra et al., 2010). Therefore, a 1D-quasi2D hydraulic model (Mike 11) was considered the best tool to pursue this research's objectives.

1.3.2. The social module

With the social module, this research evaluated the sustainability of farmer livelihoods within the delta floodplains under the influence of various agricultural land-use dynamics. Chambers and Conway (1992) defined livelihood as comprising *"the capabilities, assets and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base"* (Chambers and Conway, 1992 p. 7). The current study views the livelihoods of farmers on the VMD floodplains as consisting of their farming activities, associated mainly with intensive rice production and using different approaches for flood protection (i.e., low dikes and high dikes). The different flood-protection approaches were termed "dike-protected" and "flood-based". Dike-protected farming systems aim for complete control over the water that reaches agricultural fields, mainly through the construction of high dikes and a system of sluice gates and channels. Flood-based farming systems aim for some control over the water that reaches agricultural fields, but higher floods are allowed to spill over the low dikes and inundate cultivation areas.

Kien (2014) found that the high-dike areas in An Giang Province, within the Long Xuyen Quadrangle floodplain, had expanded significantly over the previous two decades. This had spurred a massive increase in triple rice production (Mike, 2013). That development led me to question what had attracted farmers to cultivate a third rice crop, since Käkönen (2008) wrote that the total annual yield from rice crops within the high-dike areas was less than the yield from two crops outside the high-dike areas, due to reduced soil fertility within the dike rings. Indeed, intensive land use under high-dike protection has been shown to reduce both the livelihood sustainability of farmers and sustainable development on the delta. Morse and McNamara, (2013) defined sustainability as follows: *"[I]t implies a sense of longevity—something that will last well into the future—and as a consequence it implies a resilience to the turbulence of our politics, economic systems and environmental change that seems to be so embedded within our world"* (Morse and McNamara, 2013, p. 1). I wondered how the delta could remain sustainable into the future if dike systems were still being extensively built on the floodplains. To understand this, I sought to explore farmers' views on farming systems requiring high-dike protection compared to those utilizing low dikes to protect cultivated areas. According to Kien (2014), the high dikes allow three rice crops per year, whereas the low dikes enable two rice crops, with floodwaters subsequently entering fields during the flood season. In addition, the high-dike infrastructure has been found to interrupt common pool resources provided or replenished by floodwaters, such as wild fish stocks and fertile sediments. Yet, most poor and landless people in the region derive their livelihoods largely from these resources. It would therefore seem crucial to evaluate all trade-offs arising from high dike construction in terms of benefits and losses, comparing farmer livelihoods in high-dike systems with those in low-dike systems. Furthermore, I was interested in alternative farming systems that might prove more profitable and sustainable than intensive rice production, considering impacts in the environmental, social and economic, domains. This research thus sought out alternatives and presented them for assessment by the various stakeholders, particularly farmers and experts, using a sustainable livelihood perspective. These alternatives were then assessed using different tools across spatial and temporal scales.

Multi-criteria analysis (MCA) was used to determine to what extent the alternatives were considered promising by the relevant stakeholders (Cisneros et al., 2011; Carof et al., 2013). The alternative farming systems were evaluated using a sustainable livelihoods perspective and a set of criteria reflecting the three dimensions of environment, society and economy. This study applied MCA theory following the Department for Communities and Local Government, (2009). To rank the alternatives, analytic hierarchy process (AHP) was selected, as it is among the most widely applied MCA tools (Alphonce, 1997; Huang et al., 2011). Analytic hierarchy process was first introduced by Saaty (1980) for complex decision-making on a set of alternatives. In accordance with AHP, pairwise comparisons were made and weightings assigned to attributes. Stakeholders judgments were used to derive priority scales for the alternatives (Alphonce, 1997; Chavez et al., 2012; Saaty, 2008).

1.3.3. The economic module

With the economic module, this research aimed to quantify the profitability of existing land-use trends, particularly rice-based farming systems, cultivation of vegetables and alternatives. My interest here arose initially from the finding of (Howie, 2011a) that rice farmers in a small community had to spend increasing amounts on pesticides and fertilizer over time for fields under high-dike protection in An Giang Province. However, this finding needed to be confirmed with additional data from other dike-protected areas. Expanding on this, I asked how farm profitability under triple rice cultivation had changed over the years, considering potential increases in production costs due, not least, to larger pesticide and fertilizer requirements. Long-term profits and costs were analyzed for an intensive rice production monoculture and alternatives. These analyses raised questions regarding the sustainability of the delta if development of triple rice production were to be continued across the delta floodplains. Thus, this research went on to assess the costs and benefits of different agricultural land-use scenarios on the delta scale including the economic impacts of extensive dike construction on delta sustainability. Environmental perspectives on adaptation options were qualitatively assessed using the economic costs of fertilizer and pesticide use as an indicator of negative effects on land and water.

Cost-benefit analysis (CBA) has been applied in many studies in a variety of scientific fields and on different spatial scales to convert variables into monetary terms (GIZ, 2014; Kien, 2014; Kousky and Walls, 2014). At the farm level, the costs of a farming system include productive inputs such as fertilizer and pesticides, whereas benefits can be expressed in revenue (Howie, 2011; Kien, 2014). At the regional and delta levels, the impacts of various dike development scenarios were defined in terms of internalities and externalities. Internal factors included the cost of construction, operation and maintenance for different dike systems. External factors were defined as changes in flood risk, sediment load, salinity intrusion and riverbank erosion. These were considered four primary impacts of extensive dike construction. These internalities and externalities were quantified in monetary terms.

1.4. Methodology

Quantitative model-based analyses and qualitative social assessment research are usually conducted separately. The current study integrated these two approaches to pursue the research objectives and answer the research questions. Thus, hydraulic modeling of floodwater flows was combined with analysis of the social impacts of farming systems, to more fully understand the impacts of dike construction at the local, regional and delta level and over time. Particularly investigated were changes in the flood risk downstream and the potential of alternative systems, such as agro-aquatic farming systems. In addition, this study investigated risks to agricultural production posed by changes in land use and flood protection strategies, particularly the external risks pertinent to the VMD; that is, changes in flood risk downstream, sediment load, salinity intrusion and riverbank erosion.

Figure 1.3 depicts the methodological framework. Research question 1 concerns the impacts of agricultural land use, particularly extensive high dike construction, on VMD floodwater regimes. This question was addressed using a hydrodynamic modeling tool. The findings in this part of the research helped to identify suitable locations for data collection to pursue research questions 2 and 3, on how the flood retention capacity of the floodplains had changed due to the impacts of dike construction. The findings from the first part of this research also provided data for research question 4, helping to estimate the costs of changes in the flood risk downstream due to different dike impact scenarios. To answer research questions 2 and 3, quantitative and qualitative elements were used, including surveys, interviews and group focus discussions. These enabled an exploration of farming alternatives that might maximize profitability and the sustainability of livelihoods. Data collected to answer these research questions were analyzed using tools such as the aforementioned multi-criteria analysis and cost-benefit analysis. Research question 4 required an evaluation of costs and benefits on the delta scale. The aim here was to determine what agricultural land and water management strategies might promote a more sustainable delta. The strategies investigated sought to adapt the delta to the expected changes, considering hydrological floodwater distribution patterns, socio-economic conditions and environmental aspects under the impact of extensive dike construction.

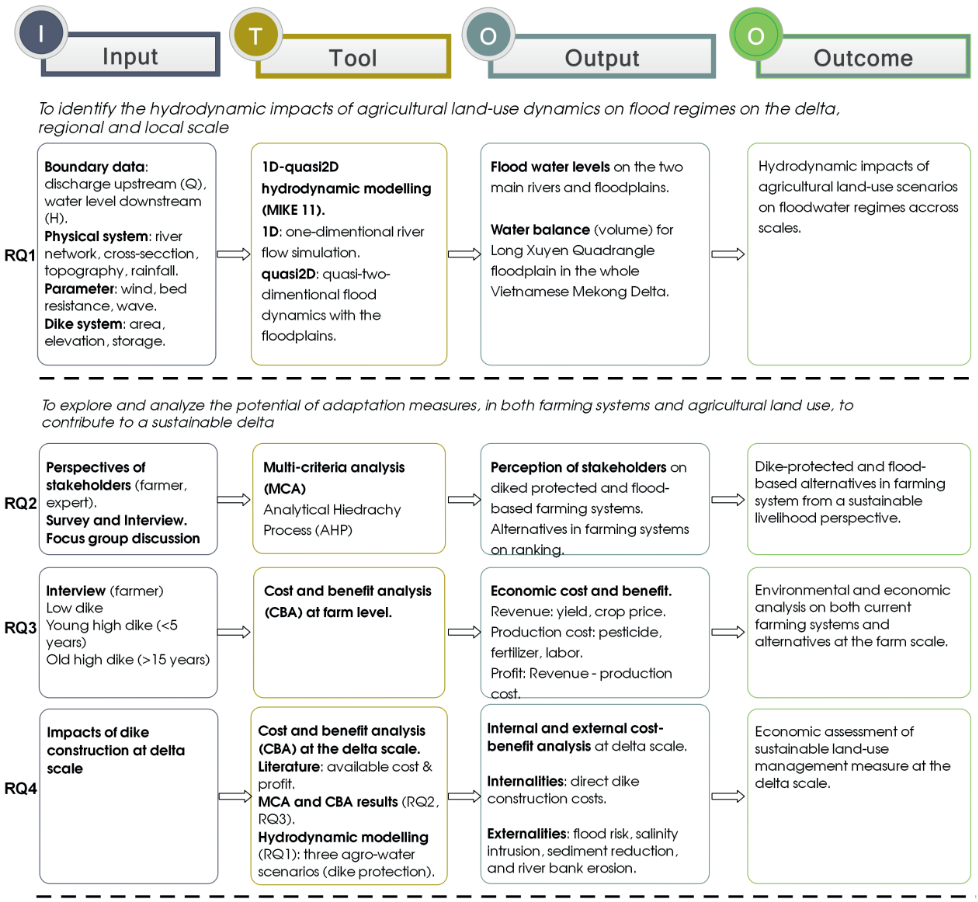


Figure 1.3 Methodological framework

1.4.1. Research objective 1

The first research objective was to identify the hydrodynamic impacts of agricultural land-use dynamics on flood regimes on the delta, regional and local scale. For this, a one-dimensional (1D), quasi-two-dimensional (quasi2D) hydrodynamic model was developed for the whole Mekong delta, including parts of both Vietnam and Cambodia. The required parameters and data were gathered and input into the model, after which calibration and verification were carried out based on measurement data from the floods of 2011 and 2013. Data from the floods of 2000 were used to check model reliability. To assess the impact of land-use changes upstream on the flood risk downstream, four dike construction scenarios were developed and assessed. The peak water levels resulting from each scenario were compared to rank the different scenarios according to the flood risks posed by each, focusing on the main rivers and branches upstream and downstream. In addition, water balances were calculated to assess where the floodwaters went and to determine shifts in the floodwater retention capacity of the Long Xuyen Quadrangle floodplain under different water management regimes.

In the model, quasi2D techniques were embedded in a 1D model to represent the water interaction between rivers and floodplains. Models were run with dike heights adjusted by changing the sill level of the control structures (reservoirs and weirs) to model inflow and outflow patterns for each compartment. Sluice gates influence the water levels across the compartments, canals and rivers and throughout the delta, especially under the current rapid expansion of such water control structures.

1.4.2. Research objective 2

The second research objective was to explore and analyze the potential of adaptation measures, in terms of both farming systems and agricultural land use, to contribute to a sustainable delta. The focus here was on adaptation measures at the farm and delta levels and land and water management strategies that could potentially maximize livelihood sustainability on the delta. Alternatives were analyzed using multi-criteria analysis, integrating the environmental, social and economic dimensions, as well as employing cost-benefit analysis on the farm and delta scale.

A qualitative assessment of adaptation measures was carried out by application of multi-criteria analysis with AHP tools. Various dike compartments within the floodplains were surveyed. Sites were selected based on the impacts of the observed farming systems on flood risk and hydrodynamics across the delta, alongside a preliminary assessment of livelihood characteristics, in line with the outputs of the earlier modeling and insights provided by local authorities and experts. To identify a preliminary set of adaptation measures in farming systems, a literature review and stakeholder interviews were carried out. To further analyze the measures thus identified, a set of criteria was drawn up for evaluating livelihood sustainability considering environmental, social and economic factors. Adaptation measures were weighted and ranked based on the defined criteria. Analytic hierarchy process was then used to explore the suitability of the measures by means of expert judgments in focus group discussions. Data on the costs and benefits of farming systems collected at the survey sites also fed into the economic evaluations conducted in the further phases of the research.

Cost-benefit analysis was used to assess the adaptation measures selected in the multi-criteria analysis from a farm-level perspective. The methodology applied followed Bruin (2011). Using the economic data collected from the survey sites, the costs and benefits of rice farming systems were estimated under different land-use scenarios. Here the focus was on local livelihoods; that is, the economics of livelihoods within local dike compartments.

Existing double rice cropping, triple rice cropping and 3-3-2[1] farming systems and floating crops were considered. I used questionnaires and interviews, refined by a survey of the literature and statistical data, to establish average cost-benefit estimates at the compartment level per land-use type, then scaled up the model applying the different scenarios. Regarding alternative farming systems, such as cultivation of melaleuca, floating vegetables and intensive aquaculture, I found some small-scale practices in the region worthy of further assessment, and used the value transfer method to determine their costs and benefits.

On the delta scale, economic benefits and costs were estimated under three dike construction scenarios. Internal and external factors were evaluated in monetary terms. Among the internal factors included were dike construction costs (investment, maintenance and management) and the cost of the agricultural farming systems developed in each scenario. These were estimated using cumulative average costs and benefits of production in the dike compartments. Among the external factors defined were the impacts of dike construction on flood risk, sediment load, salinity intrusion and riverbank erosion. In this phase of the research, the cost-benefit analysis data from earlier valuation studies and the literature were used to convert external factors into monetary values. Finally, land and water management strategies could be recommended based on the cost-benefit valuations scaled up to the delta level economy.

1.5. Thesis structure

This thesis is structured in six chapters (Figure 1.4). Following this general introduction, chapter 2 explores the hydrodynamic impacts of various dike construction scenarios on floodwater regimes across the delta. On the VMD, each dike construction scenario is associated with a particular agricultural land-use dynamic on the floodplains. A 1D-quasi2D hydrodynamic model was utilized to determine these impacts. The model results highlight the significance of the current extensive high dike construction in water level changes in rivers and floodplains upstream. Yet, downstream these impacts were found to be relatively small. Moving away from the technical assessment of the dike construction scenarios based on the hydrodynamic model, chapter 3 explores stakeholders' perceptions and preferences, based on their views of the sustainability of livelihoods derived from farming systems under low-dike and high-dike protection. This chapter uses multi-criteria analysis with AHP tools to structure the perspectives of experts and farmers regarding farming systems on the floodplains, considering a set of evaluation criteria reflecting the sustainable livelihood perspective. Chapter 4 presents an analysis of the costs and benefits of dike-protected farming systems and flood-based alternative farming systems. This chapter provides economic arguments for alternative farming systems that seem promising for the delta in

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[1] The farming system is protected by high-dikes to practice 3 rice crops per year. Farmers keep one of nine crop seasons free for the field flooded over the three consecutive years of cultivation.

the long term. The next step, presented in chapter 5, was to elaborate on costs and benefits while shifting the focus to the delta scale. This chapter comprehensively evaluates the value of internal and external factors under future land-use scenarios associated with different dike construction schemes. This chapter then presents a solution by which land-use planning might contribute to sustainable development of the delta. Finally, chapter 6 revisits the research questions and objectives, synthesizing the main findings of the research and discussing its scientific contributions. This concluding chapter also makes recommendations for effective water management on the VMD floodplains and presents the author's recommendations for subsequent research.

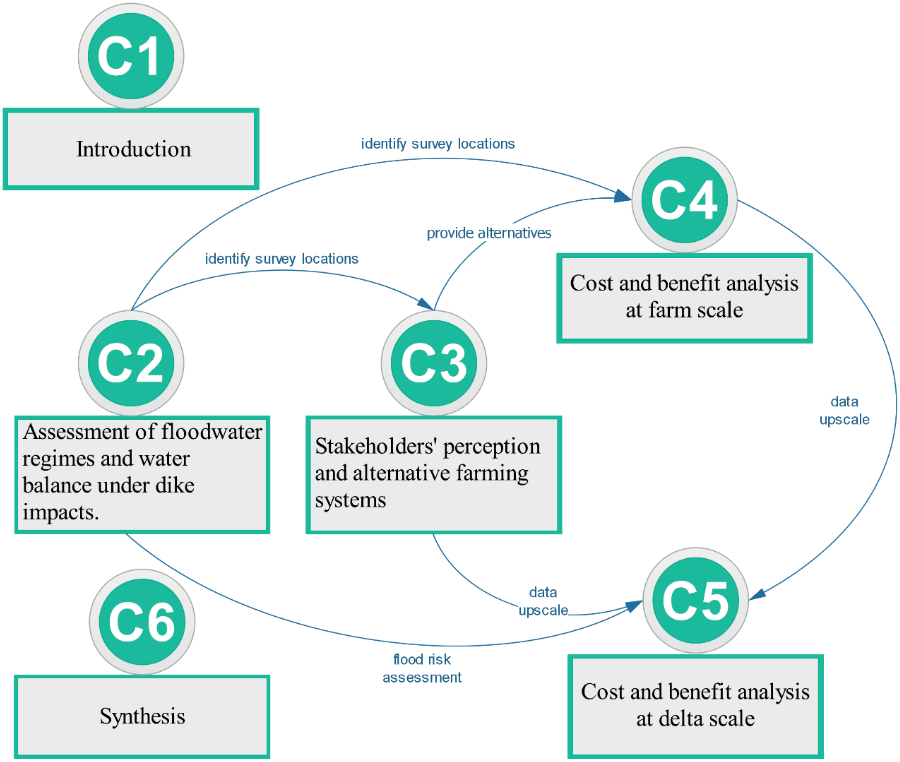

Figure 1.4 Thesis structure

CHAPTER 2

Assessing impacts of dike construction on the flood dynamics of the Mekong Delta changes and sea level rise[2]

Abstract

Recent flood dynamics of the Mekong Delta have raised concerns about an increased flood risk downstream in the Vietnamese Mekong Delta. Accelerated high dike building on the floodplains of the upper delta to allow triple cropping of rice has been linked to higher river water levels in the downstream city of Can Tho. This paper assesses the hydraulic impacts of upstream dike construction on the flood hazard downstream in the Vietnamese Mekong Delta. We combined the existing one-dimensional (1D) Mekong Delta hydrodynamic model with a quasi-two-dimensional (2D) approach. First we calibrated and validated the model using flood data from 2011 and 2013. We then applied the model to explore the downstream water dynamics under various scenarios of high dike construction in An Giang Province and the Long Xuyen Quadrangle. Calculations of water balances allowed us to trace the propagation and distribution of flood volumes over the delta under the different scenarios. Model results indicate that extensive construction of high dikes on the upstream floodplains has had limited effect on peak river water levels downstream in Can Tho. Instead, the model shows that the impacts dike construction, in terms of peak river water levels, are concentrated and amplified in the upstream reaches of the delta. According to our water balance analysis, river water levels in Can Tho have remained relatively stable, as greater volumes of floodwater have been diverted away from the Long Xuyen Quadrangle than the retention volume lost due to dike construction. Our findings expand on previous work on the impacts of water control infrastructure on flood risk and floodwater regimes across the delta.

Keywords: dike, flood dynamics, floodplain, Long Xuyen Quadrangle, Mekong Delta, hydrodynamic modelling

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[2] This chapter has been published as:

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2.1. Introduction

The Vietnamese Mekong Delta (VMD) is popularly known as the rice bowl of Vietnam, as it provides about half of the nation's food volume (Käkönen, 2008). The delta owes much of its agricultural productivity to seasonal flooding, though severe flood years have dire consequences for local populations. Severe flooding is relatively frequent too, having occurred, for example, in 2000, 2001, 2002 and 2011. In general, while extreme flooding poses a threat to people and properties, the benefits of small to medium floods outweigh the disadvantages. In particular, the fertile sediment and fish conveyed by the floodwaters help create an optimal environment for agricultural livelihoods (Käkönen, 2008; Hung, 2012). Tri et al. (2013) and Marchand et al. (2014) calculated that the seasonal floods transport some 160 million tons of fluvial sediment annually. Lu et al. (2014) estimated 67 million tons per year. Some 1.86 tons of fish, worth US $2.6 billion, were supplied by the floods in 2000. Flooding also improves soil quality by flushing fields, which reduces acidity and agrochemical residues, while contributing to wetland protection and biodiversity conservation (Howie, 2011; Danh and Mushtaq, 2011; Hung, 2012). Historically the Vietnamese have adapted their farming systems to exploit the benefits of flooding (Wesselink et al., 2015; Ngan et al., 2017). One example is cultivation of floating rice (*lua mua*) which grows in sync with rising floodwaters and is often combined with fishing (Käkönen, 2008).

Vietnam's *doi moi* economic reform policy, introduced in 1986, and the nation's resolve to become self-sufficient in rice set the VMD on a new socio-economic development path (Kingdom of the Netherlands, 2011; Toan, 2011). First and foremost, the policy gave rise to progressive intensification of rice cultivation (Sebesvari et al., 2012). Beginning with the Long Xuyen Quadrangle (LXQ) and Plain of Reeds, low dikes and irrigation and drainage canals were developed to enable cultivation of two rice crops before a delayed mid-August flood. In 1996, the land reclamation and flood protection program entered a new phase, with residents increasingly resettled to flood-protected villages (Danh and Mushtaq, 2011) and the first large-scale flood control infrastructures built. Construction of high dikes with compartments for rice cultivation continued unabated during the ensuing decades. The agricultural fields thus created were effectively cut off from natural flooding, allowing farmers to cultivate three rice crops annually.

Today, great expanses of the VMD floodplains are covered by intensively cultivated rice fields enclosed by low dikes or high dikes. This intensified land use, however, has coincided with an increased flood risk downstream in the delta, around the city of Can Tho. Comparing water levels in 2011 with those in 2000, lower water levels were observed upstream in the more recent year, with higher levels measured downstream. At the upstream station of Tan Chau, for example, water levels in 2011 were 0.63 m lower than in 2000 (4.27 m versus 4.90 m). However, water levels at the downstream Can Tho station were 0.36 m higher in 2011 than in 2000 (2.15 m versus 1.79 m). This suggests a relationship between the proliferation of dike construction on the floodplains, particularly high dikes, and higher water levels and flood risk downstream.

Several studies have concluded that the flood risk in the VMD has increased over time. Numerous reasons have been proposed, such as climate change, sea level rise, hydropower projects, land subsidence, and local rainfall (Wassmann et al., 2004; Lauri et al., 2012; Van Pham Dang Tri et al., 2012; Fujihara et al., 2015). Wassmann et al., (2004) concluded based on a hydraulic model that the higher water levels in the delta were caused by sea level rise in association with climate change. Fujihara et al. (2015) investigated the impacts of upstream runoff, sea level rise, and land subsidence on flood levels. They found that flood depths would be significantly increased in 19 tide-dominated areas, and that land subsidence and sea level rise would worsen inundation. Lauri et al. (2012) and Hoang et al. (2016) explored potential impacts of climate change and reservoir management scenarios on the future hydrology of the Mekong River. Numerous authors have considered the effects of climate change and sea level rise on flood propagation, inundated area, and sediment transport (Apel et al., 2012; Hung, 2012; Quang et al., 2012; Manh et al., 2014).

Some studies have honed in on the effects of infrastructure development on VMD flood levels. Hoa et al. (2008) used the HydroGIS hydrodynamic model to evaluate the effects of the infrastructural changes from 1996 to 2004 on floodwater levels and flood protection efficacy. They concluded that infrastructure works, such as dredging canals, raising embankments, and upgrading roads, likely mitigated the overall extent of flooding but increased flood depth by 20 to 30 cm in some regions near and between embankment systems. Using the Mike 11 hydrodynamic model, Duong et al. (2014) simulated the water-level impacts of dike construction for the floodwater conditions experienced in 2000 and 2011. Using 2000 flood conditions in combination with the river network and infrastructure system of 2011, they found 13 cm higher water levels at Chau Doc and 5 cm higher Tien River levels at Can Tho. A scenario simulating the 2011 flood volumes with the 2000 river network and infrastructure system showed 8 cm lower water levels at Can Tho. Their simulations, however, could not determine how floodwaters would be distributed. Moreover, Dung et al. (2011) noted deficiencies in the model's representation of the dike system in Vietnam.

Dikes and other water control infrastructures prevent floodwaters from entering agricultural fields. They may therefore increase floodwater flows downstream. Indeed, although floodwater volumes were less in 2011 than in 2000, the water levels observed downstream were higher in 2011 than in 2000. Duong et al., (2014) and Marchand et al. (2014) proposed that the higher downstream river water levels observed during the 2011 floods could be due to the construction of higher dikes. Fujihara et al. (2015) pointed out the need for more research to understand the impacts of high dike construction. Despite the rapid expansion of high dike systems for triple rice cultivation in the upper Mekong Delta, few modelling studies have as yet assessed the implications of such dikes for floodwater regimes[3]. Additionally, most previous studies have focused on changes in peak water levels, based on monitoring data or model results. No study has as yet analyzed the distribution of floodwaters and changes therein. However, water distribution analyses are essential for understanding how floodwaters may spread and where the impacted locations corresponding changes in water volumes are under different dike construction scenarios.

The study presented in this paper aimed to fill these knowledge gaps by using 1D and quasi2D modelling to test the hypothesis that large-scale high dike construction reduces the flood retention capacity of the floodplains and increases water levels and the corresponding flood risk downstream. We first examined the impacts of dike construction on flood dynamics, focusing particularly on changes in river water levels and the spatial distribution of floods on the VMD floodplains. We then developed and calibrated a hydrodynamic model for the entire VMD to simulate flooding under different dike construction scenarios. Using the simulation results we calculated water balances to identify and quantify changes in flood dynamics. The modelling results enabled us to analyze changes in flood patterns and river water levels across the VMD due to dike construction. Finally, we analyze and discuss some of the accompanying uncertainties, closing with a number of conclusions.

2.2. Study area

The Mekong Delta covers some 5 million ha, extending down from Kratie in Cambodia through the VMD to the Gulf of Thailand and South China Sea. At Chaktomuk, its main river, the Mekong, meets the Tonlé Sap River, which in the wet and dry season, respectively, adds and abstracts water to and from the more northern Tonlé Sap Lake. Under Phnom Penh, the Mekong again divides, entering Vietnam in two branches: the Mekong River (called the Tien River in Vietnam) and the Bassac River (called the Hau River in Vietnam) (Manh et al., 2014; Kummu et al., 2014).

Located in the North Pacific monsoon climate (Tamura et al., 2010; Manh et al., 2014), the Mekong Delta is strongly impacted by both flooding upstream and the tidal flows of the Gulf of Thailand and South China Sea. Flooding occurs in the wet season, from July/August to November/December, beginning when the annual average discharge at Kratie exceeds 13,600 m^3s^{-1} (Manh et al., 2014). At Tan Chau, on the Cambodia–Vietnam border, the Tien River carries about 80% of the floodwaters (equivalent to 20,500–25,500 m^3s^{-1}), whereas 20% (equivalent to 6,500–7,660 m^3s^{-1} at Chau Doc) is transported by the

[3] Defined as "the prevailing characteristics and distribution of flood pulses and variability within and across years, is controlled by geography, geology, climate, and human modifications and drives physical and ecological processes within floodplain ecosystems, affecting the diversity, abundance, and communities of species" (Whipple et al., 2017).

Hau River (Tri, 2012). South of Vam Nao, the water volumes of the two rivers become more balanced, owing to interconnecting tributaries. Due to the delta's flat, low-lying topography (its average elevation is just 0.8 m above mean sea level) and the impact of tidal regimes (Hung, 2012), the annual floods inundate 1.2 to 1.9 million ha of the delta (Hoa et al., 2008; Mekong Delta Plan, 2013). In a severe flood season, water depths reach up to 3 m, affecting the lives of more than 2 million residents. Tidal movements make understanding floodwater flows and distribution even more complex.

The LXQ and Plain of Reeds floodplains, due to their huge water retention capacity, play a key role in moderating peak floods. Floodwaters originate from the two main rivers and overland from Cambodia. As the aim of this study is to examine the effects of water control infrastructure on floodwater levels and distribution, we focused on the LXQ, as it has undergone the most extensive development of high dikes during the past decades. Most agricultural areas on the LXQ floodplains are protected by low dikes or high dikes. Low dikes allow floodwaters to overflow into the fields after the harvest of the second crop in mid-August. High dikes prevent floods year-round, enabling cultivation of a third rice crop (Howie, 2011b). This has made the LXQ one of the VMD's highest productivity rice areas (Quang et al., 2012). The LXQ encompasses parts of three provinces, including a large part of An Giang and Kien Giang provinces and a small part of Can Tho Province (see also Figure 2.1). The LXQ has 0.49 million ha of floodplains, located on the northern delta, west of the Hau River. Between the river and the dense network of canals that has long been a feature of this region, numerous dikes have been built, some topped by roads. Statistics from the Department of Agricultural and Rural Development show an enormous increase in the area protected by high dikes in An Giang Province, from 2,591 ha in 1998 to 87,909 ha in 2009 (Kien, 2013). In Kien Giang Province, most agricultural areas are protected by low dikes. There are very few dikes in Can Tho Province.

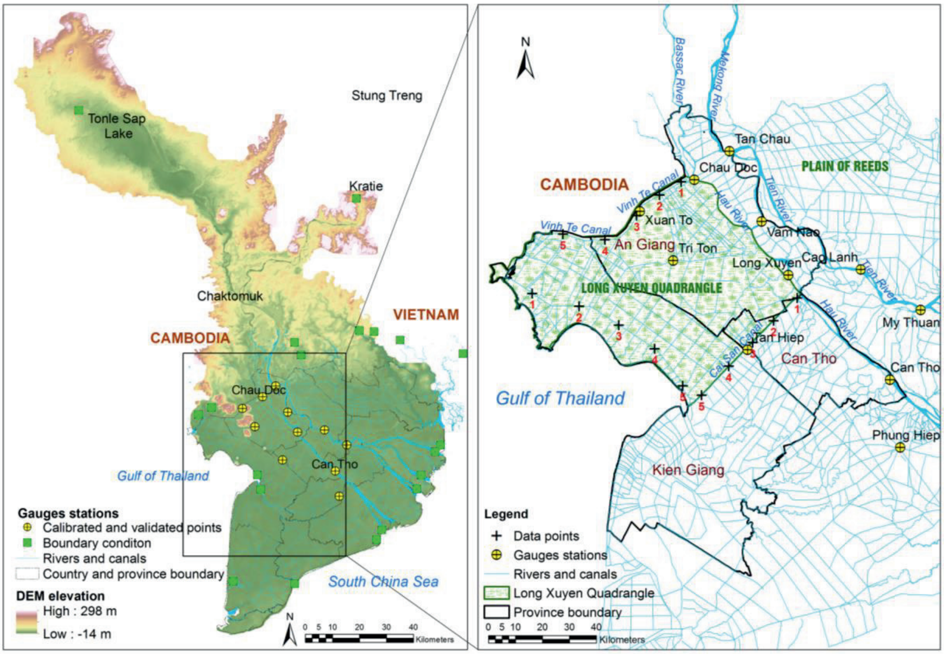

Figure 2.1 Location of the Mekong Delta and Long Xuyen Quadrangle (LXQ)

2.3. Methodology

2.3.1. Model setup and data preparation

We developed a one-dimensional (1D) hydrodynamic model using the Mike 11 software developed by the Danish Hydraulic Institute (DHI). This is an implicit finite difference model for 1D unsteady flow computation. In addition, it can be applied to a quasi-two-dimensional (quasi2D) flow simulation appropriate for detailed modelling of rivers, including special treatment of floodplains, road overtopping, culverts, gate openings and weirs (Doulgeris et al., 2012). The modelling procedure allows use of kinematic, diffusive, or fully dynamic, vertically integrated equations for conservation of continuity and momentum (the Saint-Venant equations) to solve complex flow and mass transport problems (Patro et al., 2009; Dung et al., 2011; Manh et al., 2014). In the model, the Saint-Venant equations are formulated as follows (DHI, 2011).

Continuity equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial A}{\partial t} = q \qquad (1)$$

Momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(\frac{\propto Q^2}{A}\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2AR} = 0 \quad (2)$$

with Q-discharge [m^3s^{-1}], A-flow area [m^2], q-the lateral inflow [m^2s^{-1}], h-stage above datum [m], C-Chezy resistance coefficient [$m^{1/2}s^{-1}$], R-hydraulic or resistance radius [m], $\propto$- the momentum distribution coefficient.

We developed our model to represent the river network and floodplains of the Mekong Delta. Data on the Mekong Delta river network and physical properties were derived from the Southern Institute for Water Resources Research (SIWRR). The hydrodynamic module included in Mike 11 was applied to simulate flow dynamics and inundations. We incorporated four main components: (i) the river network, (ii) boundary conditions, (iii) cross sections and (iv) a set of other parameters. Although rainfall accounted for only a small percentage of surface water inflows, we nonetheless included it in the model using the Rainfall Runoff (RR) module.

The 2011 river network was imputed into the model based on available data. The area of interest – from Kratie and the Tonlé Sap Lake in Cambodia to the river mouths in Vietnam – encompassed 5 million ha, 4,084 river branches and 21,235 computational nodes (see Supplementary A1). For the canal and water control infrastructure network, sluice gates (14), weirs (2,246), and control structures (2,657) were identified, representing the infrastructure system. Sluice gates regulate water flows to larger areas. Weirs regulate flows into and out of agricultural fields. The control structures considered were reservoirs, which prevent water overflow at a specific sill level.

Boundary conditions for the model were set using discharges and water levels observed in 2011 and 2013. All daily data were provided by the National Centre for Hydro-Meteorological Forecasting (NCHMF) and SIWRR. Discharges from six stations were imputed for the upstream boundary conditions, while the downstream boundary conditions were provided by water levels measured by nine tide gauges near the coast. Upstream, the discharge at Kratie was the most important boundary input for drawing the main flood hydrograph to simulate discharges and water levels downstream for the VMD.

We embedded 13,000 cross sections in the model. These described the topography of the rivers and branches. Cross-section data were collected from various sources. Data concerning the major streams were very reliable, as these measurements were produced and regularly updated by national projects. For the branches, bathymetric data were used for most cross sections, though this process meant that accuracy was likely lower. These cross sections had, however, been tested in various SIWRR projects.

Our set of other parameters included river roughness, wind effects, and various components derived from DHI (2011). These described the physics of the Mekong Delta. Among them, the river roughness coefficient was the most important and sensitive parameter. River roughness was represented in the model as Manning coefficients, which we initially estimated based on published values corresponding to particular types of rivers and canals (Chow, 1959; Fabio et al., 2010; Dung et al., 2011). First, referring to Chow (1959), we set the Manning coefficients as 0.020 (irrigation channel, straight, on hard-packed smooth sand), 0.025 (earth channel excavated in alluvial silt soil, with deposits of sand on the bottom and grass growth) and 0.033 (natural channel, somewhat irregular side slopes, very little variation in cross section). These were used for all rivers and branches in the three initial model runs to identify changes in water levels and discharges of the main rivers. Second, we calibrated the model by modifying these numbers for the branches in the more coastal areas. After model fitness was satisfactory for the stations near the coast, we defined a range of Manning coefficients (0.024–0.017) for the Tien and Hau rivers. Rivers in the Cambodian part of the delta were given a range of 0.1–0.05, whereas a range of 0.03–0.025 was selected for the rivers and canals on the VMD floodplains. These parameters were optimized during the calibration process.

Daily rainfall data were derived from 37 meteorological stations (28 in Vietnam and 9 in Cambodia). Thiessen polygons were used to describe the contribution of surface water flows to river and canal discharge. In the model, we divided the Mekong Delta into 120 sub-regions, with data from rainfall gauges for each. The rainfall discharge had to be calibrated using the Rainfall Runoff (RR) module provided with the Mike 11 NAM before it could be used for the hydraulic model simulations.

2.3.2. Calibration and validation

The flood model had to be calibrated and validated to ensure reliable performance. For calibration, we used the severe flood year of 2011. To validate the model, we used data from the 2013 flood season. These 2 years were selected because the river and infrastructure network, land uses and dike locations were similar in both years. The Nash–Sutcliffe efficiency (NSE) and correlation coefficients were used to check the model's goodness-of-fit for the calibration and validation periods. The NSE is one of the most commonly used efficiency criteria in hydrology. It measures how much of the variability observed is explained by the simulation. A perfect simulation has an NSE of 1 (Ritter and Muñoz-Carpena, 2013). The correlation coefficient (R^2) expresses the linear relationship between observed and simulated values.

For the calibration and validation periods, we used hourly discharge and water level time series from 15 gauging stations, including 11 stations along the Tien and Hau rivers and 4 stations on the floodplains (Figure 2.1). We selected these stations because (i) the objective of our study was to explore the water level dynamics in the main streams and LXQ and (ii) observational data were available from each.

In addition to calibration and validation for the 2011 and 2013 data, we assessed model performance for the 2000 flood hydrograph. Using flow data from 2000, including discharge at Kratie and water levels at nine tide gauges, we ran the model assuming the 2011 river network and land use system. Model outputs were compared to maximum river flows in the Hau River.

2.3.3. Modelling for the floodplains

To simulate the hydraulic dynamics of the floodplains, the quasi2D approach was combined with 1D modelling. In the quasi2D model, the floodplains were described as a network of fictitious river branches and spillovers with the main rivers. This approach had several advantages, i.e., (i) transferring some of the benefits of 2D flow calculations and flow directions to the 1D hydrological model; (ii) saving computation time because fewer input data were needed; and (iii) reliable model representation of physical processes (Karl-Erich et al., 2008; Soumendra et al., 2010).

We used different approaches to model the floodplains in Cambodia and in Vietnam. The Cambodian floodplains without channels and dikes were simulated by wide cross sections using the 1D method. For the LXQ, we applied the quasi2D approach to formulate the hydrodynamic interactions between the floodplains and rivers under various dike construction scenarios. Although the Plain of Reeds itself was not a focus of this research, we included it in the model with the dikes as constructed in 2011, to better understand the hydraulic interactions between the Tien and Hau rivers via the Vam Nao River and tributaries. The LXQ floodplains are characterized by a dense network of dikes and channels, producing multitudes of compartmentalized fields for agriculture.

Our model has 554 dike compartments representative of the floodplains of the VMD. Our modelling approach for simulating the interaction between rivers and floodplains is to consider that each dike compartment is a flood cell. It means each flood cell is specifically defined and isolated geographical area as a rectangle surrounded by real dikes and channels. This approach, from Dung et al. (2011), is illustrated in Supplementary A1. In the figure, each compartment was considered as a flood cell and modeled as a fictitious river branch with a low and wide cross section, as extracted from a SRTM digital elevation model (Shuttle Radar Topography Mission DEM, 90 m × 90 m resolution). These data also help the model to estimate each cell volume. The control structures linked these fictitious river branches to real channels. Weirs represented dikes and overflows. Dike height was adjusted by changing the sill level of the control structures. By using this approach, floodwater could flow in and out the flood cells, depending on the height of dikes as the sill level of the control structures.

2.3.4. Dike construction scenarios

Various dike construction and land use scenarios were developed to explore the impacts of dikes on flood dynamics (Figure 2.2). The first scenario (S1) provided a baseline to explore flood dynamics without the impact of high dikes4. All of the high dikes were therefore removed from the model in this scenario. Without the high dike compartments, water discharge is freely distributed over the LXQ and throughout the canals along the Hau River. The second scenario (S2) represents the dike infrastructure and land use conditions of 2011. Here, more than half of the total agricultural area in An Giang Province is set off by high dikes, with the remaining areas protected by low dikes. Kien Giang Province had only low dikes in 2011. The third scenario (S3) depicts a system in which high dikes protect the entire An Giang Province. The fourth scenario (S4) represents a system with high dikes across the entire LXQ.

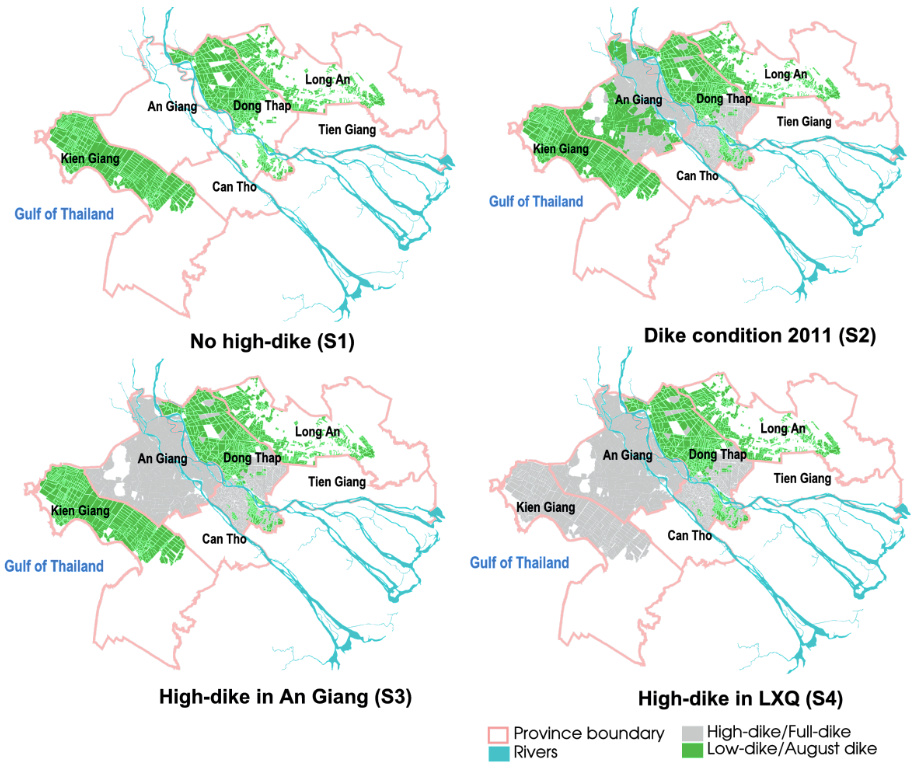

Figure 2.2 Dike construction scenarios: (S1) no high dikes, (S2) dike infrastructure as in 2011, (S3) high dikes throughout An Giang Province, and (S4) high dikes throughout the Long Xuyen Quadrangle

[4] High dikes are usually built at a height of 2.0–2.5 m, in places where maximum flood depths are less than 1.5 m, to completely prevent floodwater from entering the fields (Tran and Weger, 2017).

2.3.5. Water balance calculation

To understand why and where the water movements on the floodplains cause changes in downstream flows, we calculated water balances for each scenario. For the 1D hydrological model representing the complex hydraulic situation of the Mekong Delta, all components in the water balance equation were estimated. The water balance equation is as follows:

$$\sum_{i=1}^{n} Q_{in}(t_i) - \sum_{i=1}^{n} Q_{out}(t_i) = (V - V_o)dt_i, \qquad (3)$$

where $\sum_{i=1}^{n} Q_{in}(t_i)$ is total inflows and $\sum_{i=1}^{n} Q_{out}(t_i)$ is total outflows to the LXQ, in cubic meters per second (m^3s^{-1}), corresponding to the starting time t_1 (July) and ending time t_n (December) of the flood simulations. V is the controlled volume and V_o is the initial volume, in cubic meters (m^3).

From the output of the hydraulic model, we extracted discharge time-series data from canals along the closed boundaries of the LXQ to calculate flow volumes over the July to December period. Inflows include the water fluxes along the Vinh Te Canal and along the Hau River. Outflows were taken from the Cai San Canal and the canal along the Gulf of Thailand. The water balance was also computed for the Hau River. Here, the water fluxes at Chau Doc and the volume of the Tien River were input flows, while the output flows consisted of discharges along the Hau River to the LXQ, through the Cai San Canal, and at the point on the Hau River beyond the Cai San Canal. Rainfall volumes were calculated from the individual rainfall simulation files.

2.4. Results

2.4.1. Calibration and validation results

Table 2.1 presents the calibration and validation results. Additionally, Figure 2.3 presents the time-series plots for the streamflow results of 2011. *Q–Q* plots for representative stations and time-series plots for the 2013 results are shown in Supplementary A (Figures A2 and A3). Our NSE and R^2 values computed for selected stations suggest generally very good performance of the model, in ranges, respectively, of 0.79–0.97 and 0.89–0.98. The 2011 calibration period shows better performance than the 2013 validation period. This is expected, as changes in infrastructure and dike network may have occurred between 2011 (calibration) and 2013 (validation) which were not incorporated in the model. For example, the NSE of the water level found in Chau Doc in 2013 is 0.79 compared to 0.92 in 2011. The My Thuan station shows lower NSE values for both 2011 and 2013, but these values are still greater than 0.8. For the stations located within the floodplains, good fitness was found in water levels (0.85–0.96); unfortunately, discharge observation data were not available for those stations.

Table 2.1 Correlation coefficient and Nash–Sutcliffe efficiency of water levels (WL) and discharges (Q) for 2011 (calibration) and 2013 (validation)

Location	Correlation coefficient R^2				Nash-Sutcliffe efficiency E			
	WL 2011	WL 2013	Q 2011	Q 2013	WL 2011	WL 2013	Q 2011	Q 2013
Tan Chau	0.97	0.96	0.97	0.95	0.94	0.90	0.88	0.94
Chau Doc	0.95	0.90	0.95	0.92	0.92	0.79	0.92	0.90
Vam Nao	0.98	0.94	0.96	0.94	0.91	0.93	0.90	0.92
Long Xuyen	0.96	0.93	-	-	0.92	0.92	-	-
Can Tho	0.97	0.98	0.95	0.96	0.97	0.97	0.92	0.90
Cao Lanh	0.97	0.94	-	-	0.93	0.94	-	-
My Thuan	0.97	0.94	0.89	0.91	0.94	0.83	0.80	0.86
Xuan To	0.91	0.90	-	-	0.85	0.87	-	-
Tri Ton	0.95	0.93	-	-	0.91	0.85	-	-
Tan Hiep	0.97	0.93	-	-	0.96	0.90	-	-
Phung Hiep	0.94	0.94	-	-	0.85	0.88	-	-

(-) Missing data due to unavailability of observed discharge data from station.

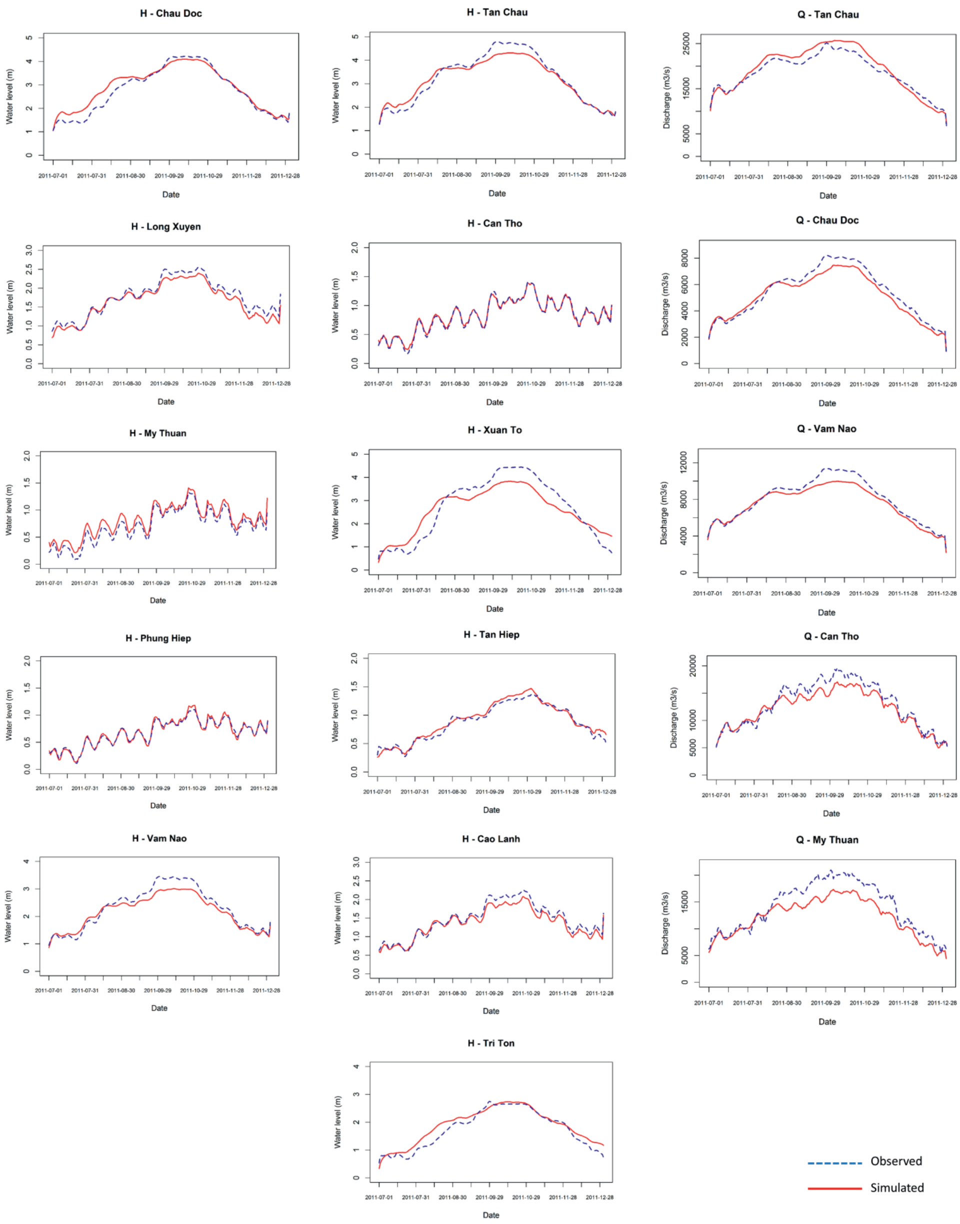

Figure 2.3 Time series of daily simulated and observed flows in 2011 at all stations used for model calibration

Model performance was also judged as good considering the small difference between the peak water levels produced by the simulation and those observed in 2011 and 2013 (Figure 2.4). However, the peak values simulated were in most cases lower than observed values.

The discrepancy was greater for 2000 than for 2011 and 2013. The simulation returned a slightly lower peak river water level at Can Tho in 2000 (2.02 m) compared to 2011 (2.10 m). According to observational data, however, the highest water level observed in Can Tho in 2000 was 1.79 m, whereas 2.15 m was observed in 2011.

This raises the question of whether the changes in river water levels at Can Tho are primarily attributable to changes in the floodplains and canal networks between 2000 and 2011, or to the effect of the higher tidal movements observed in the estuaries of the Tien and Hau rivers. Tidal flows in these estuaries were markedly higher in 2011 than in the peak flood year of 2000, suggesting potential backwater curve effects (Table 2.2). However, the model results for 2000 (using the 2011 river and infrastructure network and the 2000 river water level and tidal data) compared to those for 2011 (2011 river and infrastructure network and 2011 water levels) show just a modest increase of 0.08 m at Can Tho (Table 2.3). This suggests that the tidal backwater effect seems to be limited. It is significantly smaller than the difference in water levels observed between 2011 and 2000, which amounts to 0.36 m at Can Tho. This analysis suggests that the tidal influence is approximately 0.08 m, while the effect of changes in the river and infrastructure network and on the floodplains amounts to 0.28 m in terms of river water levels at Can Tho. Given that the total flood volume in 2011 was 30% less than in 2000 (283×10^9 m^3 compared to 402×10^9 m^3) the effect of changes in the river and infrastructure network and floodplains appears relatively large.

Table 2.2 Tidal water levels in numbers of hours above various thresholds, observed at the My Thanh and Ben Trai stations in the 2000 and 2011 wet seasons (July to December).

Water level	Numbers of hours above threshold at My Thanh		Numbers of hours above threshold at Ben Trai	
	2000	2011	2000	2011
>1.5 m	95	424	31	102
>1.6 m	35	290	8	51
>1.7 m	7	198	0	23
>1.75 m	3	160	0	12
>1.85 m	1	104	0	0

Table 2.3 Changes in river water level and origins at Can Tho, 2000 and 2011

WL at Can Tho	**Model (m)**	**Observed (m)**	**Δ (m)**	**Flood volume of VMD (10^9 m^3)**
2000	2.02*	1.79	-0.23	402
2011	2.10	2.15	+0.05	283
Δ (m)	**0.08**	0.36	**0.28**	

** Model outcomes for 2000 were derived using the observed hydrograph and tidal water levels of 2000 combined with the river network and floodplain characteristics of 2011.*

Figure 2.4 shows a good fit between the simulated and observed peak water levels for the floods in 2011 (calibration) and 2013 (validation). In the 2000 flood, the fitness is low due to the significant changes in physical topography such as river network and branches and river cross sections between the model setup of 2011 and the measured data in 2000.

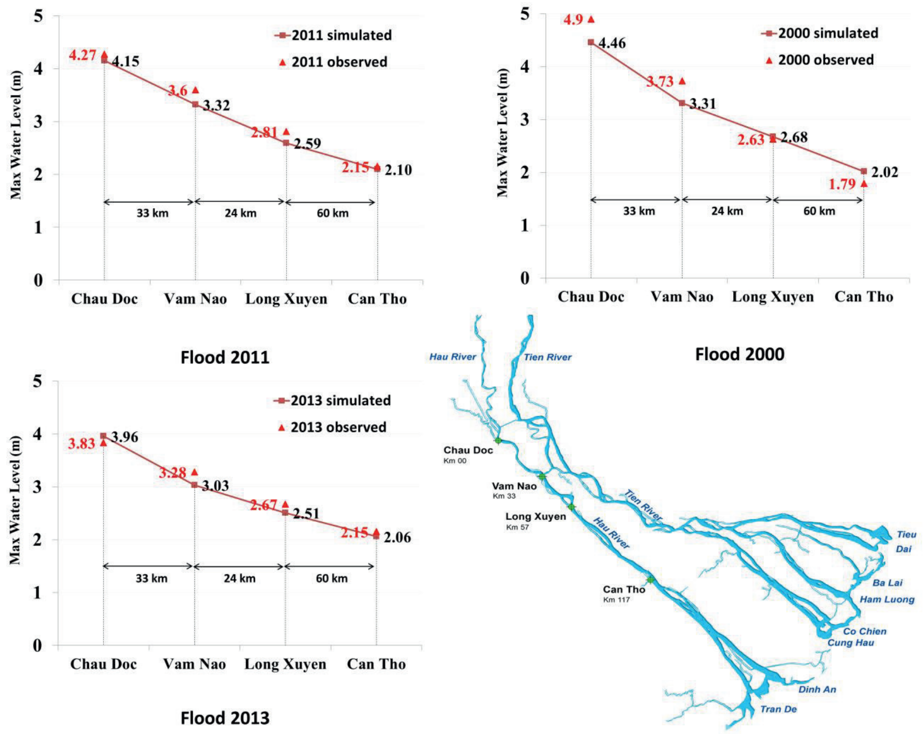

Figure 2.4 Simulated and observed peak water levels for the 2000, 2011 and 2013 flood years at four stations along the Hau River

2.4.2. Flood dynamics under the impact of dike construction

Simulation results indicate that if all high dikes were removed (S1), peak river water levels would be much lower, especially in the upper part of the Mekong Delta (Figure 2.5). Compared to the 2011 situation (S2), peak river water levels would be reduced by 66 cm at Chau Doc and 31 cm at Vam Nao if all high dikes were removed. At Can Tho, however, differences in peak river water levels were relatively small, removing all high dikes reduced peak levels in Can Tho by only about 4 cm. Within the LXQ, removal of all high dikes would result in relatively large increases in peak water levels upstream (90, 40 and 50 cm at Xuan To, Tri Ton and Tan Hiep, respectively), compared to downstream points (2 cm at Phung Hiep) (Figure 2.6). In the Vinh Te Canal, water levels fall under a no high dike scenario (by 17.2–84.6 cm from upstream to downstream), but they increase in the Cai San Canal (4.3–45.8 cm) and in the canal along the Gulf of Thailand (fluctuating 1.0–34.1 cm along the canal) (Table 2.4).

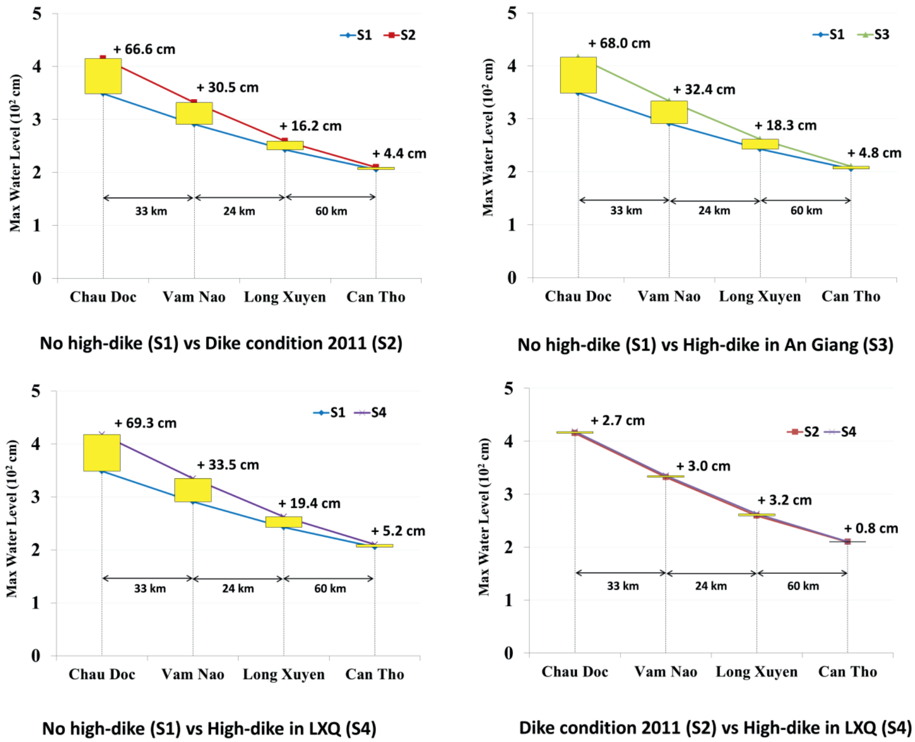

Figure 2.5 Comparison of peak river water levels at stations along the Hau River resulting from different scenarios (Note LXQ is Long Xuyen Quadrangle)

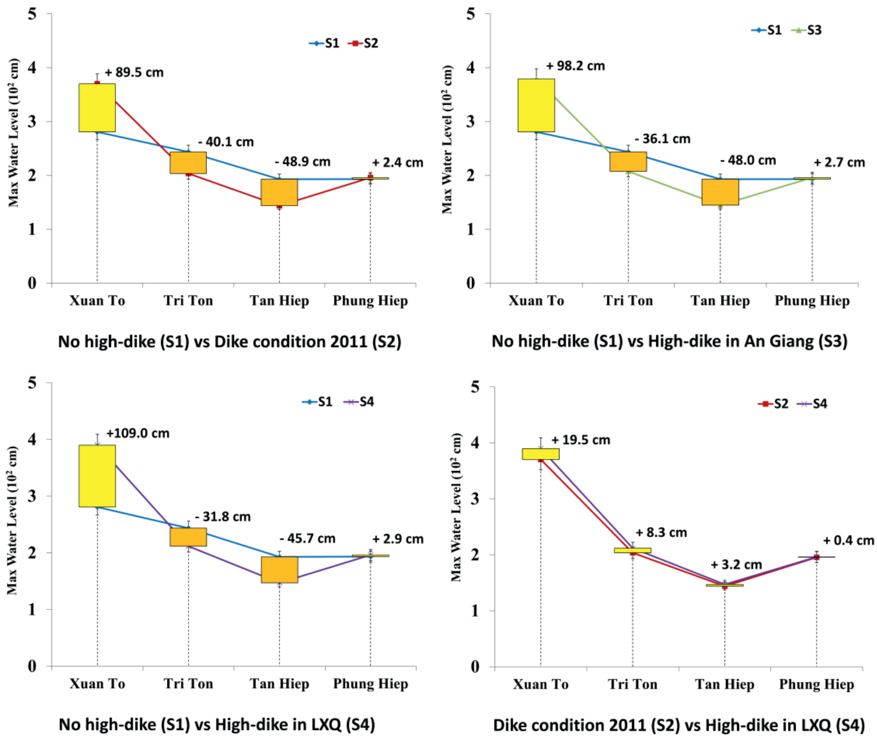

Figure 2.6 Comparison of peak water levels at stations in the Long Xuyen Quadrangle (LXQ) resulting from different scenarios

The increases in river water levels from high dike expansion in An Giang Province and the LXQ (S3 and S4) show a similar pattern to S2 (dike infrastructure as in 2011) and S1 (no dikes). The model presents very slight increases in river water levels (2–3 cm upstream and 1 cm downstream) from expansion of the high dikes (S3 and S4) compared the 2011 dike scenario (S2) (Figure 2.5 and Figure 2.6). Overall, we found major differences only between the baseline scenario (S1) and the high dike scenarios (S3 and S4).

Table 2.4 Peak water levels under different dike construction scenarios in the boundary canals of the Long Xuyen Quadrangle

Scenarios	S1 (m)	S2 (m)	S3 (m)	S4 (m)	S2–S1 (cm)	S3–S1 (cm)	S4–S1 (cm)
Vinh Te Canal							
(1) Km 0	3.40	4.18	4.20	4.22	*78.70*	*80.70*	*82.20*
(2) Km 17	3.08	3.92	3.97	4.03	*84.60*	*89.60*	*95.50*
(3) Km 31	2.39	3.01	3.31	3.64	*61.70*	*92.20*	*124.80*
(4) Km 42	2.77	2.95	3.01	3.61	*18.80*	*24.00*	*84.20*
(5) Km 54	2.81	2.98	3.04	3.62	*17.20*	*22.90*	*81.30*
Cai San Canal							
(1) Km 0	2.36	2.31	2.33	2.34	*–4.30*	*–2.80*	*–1.80*
(2) Km 10	2.23	1.98	2.00	2.01	*–25.20*	*–23.20*	*–21.50*
(3) Km 22	2.10	1.80	1.81	1.83	*–30.00*	*–28.80*	*–26.40*
(4) Km 33	1.99	1.53	1.54	1.56	*–45.80*	*–44.90*	*–42.50*
(5) Km 47	1.51	1.08	1.08	1.09	*–42.90*	*–42.50*	*–41.90*
Canal along the Gulf of Thailand							
(1) Km 0	1.02	1.11	1.14	1.05	*9.40*	*11.90*	*2.70*
(2) Km 17	1.10	1.09	1.10	1.02	*–1.00*	*–0.80*	*–8.40*
(3) Km 38	1.35	1.06	1.04	0.98	*–29.20*	*–31.60*	*–37.20*
(4) Km 56	1.29	0.95	0.95	0.92	*–34.10*	*–34.20*	*–36.80*
(5) Km 74	1.42	1.05	1.05	1.05	*–37.50*	*–37.30*	*–36.80*

Paired sample t tests indicate significant differences between simulated and observational water level data for the different scenarios at upstream stations, but not for those downstream ($p<0.05$) (see Supplementary A, Table A4).

2.4.3. Floods of 2000 and 2013

To assess the impact of different floods on peak river water levels, we ran our four scenarios with the 2000 and 2013 flood hydrographs, compared to the base runs for 2011. These simulations resulted in upstream concentrations of water level increases for all of the three flood hydrographs (Figure 2.7). The largest increases in river water levels were found for the high dike scenarios (S2, S3, and S4). These produced similar absolute increases in relation to the no dike scenario (S1) under all three hydrographs. The suggestion here is that peak levels in the Hau River are relatively independent of the amount of floodwater and flow regime, as water volumes for the simulations differed quite starkly, from 402 × 10^9 m^3 (2000) to 283 × 10^9 m^3 (2011) and 236 × 10^9 m^3 (2013).

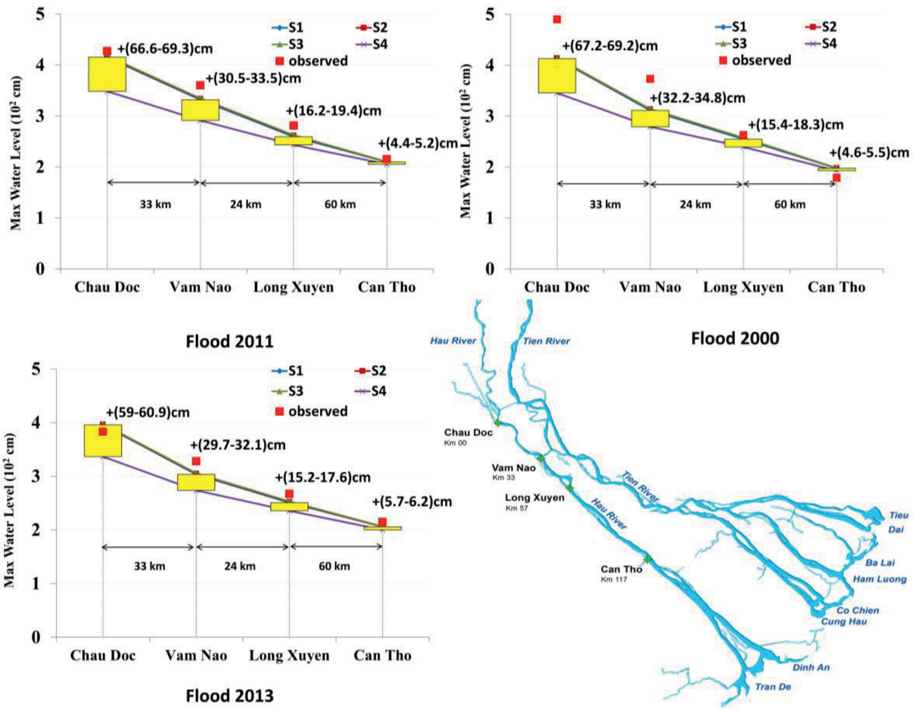

Figure 2.7 Comparison of peak water levels produced by the scenarios in different flood years

2.4.4. Variability in upstream and downstream water levels

Across the four scenarios and the three flood hydrographs, our model results indicate pronounced increases in water levels in the upstream reaches, with levels remaining fairly constant downstream (Figure 2.8). For scenarios S1 and S2 and the 2000, 2011, and 2013 flood hydrographs, we calculated coefficients of variation (CV) for the water levels. At Chau Doc, upstream, the CV was 0.47, diminishing to 0.07 downstream at Can Tho. Two explanations may account for the limited variability found in water levels downstream: (i) use of tidal water level data at the river estuary as a boundary condition for the model and (ii) the coast-to-upstream direction of our model calibration procedure.

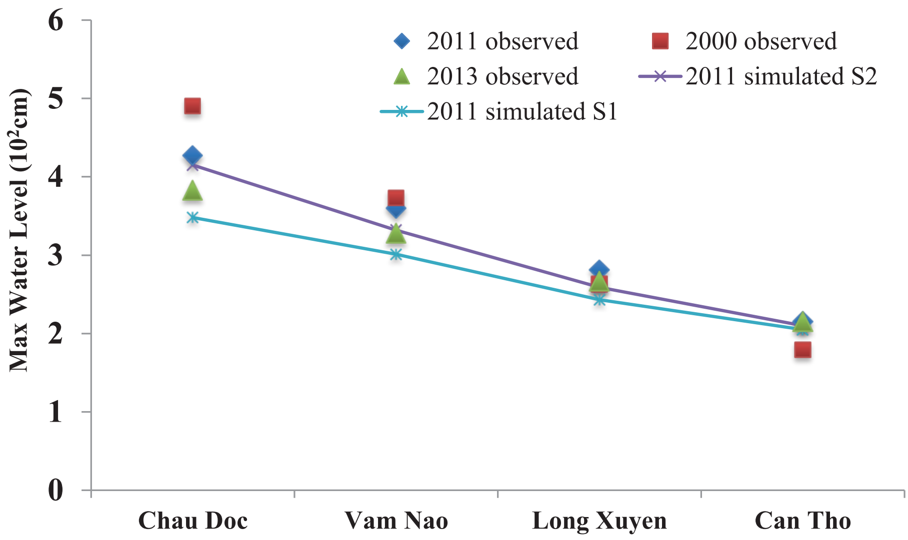

Figure 2.8 Observed and simulated peak water levels along the Hau River

The tidal water level data at the estuary of the Mekong were influenced by the (peak) river discharges in the years considered, with peak river flows particularly influencing river mouth levels at high and low tide. Thus, our model's boundary conditions were not only set by tidal movements, but also influenced by river discharges at the estuary mouth for the years considered. In calibrating our model, we first set the roughness coefficients for the coastal area to agree with recorded water levels before calibrating for river water levels and discharges in the upstream parts. This potentially reduced the variability in downstream water levels. Potential biases of water level would be propagated toward the upstream reaches and outer edges of the model.

On the other hand, the dissipation effect of a floodplain and river network as large as the Mekong Delta is expected to yield relatively smaller change amplitudes in downstream water levels, as changes are modulated across a large area. However, any further reduction in the floodplain area and its dissipation capacity would be expected to produce a markedly increased amplitude in downstream water levels.

2.4.5. Water balance

To further assess the model's simulation of the hydrodynamic characteristics of the Mekong Delta, we conducted a water balance analysis of flood volumes for the LXQ. Compared to the situation without high dikes (S1), the high dike scenarios (S2, S3, and S4) produced a reduction of floodwaters flowing into the LXQ (Figure 2.9). The floodwater volume decreased from 18.4 × 10^9 m^3 to 12.7–11.8 × 10^9 m^3 along the Vinh Te Canal bordering

Cambodia, and from 31.7 × 10⁹ m³ to 12.5–11.3 × 10⁹ m³ along the Hau River. With less water coming into the LXQ floodplains, water draining into the Gulf of Thailand and the Cai San Canal was reduced accordingly in the high dike scenarios (from 33.3 × 10⁹ m³ to 22.1–21.3 × 10⁹ m³, and from 16.6 × 10⁹ m³ to 2.4–2.6 × 10⁹ m³, respectively). The total reduction in flood volumes entering the northwestern corner of the Mekong Delta for simulation runs S2, S3, and S4 (2011 hydrograph) amounted to 15 × 10⁹ m³ (Table 2.5). This is equivalent to a reduction greater than the estimated flood retention capacity (13 × 10⁹ m³) of the entire LXQ (estimated as a flood depth of 3 m over the entire 0.49 million ha floodplain). This explains why the high dike simulations (S2, S3, and S4) return only minimal increases in river water levels, despite the significant reduction of flood retention capacity in the LXQ. In the model simulations, floodwaters are diverted away from the floodplains.

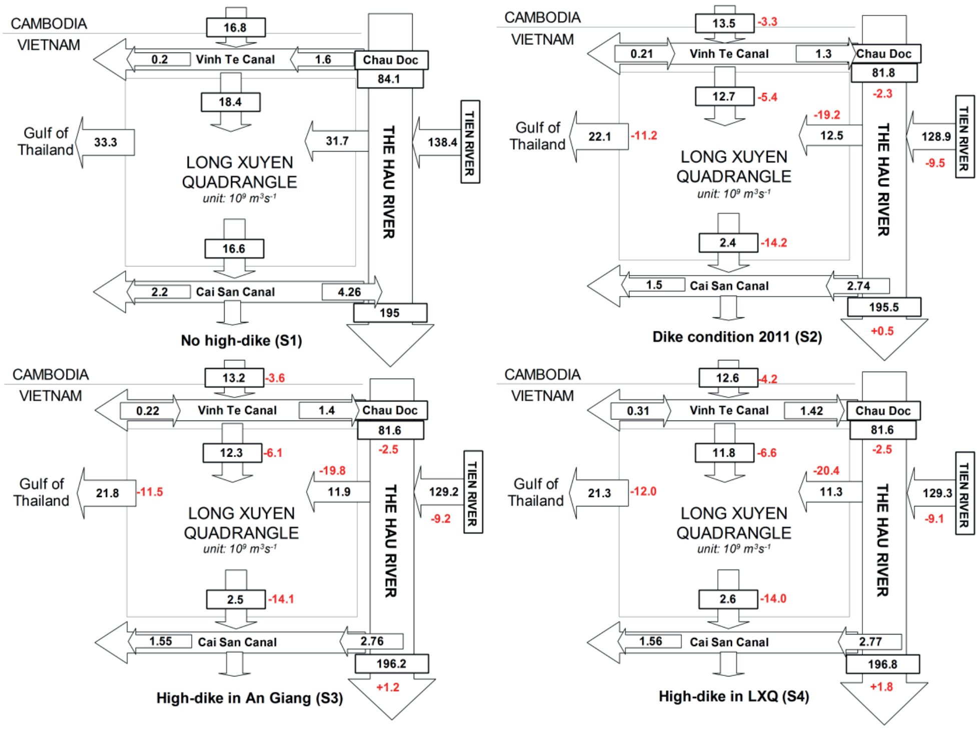

Figure 2.9 Water balance calculations for the Long Xuyen Quadrangle under the various scenarios. Red numbers indicate the difference with scenario S1 (no high dikes)

Table 2.5 Comparison of total inflow to system volume

Scenario	$\sum Qin$ (system) (10^9 m^3)	$\sum \Delta Qin$ (10^9 m^3) Compared to scenario 1	$\sum \Delta S$ (10^9 m^3) Water storage in LXQ
S1 No high dikes	239.3	–	13
S2 Dike conditions as in 2011	224.2	–15.1	6
S3 High dikes in An Giang	224.0	–15.3	4
S4 High dikes in LXQ	223.5	–15.8	0

The floodwater volumes reaching the LXQ diminish with large-scale high dike construction, that is, in scenarios S2, S3, and S4, due to several factors. First, overflow from the Cambodian floodplains into the Vinh Te Canal drops from 16.8 × 10^9 m^3 in the situation without high dikes to 13.5–12.6 × 10^9 m^3 with high dikes. Second, floodwater from upstream in the Hau River drops from 84.1 × 10^9 m^3 to 81.8–81.6 × 10^9 m^3. Finally, the volume of floodwater from the Tien River flowing into the Hau decreases from 138 × 10^9 m^3 to 128.9–129.3 × 10^9 m^3. Combined, these diverted floodwaters amount to a volume reduction of 15 × 10^9 m^3 (Table 2.5).

The high dike scenarios (S2, S3, and S4) also resulted in changes in flow directions of the modelled flood streams and in volumes. As a consequence, there was only a slight increase in flood volume in the downstream (estuary) reach of the Hau River. In the Vinh Te Canal, a flood stream amounting to 1.6 × 10^9 m^3 drains toward the Gulf of Thailand in the no dike scenario (S1, 2011). For the high dike scenarios (S2, S3, and S4, 2011), it reverses direction, diverting 1.3–1.4 × 10^9 m^3 toward the Hau River. In the Cai San Canal, a flood stream amounting to 4.26 × 10^9 m^3 flows into the Hau River, but under the impact of high dikes changes direction, with a volume of 2.74–2.77 × 10^9 m^3 flowing toward the Gulf of Thailand. In the downstream reaches of the Hau River the model returns just a slight increase in flood volume (0.5–1.8 × 10^9 m^3; < 1%) for the high dike scenarios (S2, S3, and S4) compared to the no dike scenario (S1). As the water balance analysis shows, this is caused by a diversion (rerouting) of flood volumes away from the LXQ, so that the reduction of flood retention capacity due to expansion of high dikes has little impact on downstream water levels and flows. The reduction in the flood retention capacity of the LXQ (7–13 × 10^9 m^3, Table 2.5) is thus effectively (over) compensated for in the model runs by the reduction of 24–26 × 10^9 m^3 of flood volume entering the LXQ floodplains (Figure 2.9). However, this diversion of flood volumes to primarily the Plain of Reeds (+9 × 10^9 m^3) and the Cambodian floodplains (+6.7 × 10^9 m^3) cannot be verified at present due to data limitations in these areas.

2.5. Discussion

Recent flood dynamics of the Mekong Delta have raised concerns about an increased flood risk downstream in the VMD. Some authors suggest that a greater flood risk downstream might be linked to the prevalence of high dikes on the upper VMD floodplains (Hoa et al., 2007; Duong et al., 2014; Marchand et al., 2014; Fujihara et al., 2015). Using a 1D hydrodynamic model combined with a quasi2D approach (following Dung et al., 2011), we quantified the impacts of extensive high dike construction on floodwater levels and flood risk across the VMD. Most hydrodynamic studies of the Mekong Delta have retrofitted modelled changes (e.g., dikes and canal network) to past flood events (e.g., flood levels and flood area data). Whereas good fits are generally reported between model outputs and recorded water levels, these studies are unable to explain how flood volumes are distributed over the delta. We therefore elaborate one of the new studies to explore the 1D with a quasi2D model advantage, considering potential hydraulic impacts of existing and planning dike construction scenarios on the flood regimes in the VMD. We fill this knowledge gap by using water balance calculations to explain where floodwater delivers under the dike scenarios.

In our study, we calculated water balances for the flood scenarios and events considered, to provide insight into the spatial redistribution of flood volumes due to changes in dike prevalence. Our results show a clear impact of dike construction on floodwater levels in the Hau River. The high dike scenarios (S2, S3, and S4) produced a marked increase in peak river water levels in the upstream reaches of the Hau River (+68 cm at Chau Doc), while minimal increases occurred downstream (+5 cm at Can Tho). A similar trend and effect was found on water levels in the canal network of the LXQ and western floodplains. The model showed that high dike construction would have a substantial impact (+100 cm) on water levels along the upstream boundary of the LXQ (i.e., at Xuan To). This was paired with a diminishment in water levels (–45 cm) within the dike-protected floodplains and a limited or no effect on the downstream floodplains of the LXQ and in Can Tho (i.e., at Phung Hiep). These results suggest that further expansion of high dikes in the LXQ would have little impact on peak water levels, as simulated in scenario S3 (a fully diked An Giang Province) and scenario S4 (a fully diked LXQ). Furthermore, only a fraction of the reported differences in water levels between the no dike scenario (S1), and the 2011 scenario (S2) could be attributed to changes in dike infrastructure. Compared to the dike condition in 2011 (scenario S2), additional expansion of dikes is thus expected to have only small additional impact on river water levels. The greatest impact appears to have already occurred with the extent of dike construction in 2011.

Regarding the flood hydrographs and floodwater volumes examined, representing the flood conditions of 2000, 2011, and 2013, we found fairly limited effects of extensive dike construction on the water levels of the Hau River and canal network. Although total flood volumes differed markedly (402×10^9 m^3 in 2000, 283×10^9 m^3 in 2011 and 236×10^9 m^3 in 2013), impacts on peak levels in the Hau River were minimal in our simulation runs. The largest effects were found for the upstream reaches at Chau Doc, but these were a fraction of the impacts in scenarios S1 and S2. Both with further extension of high dikes (S2, S3 and S4) and use of the different flood hydrographs (2000, 2011, and 2013), we found little change in peak water levels downstream in the Hau River (i.e., at Can Tho). The impacts of doubling the area of agricultural fields protected by high dikes (S2, S3, and S4) and increasing Mekong River discharge volumes (2011 compared with 2000) were absorbed elsewhere in the lower Mekong Delta, according to our model simulations.

These results are consistent with those of other authors making use of 1D hydrodynamic models with quasi2D approaches. Previous studies report water level increases of +60 to +100 cm concentrated in the upper reaches in the LXQ (Hoa et al., 2007; Duong et al., 2014; Fujihara et al., 2015) and limited increases (4–5 cm) downstream (Duong et al., 2014). Nonetheless, these large increases in water levels and flow velocities in the upper delta point to a heightened risk of bank erosion and catastrophic dike failures there (Hoa et al., 2007).

Our model performed well in the calibration (S2, 2011) and validation (S2, 2013) runs, in which the state of high dikes in 2011 was compared with the recorded water levels from gauging stations for the hydrographs of 2011 and 2013. Consistent with previous work, this suggests that our model setup and calibration were able to reproduce recorded water levels. Our simulation runs did not return a neat fit with the recorded water levels in the Hau River in the 2000 flood hydrograph (Figure 2.8). Upstream, our scenarios returned lower than recorded values, and downstream at Can Tho our values were slightly higher. In part, this may be attributable to changes in the river and canal network between 2000 and 2011 (e.g., additional dredging and excavation). These may have altered the hydraulic properties of the Hau River in ways not captured in our scenarios.

The major known change in this period, that is, expansion of high dikes (from <10,000 ha in 2000 to >140,000 ha in 2011 in An Giang Province alone), was captured in our no dikes scenario (S1). The recorded rise in water levels at Can Tho (from 1.79 m in 2000 to 2.15 m in 2011/2013) over this period can also be partly attributed to the siltation of the Hau River (reported as Bassac estuary in Hoa et al., 2007). According to Hoa et al. (2007), progressive siltation would lead to an increased backwater effect, as the discharge capacity of the river would be gradually reduced with siltation, sea level rise and storm surges. This could potentially raise water levels at Can Tho up to 100 cm (Hoa et al. 2007).

At the outset of our study, we expected expansion of high dikes to produce greater discharges in the Hau River, resulting in a more pronounced backwater curve and higher water levels at Can Tho, such as those reported at the peak of the 2011 floods. However, this was not corroborated by our modelling results. Water levels at Can Tho were stable, the main changes in water levels being upstream. The relative stability of the water level at Can Tho can only be explained by a relative stability in discharge in the lower reaches of the Hau.

Our water balance analysis used the 2011 hydrograph for all of our scenarios to show how water is redistributed over the delta in the various model simulations. According to the scenario runs, the impacts of floodwater retention losses in the LXQ due to high dike construction are concentrated in the upstream and eastern reaches of the delta, with minimal impacts downstream in the Hau River and at Can Tho. The simulation runs further show increases in floodwater volumes and flood risk to be redirected toward the Tien River and Plain of Reeds, as well as the Cambodian floodplains. To be able to return fairly stable water levels downstream in the Hau River (at Can Tho and the estuary mouth), reductions in flood retention capacity of the LXQ (S2, S3, and S4) are compensated by reduced floodwater volumes entering the system and the LXQ floodplains (Δ Storage LXQ = -7 to -13×10^9 m^3; ΔQ entering the western delta = -15.8×10^9 m^3; and Δ Q entering the LXQ plain = -26×10^9 m^3). This enables the model to return a relatively constant water level and floodwater volume (195×10^9 m^3 $\pm$ 1%) downstream. Whereas this may be a function of the current model configuration, there are at present no means of verification, as water level and discharge data are currently unavailable for these areas.

Some limitations need to be considered in our study. We could not fully validate the suggested reduced flood inflows to the Long Xuyen Quadrangle, and subsequent diversion of floodwaters to the Plain of Reeds and Cambodian floodplains, due to lack of monitoring data for these areas. Our model results regarding the spatial redistribution of floodwater volumes could have been influenced by the way we calibrated the model as well as the model uncertainty. The hydrodynamic model approach applied could also have influenced the accuracy of flood simulation and water balance equations. On a small scale, two-dimensional and three-dimensional hydrodynamic models (2D and 3D) are most suitable for simulating the flood dynamics of a complex floodplain. However, 2D and 3D models are at present difficult to apply to large areas, such as the Mekong Delta, due to the detailed data and computational capacity required (Soumendra et al., 2010; Dung et al., 2011). The aims of our study dictated a focus on a large part of the delta, as we were interested in the impacts of upstream water control measures on downstream river water levels. Given the constraints in data and available model configurations, we combined the 1D model with a quasi2D approach. Our modelling results are in line with previous studies applying similar methods. Our water balance analysis suggests that it would be recommendable to invest in better and more comprehensive data availability, as well as additional computational capacity, to enable more in-depth study of floodwater movements on the delta through 2D and 3D modelling.

2.6. Conclusions

Development of extensive high dikes to enable triple rice cultivation in the upstream floodplains of the VMD has raised critical concerns about environmental impacts, especially changing water flows and downstream flood risk. We used a 1D-quasi2D modelling approach to assess the impacts of four dike development scenarios on floodwater volumes and distributions on the delta, focusing on changes in peak water levels and the delta-wide water balance. Our study's main findings were three.

- *First*, expanded high dike construction in the upper Mekong Delta from 2000 to 2011 has had large hydraulic impact, demonstrated by significant increases in floodwater levels of up to +68 cm in the upper delta. Whereas dike expansion has substantially affected flood levels and distribution in the upper delta, impacts have been remarkably small in the downstream regions.
- *Second*, continued high dike construction over the period from 2000 is likely to increase the flood risk across the entire LXQ, as peak water levels there are set to rise up to an additional +100 cm.
- *Third*, dike construction has produced radical changes in the floodwater balance and distributions. High dikes have reduced the volumes of floodwater reaching the LXQ, in amounts in excess of the retention volume lost due to dike construction.

All in all, our results indicate substantial impacts of large-scale dike construction on peak flood levels, flood retention capacity and the delta-wide water balance in the Mekong Delta. Flood risk in the Mekong Delta will likely increase as a direct consequence of high dike construction, especially in view of the cumulative impacts of other factors, such as sea level rise, land subsidence and more extreme rainfall due to climate change. Any plans for future expansion of high dikes should therefore be subject to careful deliberation and detailed impact assessment. From a hydraulic modelling perspective, dike impact assessment should be conducted on a delta-wide scale and pay special attention to opportunities for model calibration and validation for the Cambodian floodplains and Plain of Reeds.

CHAPTER 3

Stakeholders' assessment of dike-protected and flood-based alternatives from a sustainable livelihood perspective in An Giang Province, Mekong Delta, Vietnam[5]

Abstract

Construction of extensive high dike compartments has spurred land use intensification on the upper floodplains of the Vietnamese Mekong Delta. Increasingly intense rice-based farming within these compartments has changed the water dynamics of the delta, making it impossible to exploit the erstwhile benefits of floodwaters. Progressive contraction of the natural floodplains has led to reduced deposition of fertile sediments and environmental degradation, endangering the sustainability of farmers' livelihoods. The Mekong Delta Plan recommends discontinuance of high dike construction in the upper delta and restoration of the floodplains. However, this requires a radical shift in the agricultural economy, halting intensification of rice-based farming systems and developing alternative farming systems that can flourish on restored floodplains using "living with floods" livelihood strategies. This paper explores stakeholders' perceptions and appreciation of these contrasting farming and livelihood systems for the upper delta. It also examines the extent that alternatives to flood-based agricultural systems are viewed as feasible and attractive. We applied multi-criteria analysis (MCA) with analytic hierarchy process (AHP) to explore the views of double and triple rice farmers and experts on alternatives based on a set of economic, water management and environmental aspects. MCA results indicate a clear preference among both farmers and experts for flood-based farming systems with low dikes. Floodwater retention capacity, infrastructure for flood protection, environmental sustainability, and market stability were ranked as the most important factors contributing to livelihood sustainability on the delta.

Key words: Flood-based farming systems, dike, livelihoods, Mekong Delta, multi-criteria analysis

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3.1. Introduction

Nowadays, the world's deltas display different structural development states, or "socio-ecological systems". The Ganges and Indus deltas, for instance, are in the Anthropocene[6] state, and in danger of tipping into a collapsed state.[7] In contrast, the Rhine-Meuse delta, now also in the Anthropocene state, could potentially revert to a modified Holocene[8] state, as programmes such as the Dutch "Room for the River" are progressively implemented and expanded (Renaud et al., 2013; Van Herk et al., 2015; Van Staveren and Van Tatenhove, 2016). Indeed, the Netherlands, and many other countries, such as the UK, Germany and Bangladesh, are increasing their emphasis on ecosystem-based spatial planning and flood defences in response to environmental concerns and the rising cost of flood protection infrastructure, particularly in the face of climate change (Kundzewicz, 2002; Samuels et al., 2006; Temmerman et al., 2013; Van Wesenbeeck et al., 2014; Bubeck et al., 2015). The degrading effects of flood control measures on the environment are now also increasingly clear, alongside the lost economic opportunities associated with ecosystem services that natural floodwaters could provide (Wang et al., 2016) In Vietnam, the Mekong Delta is presently at a crossroad. It could enter a collapsed state, or return to a modified Holocene condition. The direction it takes will depend largely on whether intensification of rice production continues or if, instead, alternative flood-based farming systems are adopted.

Land use intensification has strongly affected water management on the Vietnamese Mekong Delta (VMD). During the past decades, Vietnam's food security policies have stimulated intensification of rice production. This has transformed the upper VMD from a seasonal floodplain into a highly intensified rice farming area with large-scale flood-control structures. Increased triple cropping of rice in combination with high dike protection has altered the flood dynamics of the delta (Table 3.1). High dikes, however, have increased peak river discharges, changed floodwater distribution, reduced flood retention capacity of floodplains and increased flood risk in surrounding and downstream areas (Hoa et al., 2007; Tri et al., 2012; Kingdom of the Netherlands and The Socialist Republic of Vietnam, 2013; Duong et al., 2014; Dung et al., 2018c). In addition, extensive high-dike constructions have reduced the floodplain's water storage capacity to such a level that it is inadequate to mitigate saltwater intrusion in downstream provinces during the dry season.

Triple-crop rice farming systems under high dike protection may be environmentally unsustainable in the region, endangering farmers' livelihoods in the long run (Kingdom of

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[6] Anthropocene: completely altered system through human intervention (Renaud et al., 2013)

[7] Collapsed: a delta that society has chosen to abandon or no longer protect (Renaud et al., 2013)

[8] Holocene: river delta in equilibrium with geography and dynamic processes dominant (Renaud et al., 2013)

the Netherlands and The Socialist Republic of Vietnam, 2013). High dikes interrupt interactions between rivers and floodplains. Wetland ecosystems need this interaction to exploit natural benefits, such as deposition of fertile sediment and provision of wild fish stocks (Danh and Mushtaq, 2011; Opperman et al., 2013; Hung et al., 2014a; Manh et al., 2014). The quality of soils, in particular, sulphate acid soils, may be degraded as a result of triple-crop rice farming, combined as it typically is with excess pesticide and fertiliser use (Howie, 2011). Triple-crop rice farming may even cease to be profitable due to the rising production costs resulting from soil degradation.

These have raised the discussion in Vietnam on how sustainable triple rice cultivation in the floodplains of the upper delta (Käkönen, 2008; Howie, 2011; Kingdom of the Netherlands and The Socialist Republic of Vietnam, 2013; Chapman et al., 2016; Chapman and Darby, 2016). In the Mekong Delta Plan, a clear recommendation has been made to stop conversion of floodplains to triple rice and restore the retention capacity of the floodplains in lights of climate change, environmental sustainability and economic viability. Recommendations are made to invest in flood-based livelihood systems that can provide economic livelihoods from flood-based activities as aquaculture, floating rice, lotus, and floating vegetables etc.

Most previous studies of farming systems and farmers' livelihood sustainability have focused on two aspects: (i) evaluation of the costs and benefits of farming practices associated with different water management strategies and (ii) exploration of stakeholders' views on the impacts of farming systems on livelihood sustainability. The first aspect is usually investigated using economic tools to calculate the costs and benefits of different farming systems in monetary terms. Many studies of this kind have been carried out in the case-study area (Dan, 2015; Kien, 2014; GIZ, 2014; Mike, 2013). Yet, by focusing only on the monetary profitability of farming systems, these have mostly overlooked social and environmental impacts. The second aspect has been addressed mainly with qualitative surveys or interviews with stakeholders. Substantially fewer studies of this kind are available for the case-study area (Howie, 2011; Trieu et al., 2010; Trung et al., 2013; Berg et al., 2017). Both kinds of studies have concluded that farming systems under low dike protection are more beneficial to farmers than those under high dike protection. No previous studies, however, have combined multiple economic, social and environmental evaluation considerations. Also, farmers' perspectives on their livelihood options under low dike and high dike protection have not been explicitly addressed. Incorporation of these elements is necessary to fully grasp the impacts of high dike construction, beyond the economic effects. In addition, inclusion of alternative farming systems could broaden our understanding of environmental and livelihood sustainability options.

Against the background of a delta at a developmental crossroad and considering our fragmented understanding of farmers' preferences, the current study explores stakeholders' views of alternative farming systems from a sustainable livelihoods perspective. We hypothesise that double and triple rice farmers prefer flood-based farming systems under low dike protection[9] instead of farming systems requiring high dikes. This is because low dike systems are associated with more sustainable livelihoods. We test this hypothesis in An Giang province, located in the Long Xuyen Quadrangle, which is one of the VMD's two main floodplains (Figure 3.1).

We used a two-step approach to examine stakeholders' views on the livelihood sustainability effects of alternative farming systems. In step one, we conducted an interview survey with farmers to identify farming systems and obtain a better understanding of the challenges farmers faced. In step two, we conducted focus group sessions with experts and with farmers to explore their ideas on alternative farming systems in relation to a set of economic, water management and environmental considerations using multi-criteria analysis (MCA).

[9] Flood-based farming systems involve cultivation of, for example, lotus and floating rice, under the protection of low dikes that allow floodwaters to enter fields in the flood season.

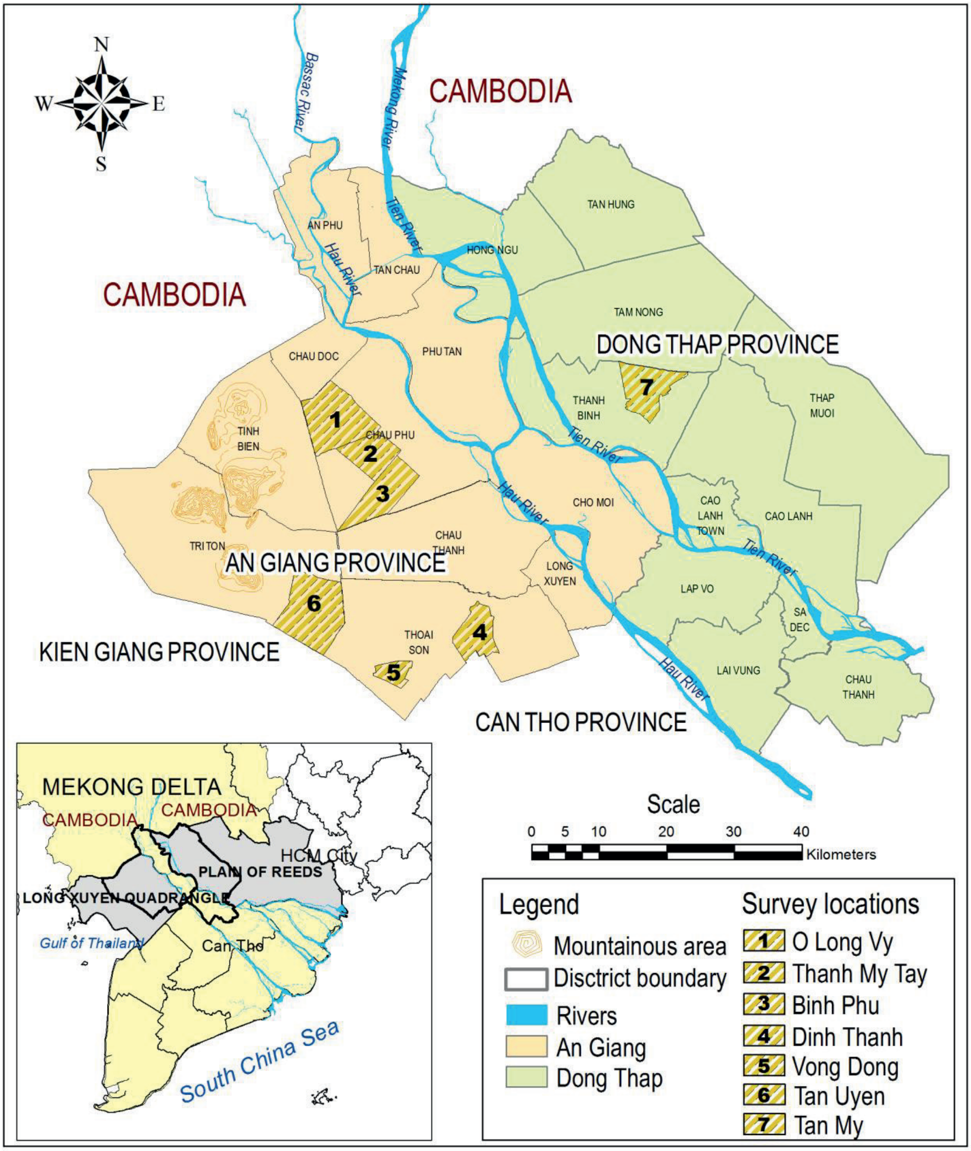

Figure 3.1 An Giang province and survey locations

3.2. Research context

3.2.1. Flood-based farming systems

Every floodplain has distinct characteristics that govern the regularity of its flooding patterns and to which particular flood-based farming systems have been adapted (Abraham et al., 2013; Spate Irrigation Network Foundation, 2013). In their natural state, the VMD floodplains are usually under water from July to December, and farmers cultivate lands protected by either high dikes or low dikes. High dikes in effect create dike-encircled polders on which farmers can produce three rice crops each year with full flood protection. Thus, high dikes increase crop production potential for farmers, but if they fail the risks and costs are very substantial. Low dikes,[10] in contrast, allow floodwaters to enter fields during peak flooding, while providing sufficient protection for two rice crops each year. In the low dike system, the eco-hydrological dynamics are environmentally favourable, as floodwaters flow in and out of farming systems, depositing fertile sediments, creating lush fish habitats and flushing the land of agrochemicals and sulphate-acid deposits (Howie, 2011; Kingdom of the Netherlands and The Socialist Republic of Vietnam, 2013; Trung et al., 2013). Flood-based farming systems are adapted to the floodwater regime, optimising productivity in relation to the rise and recession of floods, contributing to agroecological sustainability (Nguyen and James, 2013).

The seasonal flooding of the Mekong River may offer opportunities for a variety of flood-based production systems within the VMD, including freshwater aquaculture, floating rice and other floating "crops", such as river bean (*sesbania sesban*; called *dien dien* locally), water mimosa (*Neptunia oleracea*, called *nhut*), lotus (*Nelumbo nucifera*, called *sen*) and water lily (*Nymphaea*, called *sung*). Floodplains with more active hydro-ecological dynamics may thus offer opportunities for diversification of farming.

3.2.2. Maximising sustainable livelihoods

The terms "livelihoods" and "sustainable livelihoods" have been used increasingly in the scientific literature since 1990 (Ian, 2015; Morse and McNamara, 2013a). Numerous studies have applied the idea of "livelihood sustainability" in various sectors, such as agriculture, aquaculture, geography, urban development, forestry and fisheries (see, e.g., Ian, 2015; Meyer-Aurich, 2005; Murshed-E-Jahan and Pemsl, 2011; Rasul and Thapa, 2004; Wang et al., 2016). The term "sustainability" is understood as "the intersection of a series of three overlapping circles that symbolise the environment, the economic system and society" (Morse and McNamara, 2013b). A much-cited definition of sustainable livelihoods is that of Chambers and Conway (1992, p. 7):

> "*A livelihood comprises the capabilities, assets and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base.*"

[10] Low dikes are known as "August dikes" in Vietnam and comprise farmer-built low dikes of about 1 m height. These protect the fields against the onset of floods, permitting the harvesting of a second rice crop before mid-August. After harvesting, and as flood levels rise, fields become flooded to a peak depth of some 3-4 m.

The current study explores the maximisation of sustainable livelihoods at the farm system level. This refers to a situation wherein the income of a farmer is optimised using sustainable farming practices. Farming practices are sustainable when they balance economic, ecological and social aspects. They can thus be implemented for many years and continue to generate a good income without ill effects on the natural environment.

3.2.3. Study area

An Giang province was selected as the case-study area for three main reasons: (1) its geographical position in the upper floodplains of the VMD, (2) its distinction as the province with the greatest amount of land converted to triple-crop rice farming under high dike protection and (3) its position as one of the highest rice producing provinces of the delta.

An Giang covers most of the Long Xuyen Quadrangle, which forms the western floodplain of the VMD. During flood events, the province in its natural state is inundated to a depth of 1.5 m to 4 m, rendering the entire area a large pond that retains floodwater for a number of months (Kingdom of the Netherlands and The Socialist Republic of Vietnam, 2013). The floodplain holds some 16.109 m3 of water in its natural state (Dung et al., 2018c). Together with the more easterly Plain of Reads, it is a principal water retention and flood regulation reservoir for the VMD, which is connected to the Cambodian floodplain.

Thanks to sediment transport by floodwaters, there is a dominance of alluvial soils in the region. This makes the province an ideal location for growing high-yielding rice varieties (Kien, 2014). Rice production has been greatly intensified since the late 1980s, spurred by government food security objectives and the doi moi economic policy reforms. Strong growth in double-crop rice under low dike protection was followed by increased triple-crop rice under high dike protection. The expanse of lands protected by high dikes in An Giang province grew rapidly starting in 1998 (Table 3.1). Data from the Department of Agriculture and Rural Development (DARD) indicates that by 2014 almost all agricultural lands in the province were protected by high dikes (Figure 3.2).

Nowadays, about 91% of the agricultural area in the province is used for paddy rice production, with the remaining 9% under vegetables, fruit trees and aquaculture (AGGSO, 2014). An Giang was the second highest producer of rice among all VMD provinces from 2000 to 2015, with production of 3.2 million tons/year compared to 3.3 million tons/year in Kien Giang province and 2.7 million tons/year in Dong Thap province (GSOVN, 2015).

Table 3.1 High dike triple-crop rice production areas in An Giang province

Year	High dike area (ha)	Source
1998	2,591	Kien (2013)
2009	87,909	Kien (2013)
2011	122, 222	SIWRR (2012)
2015	150,000	MARD (2015)
Planned to 2020	163,000	MARD (2015)

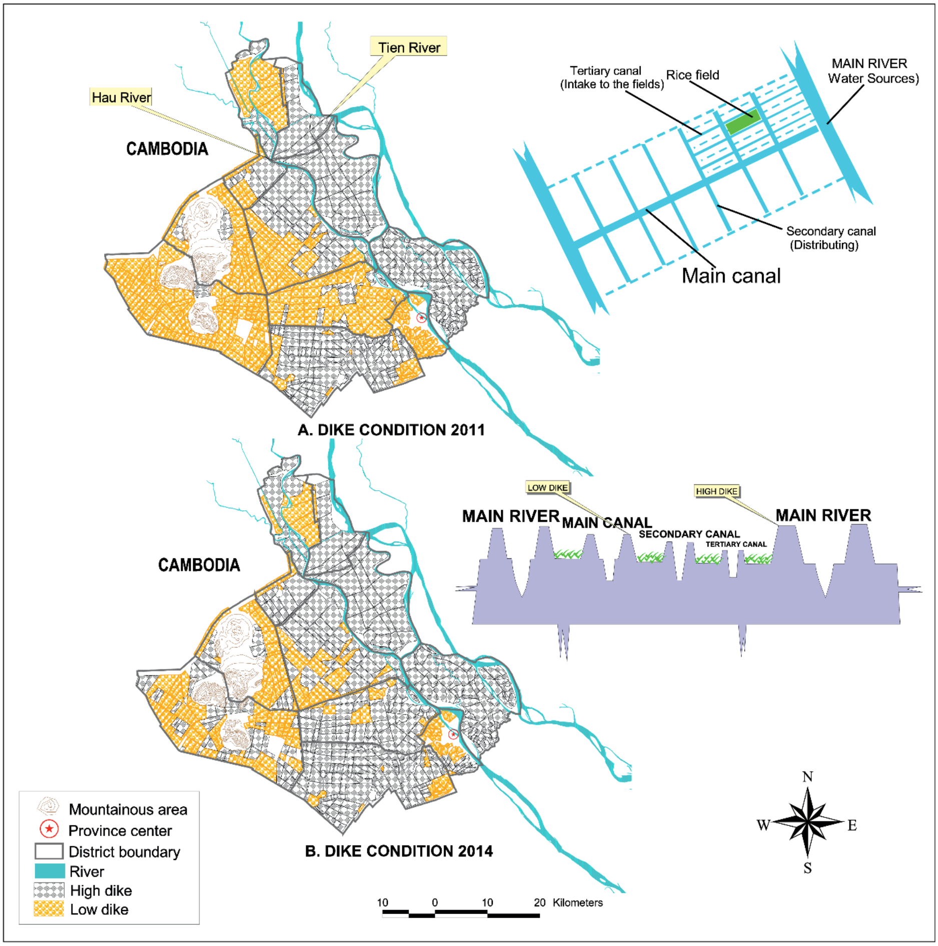

Figure 3.2 Low dikes and high dikes in 2011 and 2014
Source: Data from the Department of Agriculture and Rural Development (DARD) of An Giang province, map by the authors.

3.3. Methodology

3.3.1. Interview survey and literature review

We conducted an interview survey of 60 farmers in An Giang and Dong Thap provinces to identify alternative farming systems and capture the challenges farmers faced in their present farming systems and livelihoods, under either low dike or high dike flood protection. Most surveys (45) were carried out in six communes in An Giang: Dinh Thanh and Vong Dong communes in Thoai Son district, O Long Vy commune in Chau Phu district, Thanh My Tay and Binh Phu communes in Chau Phu district and Tan Uyen in Tri Ton district. The remainder (15) were done in Dong Thap (Tan My commune in Thanh Binh district) (see Figure 3.1). Surveying in two provinces enabled us to capture different experiences and perspectives of farmers regarding high dike protected rice production systems, which were predominant in An Giang, and low dike systems, which were still predominant in Dong Thap.

Surveyed farmers were selected through random sampling, followed by snowball sampling to capture the broadest variety of farming systems in rice, vegetables and aquaculture. The number of farmers interviewed was not fixed in advance for each region. Instead, following Kumar, (2014), we terminated surveying once information saturation was reached, that is, when additional surveys yielded no additional information on farming or livelihood systems.

We combined the survey results with a literature review to identify the range of farming systems present and to define valuation criteria for low dike and high dike farming systems, for later use in the MCA. Finally, we interviewed five experts and four local officials, to deepen our understanding of the difficulties involved in flood-based farming and to gain experts' opinions on dike protection strategies.

Two sets of structured questionnaires were developed: one for use with farmers in low dike areas and the other for use with farmers in high dike areas. Both explored farm characteristics, advantages and disadvantages of dike protection and alternative farming systems for sustainable livelihoods. Whereas the low dike questionnaire focused more on the advantages and constraints of flood-based agriculture in the flood season, the high dike questionnaire had greater emphasis on advantages and disadvantages of the high dikes with respect to livelihoods and environmental aspects. Each interview was recorded and notes were taken to enable verification of the information provided.

3.3.2. Multi-criteria analysis (MCA)

MCA is a method of engaging stakeholders in an evaluation of alternatives based on set criteria and sub-criteria (Mendoza et al., 1999; Department for Communities and Local

Government, 2009). MCA has often been used in agricultural and environmental studies (Carof et al., 2013; Cisneros et al., 2011; Fontana et al., 2013; Huang et al., 2011; Reidsma et al., 2011; Teshome et al., 2014; Tiwari et al., 1999).

Our study implemented an MCA employing criteria related to economic, social and environmental sustainability. The aim was to evaluate the livelihood, flood management and environmental effects of alternative farming systems (further details in section 3.3). These aspects have been used in numerous previous studies to evaluate agricultural sustainability (Kundzewicz, 2002; Reidsma et al., 2011; Kremen et al., 2012; Mark and Patrick, 2013; Teshome et al., 2014). Our MCA involved a complex evaluation of ten alternative farming systems assessed based on three criteria and 14 sub-criteria (Figure 3.3). We organised three MCA workshops, one with experts and two with farmers, to evaluate the farming systems based on the criteria defined. To organise the rankings and assess the consistency and coherence of participants' scores and responses, we used analytic hierarchy process (AHP) (Saaty, 2008).

Though the location of our research is the upper part of the delta, our analysis incorporates potential impacts of land use changes on the delta as a whole. We did this by including various internalities and externalities of floodwater management. Internalities are benefits at the local level, such as soil fertility, water quality, goods and profits. Externalities are benefits and costs on the deltaic scale, such as flood protection and salinity intrusion downstream. This means we explore the effects of alternatives not only at the local level, but also for the delta as a whole.

AHP

AHP is a means of ranking options using pair-wise comparisons and weighted attributes. It is among the widest applied MCA tools (Huang et al., 2011). Many studies have used the method, introduced by Saaty (1980), to evaluate alternatives in agriculture and other fields (Alphonce, 1997; Chavez et al., 2012; Karami, 2006; Reed et al., 2014). All criteria (the first hierarchy) and sub-criteria (the second hierarchy) are compared in pairs using a 1 to 9 numerical scale. Then weightings are applied to produce alternative comparisons (Saaty, 1980). An advantage of AHP is that the pair-wise comparison of alternatives structured hierarchically facilitates stakeholders' assessments and consideration of defined goals, criteria and sub-criteria.

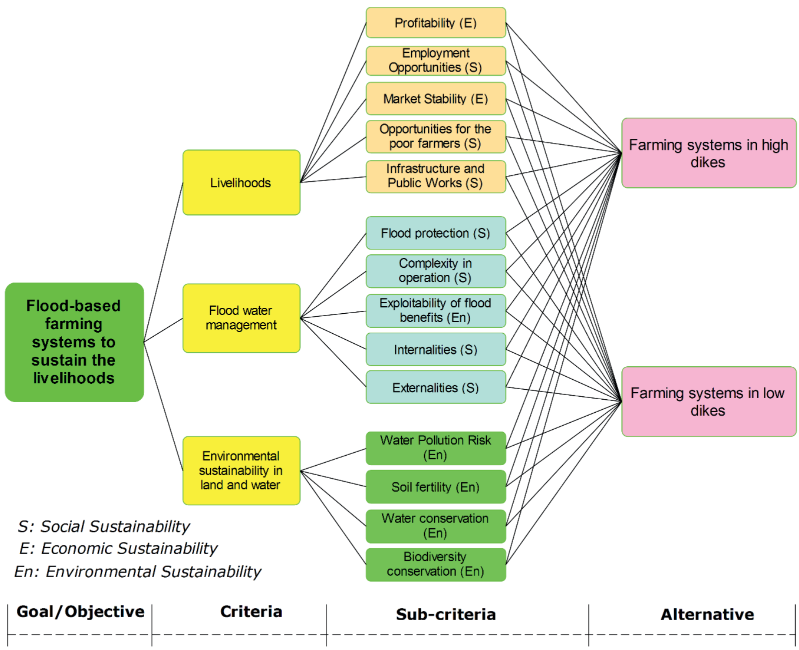

Figure 3.3 Structure of multi-criteria analysis (MCA)

Workshops with experts and farmers

We first conducted the MCA at an international workshop on participatory decision support tools for strategic delta planning and management. Nine Vietnamese experts took part. Each was knowledgeable about farming systems and farmers' livelihoods in the VMD. The workshop began with a presentation of our study objective, methodology, the farming systems included and a "how-to" scoring guide for the MCA. We then handed out the MCA questionnaires, so that each expert could individually score the alternative farming systems based on the given criteria and sub-criteria.

In addition to the workshop, we organised two farmer focus group sessions: one in Thanh My Tay commune (high-dike area) and one in Binh Phu commune (low-dike area). Both communes are located in the Chau Phu district of An Giang. This was a district in which we had previously done farmer interviews. The district, moreover, had both types of dikes and a range of different farming systems. Each focus group session involved ten invited farmers, who were divided into two groups, thus forming four groups of five farmers each. Though the farmers conducted the MCA in these groups, they used individual scoring cards. They could thus individually rate the criteria and alternatives while simultaneously discussing their views and implications as a group. Each farmer was, furthermore, given a different coloured set of sticky notes on which to write their scores and the alternatives they preferred. The different colours enabled facilitators to ensure that the outcomes were not dominated by any one group member.

Experienced from the workshop with the experts, in the farmer sessions we checked the consistency of the pair-wise comparisons as the MCA progressed using Excel sheets with AHP software provided by Dr Klaus D. Goepel from the website http://bpmsg.com/.

3.3.3. Criteria and sub-criteria

Livelihoods, floodwater management and environmental sustainability were the three main criteria used for evaluating the alternative farming systems (both farming systems in low dike areas and farming systems in high dike areas). For each criterion, four to five sub-criteria were identified (14 in all). These described social, economic and environmental aspects. Sub-criteria were derived from the literature and the farmer interviews and selected for their pertinence to the socio-economic development and agricultural context of the VMD. We developed indicators and descriptions for each sub-criterion to clarify them to both the experts and the farmers during their respective MCA sessions. Table 3.2 presents details on the sub-criteria used. See Figure 3.3 for the MCA structure.

Table 3.2 Sub-criteria used in the MCA

1. Livelihoods	2. Floodwater management	3. Environmental sustainability
1.1 Profitability: Net income from agricultural production, being the total gain from crops and fish per year. *Value=Production Benefit* (total product sales)–*Production Cost* (pumping, seeds, pesticides, fertiliser, labour, etc.).	*2.1 Flood protection:* Local flood protection for farming systems in An Giang is provided mainly by low dikes, high dikes and sluice gates.	*3.1 Water pollution:* Acid sulphate soils are dominant in the delta (Cosslett and Cosslett, 2014). Increase in pesticides and fertilisers in combination with sulfidation and acidification of sulphate acid soils increase water pollution.
1.2 Employment opportunities: Direct (on-farm) and indirect (off-farm, e.g., processing) employment provided throughout the year or season (as opposed to no employment opportunities in the flood season).	*2.2 Complexity of operation*: Water flows in and out of farming systems via structures such as canals, sluice gates and pumps or gravity pipes.	*3.2 Soil fertility:* Soil fertility is strongly reduced by higher intensity cultivation on farms, requiring increased fertiliser application.
1.3 Market stability: Livelihoods of farmers are better if there are stable markets and prices for the products of their farming system.	*2.3 Exploitability of flood benefits:* Floodwaters play an important role in An Giang because they bring common pool resources, such as fertile sediment and wild fish stocks (Howie, 2011). This sub-criterion expresses the extent that such benefits can be exploited.	*3.3 Water storage capacity:* This is the ability of the system to retain floodwaters from the wet season for use in the dry season (locally and system-wide).
1.4 Opportunities for poor farmers: In rural areas, farmers' livelihoods are better if living conditions for the poor improve over the years (e.g., through livelihood opportunities for the landless and smallholders).	*2.4 Internalities:* This sub-criterion signifies the potential costs (impacts) of the floodwater management regime for local farming systems. For example, high dikes increase peak discharges in local rivers due to their protection for third rice crop protection reducing space for floodwater stored in the flood season. The large-scale constructions of high-dike reduce flood retention capacity and cause costly damages if they fail. Low dikes allow floodwaters entering to fields, require maintenance after floods, but there are less damages.	*3.4 Biodiversity conservation:* Biodiversity in An Giang includes wild fish stocks and bird and plant species. Biodiversity is defined as "the different plants, animals and micro-organisms, their genes, and the terrestrial, marine and freshwater ecosystems of which they are a part"(DERM, 2010, p. 3).
1.5 Infrastructure and public works: Farmers' wellbeing is improved by availability of better houses, hospitals, schools and transportation infrastructure.	*2.5 Externalities:* This sub-criterion signifies the potential costs (impacts) of the floodwater management regime on the regional and deltaic scale. For example, the large-scale constructions of high-dike for triple-rice production will not allow floodwaters stored in the fields which may raise the flood risk downstream.	

3.4. Results

3.4.1. Interviews with farmers

In An Giang, 40 of the 45 farmers interviewed preferred high dikes to low dikes (Dung and Jacob, 2017). The preference was made because (i) high dikes improved residential safety and public welfare and (ii) they enabled cultivation of a third rice crop, for which a stable market was readily available. Farmers indicated that the high dikes protected their lives, belongings and farms against flooding and created a safe place for them to earn a living. In addition, the high dikes facilitated transportation, improving farmers' access to markets and protecting their lands from flood damages. Cultivation of a third rice crop during the flood season was said to increase farmers' incomes. Nonetheless, farmers living under the protection of the high dikes expressed concern about environmental problems caused by the triple cropping of rice. All of the farmers in high dike farming systems acknowledged disadvantages of the high dikes, such as increased fertiliser and pesticide use; nonetheless, seven of them observed that rice was a traditional, easy-to-sell crop. Also, the third rice crop, which could be produced thanks to the high dikes, was credited with eliminating social problems, such as drinking wine and playing cards, which were typical during the many hours of spare time people otherwise had in the flood season. Regarding the five farmers who disapproved of the high dikes, it was responded that additional profit from triple-rice practice is lower than the production costs.

Interviews indicated that farmers with larger lands liked the high dikes even more than farmers with smaller lands, because profits from rice cultivation were proportional to the cultivated area. Three farmers noted the decrease of wild fish stocks and fertile sediments due to the hydropower developments upstream along the Mekong River. All 33 interviewed farmers from high dike areas agreed that the high dikes had reduced fertile sediment deposition in their rice fields. Five suggested that the decrease in wild fish and sediment was due to the minor flooding of recent years, following the large 2011 flood.

In Dong Thap province, where fewer high dikes had been constructed, seven of the 15 farmers interviewed did not prefer the high dikes (Dung and Jacob, 2017). These farmers, thus, had a distinctly different view from those in An Giang. They gave several reasons for their opinion: (i) they were unwilling to invest the three-year financial contribution required by government for dike construction; (ii) they had heard from neighbours in high dike areas that the profitability of triple-crop rice farming was outweighed by negative environmental impacts and increased investment costs; and (iii) farmers saw the low dikes as safeguarding natural benefits of floods and considered the current double cultivation system within low dikes to be good for the soil.

We found that pressure to convert to triple cropping of rice was still active in the region. Two farmers noted that local government had held several meetings to encourage farmers to switch from the low dike farming system to the high dike system.

Various constraints were noted for flood-based (low dike) farming: (i) it was difficult to plant the flooded lands if there were strong winds, waves or heavy rain; (ii) most farmers were unfamiliar with improved planting techniques; (iii) crop failures due to golden apple snails (*Pomacea canaliculata*) and water pollution were commonplace; (iv) fishing was dangerous, particularly as boats on open waters were exposed to strong winds and waves in the flood season; (v) markets for commodities other than rice were less readily available and less stable than the rice market; and (vi) wild fish stocks had fallen sharply compared to previous years.

Both the interview survey and the literature pointed to numerous farming systems that had been applied in the region. We had to narrow these to a feasible selection, to keep our analysis from becoming overly complex. We selected ten farming system alternatives which we judged as maximising livelihood sustainability. That is, they appeared to provide the best income potential with the least environmental degradation (Table 3.3). Half of these (5) were for low dike areas, and half (5) were for high dike areas. These alternatives were used in the MCA process.

3.4.2. Multi-criteria analysis

Our groups assigned each criteria and sub-criteria weights from 0 to 1. Zero (0) signifies the least importance while (1) represents the highest importance. Thus, if three criteria (factors) were deemed equally important, all three would have weights of 0.33.

Experts' and farmers' weightings of the three main criteria differed markedly (Table 3.4). Vietnamese experts considered livelihoods to be the most important criterion (0.46), whereas farmers considered environmental sustainability in land and water to be most important (assigning them weightings ranging from 0.50 to 0.57). Experts and farmers were in alignment, however, on flood protection as the least important criterion. Thus, while the experts seemed to be primarily concerned about the livelihoods of farmers in relation to farming systems, farmers surprisingly appeared to attach higher importance to sustainability of the soil and water environment than to their livelihoods or floodwater management.

Experts and farmers also differed in their valuations of the sub-criteria. Under the livelihood criterion, experts scored profitability (0.24) and infrastructure and public works (0.24) as the most important. Farmers, however, scored market stability (0.40) as the most important factor. Under floodwater management, both experts and farmers emphasised the ability to exploit the benefits of floodwaters (0.33 and 0.36, respectively), but farmers also valued flood protection (0.32). Complexity of operation and externalities were ranked as the least important factors by both experts and farmers. Under environmental sustainability in land and water, experts considered water storage capacity (0.30) and water pollution risk (0.29) as the two foremost factors. Farmers ranked water pollution risk (0.30), water storage capacity (0.22) and soil fertility (0.21) as most important.

The MCA results show that both experts and farmers preferred the flood-based farming systems in low dike areas over all farming systems in the high dike areas (Table 3.5). Exploiting the benefits of floodwaters for farming was considered the best means of maximising sustainable livelihoods. Among the farming systems under low dike protection, the double vegetable (*LD2*) and double mixed crop (*LD3*) were deemed the best options, which involved dry season cultivation combined with floating crops in the flood season. Although farming systems in the high dike areas were not preferred, three farming systems were suggested as the most promising alternatives if the high dikes could not be eliminated. These were *HD2* (double rice + vegetables), *HD3* (triple mixed crops) and *HD4* (mixed crops + poultry or cattle). The triple-crop rice farming system (*HD6*) came in the lowest position among both farmers and experts, even though this system offers the ability to produce three rice crops in a single cultivation year.

Table 3.3 Alternative farming systems for low dike and high dike areas

Farming system	Description	Farm condition	Profit/ Livelihood aspects	Flood water management aspects	Ecology/environmental aspects
1. *LD1* (double rice + floating crops) See Kien (2014)	Two rice crops cultivated in winter-spring[1] and summer-autumn[2]. In the flood season[3], farmers cultivate floating crops such as floating rice, lotus and water lily. Farmers may catch wild fish by various means.	Low dike: Low-lying areas planted to rice; floating crops cultivated in canals, rivers or ponds. With high or medium flooding, famers plant floating crops on flooded fields in protected areas away from strong waves and wind.	Low profit but stable market.	Low dikes offer low protection but preserve benefits of floodwater.	Rice cultivation impacts soil and water quality, particularly due to the use of agrochemicals, but floodwaters flush away build-up to some extent.
2. *LD2* (double mixed crop + floating crops) See Phong et al. (2010), Tsuruta et al. (2011) and Berg et al. (2017)	Two mixed crops cultivated in winter-spring and summer-autumn (largest area planted to rice, combined with vegetables, a fish/shrimp pond or fishing). In the flood season, farmers cultivate floating crops, such as floating rice, lotus and water lily. Farmers may catch wild fish by various means.	Low dike: Low-lying areas planted to rice; higher elevated areas under vegetables; floating crops planted in canals, rivers or ponds. With high and medium flooding, famers plant floating crops on flooded fields in protected areas away from strong waves and wind.	Average profit but unstable market. Because this farming system is diversified, it is considered more sustainable than a rice mono-crop.	Low dikes offer low protection but preserve benefits of floodwater.	Rice cultivation and farming of other crops impacts soil and water quality, particularly due to the use of agrochemicals, but floodwaters flush away build-up to some extent.
3. *LD3* (double vegetable + floating crops) Fieldwork interviews and observations	Two vegetable crops cultivated in winter-spring and summer-autumn. In the flood season, farmers cultivate floating crops, such as floating rice, lotus and water lily. Farmers may catch wild fish by various means.	Low dike: High-elevation areas planted to vegetables; floating crops cultivated in canals, rivers or ponds. With high and medium flooding, famers plant floating crops on flooded fields in protected areas away from strong waves and wind.	High profit but unstable market. Because this farming system is diversified, it is considered more sustainable than a rice mono-crop.	Low dikes offer low protection but preserve benefits of floodwater.	Vegetable cultivation impacts soil and water quality, particularly due to the use of agrochemicals, but floodwaters flush away build-up to some extent.
4. *LD4* (double vegetable + flooded fields) Fieldwork interviews and observations	Two vegetable crops cultivated in winter-spring and summer-autumn. In the flood season, farmers do nothing.	Low dike: High-elevation areas planted to vegetables.	High profit but unstable market.	Low dikes offer low protection but preserve benefits of floodwater.	Vegetable cultivation impacts soil and water quality, particularly due to the use of agrochemicals, but floodwaters flush away build-up to some extent.

5. *LD5* (eel feeding + straw mushroom) Fieldwork interviews and observations	Eel feeding and mushroom planting on dry areas such as in house yards year-round without the impact of floods	Low dike or high dike: dry and high-elevation lands such as house yards where floodwaters could not reach.	High profit but unstable market. This farming system is suitable for poor or landless farmers.	Low dikes offer low protection but preserve benefits of floodwater.	Good environment due to benefits of floodwaters. However, dedicated water quality treatment needed for eel feeding.
6. *HD1* (8 rice crops in 3 years) Fieldwork interviews and observations; see also Chapman and Darby (2016)	Eight rice crops planted over 3 consecutive years (3-3-2). In the third year, farmers flush rice fields by allowing floodwaters to enter, either by pumping it in or by overbank flow in the flood season.	High dike: Fields protected by high dikes planted to rice in consecutive seasons.	Low profit but stable market.	High dikes offer high protection but with the potential of costly damages in case of a dike breach. Farmers are unable to exploit the benefits of floodwater.	Intensive rice production strongly impacts soil and water quality, particularly due to the use of agrochemicals. Triple-rice farmers are encouraged to flood their rice field once after 3 consecutive years ~9 crops used for rice production. This means that the field is flooded in the 9th crop, in the third years. But this system is not effective in soil improvement. (Chapman and Darby, 2016).
7. *HD2* (double rice + vegetables)	Rice cultivated on the whole field in the first two crops and vegetables cultivated on the whole field in the third season.	High dike: Low-lying areas planted to rice, but with high-elevation areas under vegetables	Average profit but unstable market.	High dikes offer high protection but with the potential of costly damages in case of a dike breach. Farmers are unable to exploit the benefits of floodwater.	Without floodwater, land and water quality is strongly impacted by farming activities.
8. *HD3* (triple mixed crops) See Roel et al. (2006)	Crops mixed during three planting seasons: rice or rice mixed with fish/shrimp cultivation on the main field, and a fish pond and vegetable cultivation on a smaller land area.	High dike: Low-lying areas planted to rice with high-elevation areas under vegetables	High profit but unstable market. Because this farming system is diversified, it is considered more sustainable than a rice mono-crop.	High dikes offer high protection but with the potential of costly damages in case of a dike breach. Farmers are unable to exploit the benefits of floodwater.	Without floodwater, land and water quality is strongly impacted by farming activities.
9. *HD4* (mixed crops + poultry or cattle) See Roel et al. (2006)	Other crops mixed with rice and paired with poultry or cattle raising on an average or large scale with fish or shrimp cultivated flexibly in pond year-round.	High dike: Low-lying areas planted to rice with high-elevation areas under vegetables	High profit but unstable market. Because this farming system is diversified, it is considered more sustainable than a rice mono-crop.	High dikes offer high protection but with the potential of costly damages in case of a dike breach. Farmers are unable to exploit the benefits of floodwater.	Without floodwater, land and water quality is strongly impacted by farming activities.
10. *HD5* (fruit trees) Field observations	Fruit trees planted year-round.	High dike protection areas where trees can be grown year-round	High profit but unstable market.	High dikes offer high protection but with the potential of costly damages in case of a dike breach. Farmers are unable to exploit the benefits of floodwater.	Without floodwater, land and water quality is strongly impacted by farming activities.

[1] *The season is from January/February to April/May.* [2] *The season is from April/May to August/September.* [3] *The season is from August/September to January.*

Table 3.4 Performance evaluation matrix of experts and farmers for criteria and sub-criteria

Criteria and sub-criteria	Vietnamese experts		Farmers									
			Focus group 1		Focus group 2		Focus group 3		Focus group 4		All farmers	
	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
1. LIVELIHOODS	**0.46**		**0.33**		**0.24**		**0.25**		**0.30**		**0.28**	
1.1 Profitability	0.24	**1**	0.11	4	0.17	4	0.12	3	0.28	2	0.16	3
1.2 Employment opportunities	0.12	5	0.03	5	0.19	3	0.08	5	0.13	5	0.09	5
1.3 Market stability	0.23	3	0.46	**1**	0.38	**1**	0.48	**1**	0.31	**1**	0.40	**1**
1.4 Infrastructure and public works	0.24	2	0.22	2	0.22	2	0.21	2	0.14	3	0.19	2
1.5 Opportunities for poor farmers	0.17	4	0.18	3	0.05	5	0.11	4	0.14	3	0.11	4
2. FLOODWATER MANAGEMENT	**0.23**		**0.10**		**0.21**		**0.25**		**0.16**		**0.17**	
2.1 Flood protection	0.13	5	0.35	**1**	0.37	**1**	0.31	2	0.27	2	0.32	2
2.2 Complexity in operation	0.15	4	0.07	5	0.06	5	0.05	5	0.10	4	0.07	5
2.3 Exploitability of flood benefits	0.33	**1**	0.34	2	0.35	2	0.39	**1**	0.36	**1**	0.36	**1**
2.4 Internalities	0.24	2	0.16	3	0.13	3	0.17	3	0.17	3	0.16	3
2.5 Externalities	0.16	3	0.08	4	0.09	4	0.08	4	0.10	4	0.09	4
3. ENVIRONMENTAL SUSTAINABILITY IN LAND AND WATER	**0.31**		**0.57**		**0.55**		**0.50**		**0.54**		**0.54**	
3.1 Water pollution risk	0.29	2	0.35	2	0.16	3	0.42	**1**	0.36	**1**	0.30	**1**
3.2 Soil quality/fertility	0.18	4	0.37	**1**	0.33	2	0.09	4	0.19	3	0.21	3
3.3 Water storage capacity	0.30	**1**	0.17	3	0.36	**1**	0.12	3	0.33	2	0.22	2
3.4 Biodiversity conservation	0.24	3	0.11	4	0.15	4	0.37	2	0.12	4	0.17	4

Table 3.5 Performance evaluation matrix of experts and farmers for alternative farming systems based on criteria and sub-criteria assessment

No	Farming system	Experts		Farmers									
		Expert		Focus group 1		Focus group 2		Focus group 3		Focus group 4		All farmers	
		Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
1	*LD1* (double rice + floating crops)	0.953	3	0.810	3	0.662	6	0.903	3	0.778	5	0.746	5
2	*LD2* (double mixed crop + floating crops)	0.988	2	1.000	1	0.739	5	1.000	1	0.946	2	0.878	2
3	*LD3* (double vegetable + floating crops)	1.000	1	0.883	2	0.814	3	0.917	2	1.000	1	1.000	1
4	*LD4* (double vegetable + flooded fields)	0.922	5	0.684	7	0.832	2	0.885	4	0.880	3	0.802	3
5	*LD5* (eel feeding + straw mushroom)	0.947	4	0.688	6	1.000	1	0.542	7	0.786	4	0.784	4
6	*HD1* (8 rice crops in 3 years)	0.446	10	0.445	10	0.603	7	0.352	10	0.529	10	0.388	10
7	*HD2* (double rice + vegetable)	0.496	9	0.658	8	0.762	4	0.444	9	0.701	6	0.584	6
8	*HD3* (triple mixed crops)	0.718	7	0.717	5	0.595	8	0.583	5	0.570	8	0.584	6
9	*HD4* (mixed crops + poultry or cattle)	0.810	6	0.790	4	0.518	9	0.555	6	0.561	9	0.546	8
10	*HD5* (fruit trees)	0.674	8	0.596	9	0.472	10	0.457	8	0.605	7	0.438	9

3.5. Discussion

Triple-crop rice farming systems implemented under the protection of high dikes have spread throughout the floodplains of the VMD during the past two decades. This has greatly reduced the floodplains' water retention capacity, changed local floodwater dynamics and undermined potential benefits of floodwaters for the agroecology of the delta. The effects of climate change and hydropower developments upstream have exacerbated the negative impacts of intensified rice farming, particularly with regard to water management regimes and sedimentation loads (Lu and Siew, 2006; Västilä et al., 2010; Fredrik, 2011; Hoang et al., 2016). Intensive rice production, stimulated by national food security policies and reliable and readily available rice markets, has resulted in environmental degradation, especially in the high dike compartments. Across the delta, livelihoods are becoming less sustainable because the high dike farming systems require increased fertiliser and pesticide applications to maintain rice production levels. All of the stakeholders in the current research recognised the need to explore alternatives.

We started with an interview survey, which found a preference among (double triple rice) farmers for high dikes over low dikes, due to the protection that high dikes offered for residential zones and the stability of the national market for rice. Indeed, while high dikes and similar water-related infrastructure are costly, they are often needed to protect human settlements and property against flood damages. Moreover, high dikes have enabled farmers to cultivate three rice crops per year and thus increase their incomes. The market for rice is stable because the Vietnamese government has invested great effort over the past 40 years in developing the rice market and the rice processing industry (Huu Nguyen et al., 2016). Markets for other crops are far less mature as yet. In addition, rice grains are relatively easily preserved, even for long periods of time after harvest, so farmers have less need to worry about market risks (Berg et al., 2017).

Our MCA results contradicted the findings of our interview survey. According to the MCA, flood-based farming systems under low dike protection were most preferred and acknowledged as the best means of maximising livelihood sustainability. Experts weighted the livelihood criterion as most important, as they supposed farm profitability, infrastructure for flood protection and market stability would be most important to farmers. Farmers, however, indicated that their greatest concern was environmental sustainability (more than 50% of weights), underlining the importance of floodwaters for environmental preservation and worries about the negative impacts of soil degradation caused by triple-crop rice farming. Floodwater retention capacity and exploitability of floodwaters' benefits were deemed important by both farmers and experts, recognising the advantages of flooding for the environment and for farmers' livelihoods. The heavier weightings assigned to these criteria by both farmers and experts indicate a demand for sustainable farming systems, which were provided only by the low dikes. Our MCA results can thus also be interpreted as progressive exposure to an awareness of environmental degradation.

The MCA further validates the earlier findings of the interviews that market stability and flood protection are highly valued as benefits by farmers. To invest in and develop flood-based farming systems within low dike systems, two factors have to be addressed: (i) provision of dependable flood protection for residential zones, to safeguard people and their property as well as transportation infrastructure and public services, such as hospitals and schools; and (ii) strengthening of markets for other commodities, perhaps in association with development of modern food processing and perishable food preservation industries for new products grown in the alternative farming systems.

The lowest score in the MCA assessment was for the farming system with eight rice crops in three years (a 3-3-2 cycle). Similar to Chapman and Darby (2016), our results suggest inadequate economic and environmental benefit of the 3-3-2 rice system for farmers. Furthermore, Chapman et al. (2016) indicate that the 3-3-2 cycle did not improve on the triple-crop rice system in regard to trapping fertile sediment. The system of high dike compartments traps little fertile sediment, because the position, capacity and physical barrier of the sluice gates carries water differently than floodwaters flowing over low dikes (Hung et al., 2014b). Moreover, farmers tend to use excess rainwater pumped from compartment to compartment, instead of irrigation based on floodwaters, which bring trapped sediment (Joep, 2015). There is as yet no effective means of trapping sediment for triple-crop rice systems. It therefore seems recommendable to discontinue, or at least to reduce, triple cropping of rice, thus eliminating the main reason for high dike construction. Instead of continuing to focus on quantity, a shift may be proposed to a greater focus on rice quality for the international market, in combination with more concern for the environmental quality of farming systems (Tong, 2017). In addition, water and fertilizer managements are also recommended for the whole farming systems (Jang et al., 2012).

In line with our MCA results, most previous studies also found a preference for low dike farming systems over the high dike systems of the VMD. Käkönen (2008) and Trung et al. (2013) suggest more government stimulus for developing farming systems under low dikes, to reduce agrochemical use from the levels needed for farming in the high dike compartments. Howie (2011) studied relationships between farmers and the state and among farmers themselves, showing increased production costs in high dike farming systems compared to low dike systems. Kien (2014) conducted a cost-benefit analysis and concluded that farming practices under low dike protection had the highest economic benefit compared to those under high dikes or no dikes. GIZ (2014) carried out a cost-benefit assessment for four land management change scenarios in An Giang. That study determined that converting a large proportion of triple-crop rice area to seasonal rice plus vegetables could be an optimal future land use in terms of economic profit. Using a different method to analyse the costs and benefits of dike heightening on the VMD floodplains, Dan (2015) showed decreased profit from the first and second rice crops – due to the higher input costs – as the main cost of dike heightening, and recommended that rice intensification under high dike protection no longer be encouraged in the VMD. IUCN and VAWR (2016) produced results similar to ours, using farmer interviews and focus groups to explore adaptation of farming models for different areas in the Mekong Delta. That research also stressed the need to address the market obstacles associated with non-rice crops. Overall, the results of these studies are comparable with our MCA finding that low dike farming systems are economically more advantageous than high dike farming systems. Furthermore, the multiple methods used in the current research – an interview survey combined with a literature review, focus groups and an MCA) – contributes new insights on farmers' views of farming systems.

Our two-step approach showed initially contradictory results, which underlines the importance of the scientific method applied in any research context. If we had carried out only the interview survey, combined with the literature review, or if we had carried out only the MCA, our conclusions may well have been different. For example, we may have concluded that the majority of farmers advocated the high dikes, since many of the farmers interviewed were enthusiastic about the protection the high dikes offered and the ability to engage in triple-crop rice production. However, the focus group sessions conducted during the MCA showed a clear preference among farmers for flood-based farming systems with low dikes. Our combination of the two methods revealed that farmers were aware of the importance of sustainable farming systems, but that their livelihoods depend on stable markets and flood safety in the current social and economic context of the delta. Approaching the problem using these different methods brought out, to some extent, the dilemma that farmers face. The qualitative insights gained in this study on preferred alternative farming systems could be tested in further research across a broader sample of farming communities using quantitative surveys.

The method used in this study, a combined multi-criteria analysis (MCA) with analytic hierarchy process (AHP), could be applied in other areas when comparisons are made on the socio-economic and environmental performance of different farming systems. The MCA-AHP method can be used to support decision makers in deciding which farming systems are suitable and effective for improving livelihood sustainability. Under a set of evaluation criteria (i.e. economic, social and environmental perspectives), alternatives can be evaluated by different stakeholders. With the AHP, various levels of pair-wised comparisons can be done by weighing and ranking the alternatives/options based on a set of criteria (Mark and Patrick, 2013). The AHP helps to reduce the inconsistency from stakeholders' judgements (Saaty, 2008). In order to apply MCA-AHP, users should address the following three issues. First, integrate experts recommendations into a set of evaluation criteria that fit the research objective. Second, ensure that participants for the evaluation workshops or focus group are familiar with the farming systems and activities in the study area. Finally, the consistency of stakeholders' scores needed to be checked during the process in the pair-wise comparisons using AHP.

3.6. Conclusions

Our study uses both interview survey and multi-criteria analysis (MCA) to understand stakeholders' views on the current and alternative farming systems from a sustainable livelihoods perspective. Based on the findings of the study, three main conclusions are drawn:

Stakeholders' perception and alternative farming systems

- Double and triple rice farmers share their concern about environmental degradation of triple rice cultivation in high dikes, based on the MCA results. Our surprise to such an extent is that farmers valued the concerns of environmental degradation as the highest weight (larger than 50%), above concerns for livelihood (28 %) and floodwater management (17 %). Their concerns for the environment even outweighed those from the experts. It shows a strong appreciation of farmers on the detrimental effects of environmental degradation of soil and water in triple rice on their livelihoods and income. The progressive and compounding nature of environmental degradation may explain changing attitudes of farmers in their appreciation and valuing of triple rice cultivation and environmental concerns; as shown by Dung et al., (2018) initially benefits of higher rice production outweigh the extra cost and burdens, but as deterioration compounds over the years increases in production costs will surpass the gains, resulting even in negative results.
- The MCA results and valuation of the alternative farming systems provide a clear indication that farmers and experts underwrite the analysis of environmental degradation of triple rice, and the prospects for sustainable flood-based alternatives as putting forward in recent analysis and the Mekong Delta Plan (MDP). The ranking of alternative farming systems, though not unanimous in system specific preference, attributes a clear preference for flood-based (low dike) farming systems (addressing environmental concerns) and diversification towards higher value crops away from low economic rice. This provides scope and support for the MDP recommended priority strategy to stop expanding triple rice cultivation behind high dikes in the upper delta and invest in agricultural flood-based (or controlled flooding) diversification. As these alternative systems are only emerging at this stage, it will take considerable effort to upscale them to the scale of the vast floodplains of the delta, for which a robust support from farmers and stakeholders will be needed. The compounding effects of environmental degradation in triple rice may accelerate this process.

A clear challenge will be to retain the clear benefits of a stable market and flood protection to life and homestead in a diversified flood-based livelihood, as found as the preference of farmers to the high-dike farming systems based on the interview results — a failure to attain these may otherwise quickly turn the scales of costs and benefits on these now seemingly attractive alternatives.

CHAPTER 4

Questioning triple rice intensification on the Vietnamese Mekong Delta floodplains: An environmental and economic analysis of current land-use trends and alternatives[11]

Abstract

Large areas of the Vietnamese Mekong Delta floodplains (VMDF) are protected by high dikes to facilitate three rice crops per year. While this has increased rice production, there is evidence that triple rice systems have negative long-term effects, both environmental and economic. Double rice cropping, or other alternatives, may be more advantageous. We analyzed the costs and benefits of intensive rice systems over time and compared these with alternatives farming systems, based on data collected via field surveys and interviews with farmers in two provinces in the VMDF. Results show that farmers in areas with dikes high enough for triple rice production incurred rising production costs over time. Production costs were 58% to 91% higher in high-dike, triple crop areas, than in low-dike double rice crop areas. Higher production costs are mainly the result of increased fertilizer and pesticide use. Profitability of triple rice farming systems was initially 57% more compared to double crop systems. After about 15 years, however, triple rice farmers earned only 6% more than double crop counterparts. Our results indicate that alternative farming systems, such as rice combined with vegetables, fisheries or other flood-based livelihood, could offer greater benefits than intensive rice monocultures. Importantly, these higher benefits can be obtained without the environmental costs and impact currently endured across the delta with triple rice cultivation in high dikes.

Key words: costs and benefits; Mekong Delta; dike; farming system; rice

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4.1. Introduction

Deltas around the world face environmental degradation caused by agricultural intensification (Renaud et al., 2013). For sustainable intensification, appropriate land-use policies and methods are crucial (Dogliotti et al., 2014). The environmental and economic costs of intensive production systems are sometimes found to outweigh their benefits in the long term (Rasul and Thapa, 2004; Bezlepkina et al., 2011; Murshed-E-Jahan and Pemsl, 2011; Gerdessen and Pascucci, 2013). The current intensified rice production system in the Vietnamese Mekong Delta (VMD) is an example of this dilemma.

Vietnam has been a leading rice exporter for two decades (Kingdom of the Netherlands and The Socialist Republic of Vietnam, 2013). Known as the rice bowl of the nation, the VMD contributes more than half of Vietnam's total rice output (GSOVN, 2015). This success could not have been achieved without the Doi Moi reforms of 1986 (Kingdom of the Netherlands, 2011; Sebesvari et al., 2012; Cosslett and Cosslett, 2014). In particular, Vietnam's "rice first" policy initiated an expansion and intensification of rice production on the VMD floodplains. This was made technically possible by construction of a system of dikes, canals and sluice gates to regulate water flows. Since 2000, farmers have been encouraged to further intensify production, shifting to triple rice systems on fields protected by high dikes (Sakamoto et al., 2009; Chen et al., 2012; Renaud and Kuenzer, 2012). Today, high dikes are a prominent feature throughout the VMD upper floodplains, and agricultural policies still promote expansion of the high-dike, triple rice production system (MARD, 2015).

Large-scale construction of high dikes, however, has had numerous negative side effects. On the regional and delta scale, high dikes have reduced the water retention capacity of the floodplains (Kingdom of the Netherlands and The Socialist Republic of Vietnam, 2013). Because there is less space for floodwater storage, river levels have increased, leading to greater flood risk downstream (Dung et al., 2018). Reduced water retention capacity, furthermore, has led to diminished flows in the dry season, exacerbating saltwater intrusion into freshwater areas (Hoang et al., 2016). In addition, the high dikes have erected a barrier between the floodplains and rivers, interrupting ecosystem services (Opperman et al., 2013). On the local scale, the high dikes have prevented fertile sediments and wild fish from washing into and replenishing the rice fields (Käkönen, 2008; Danh and Mushtaq, 2011; Danh, 2011; Trung et al., 2013). All such downsides of high dike construction need to be weighed against the potential benefits of triple rice production across the different scales and over time, to determine what land-use policies are suitable and sustainable in the long term.

A number of authors have looked at the economic and social outcomes of intensified farming systems in the VMD. Howie (2011) investigated state-farmer relations in agricultural transformation, including the advantages and disadvantages of low dikes and high dikes. He concluded that fertilizer use increased in rice fields under high dike protection. An economic evaluation by Kien (2014) showed that low-dike systems provided the greatest net benefit compared to no-dike and high-dike systems. A cost-benefit analysis by GIZ (2014) considered four hypothetical scenarios and concluded that the scenario of floating rice plus vegetable cultivation without high-dike protection was most advantageous to farmers in both social and economic terms. Tong (2017) identified hidden costs of dike heightening, such as an increased need for pesticides, loss of natural floodplains and reduced profit with successive rice crops. These evaluations raise doubts about whether intensive rice cultivation in the VMD is indeed beneficial to farmers in the long run, after factoring in all of the costs involved. Nonetheless, regional and national policies continue to stimulate intensive triple rice production, proposing it as the best farming option, though without adequate study of alternatives, such as flood-based systems.

This research addresses that gap. Taking a long-term perspective, we compared the costs and benefits of different production systems in two provinces of the VMD. We hypothesized that agrochemical use in triple rice cultivation increases proportionally to the number of years of cultivation. Farm profits are therefore expected to diminish over time in the most intensive rice production systems: a triple rice monoculture with high dikes. We expected flood-based farming systems to be more sustainable, both environmentally and economically. We began our research with a cost-benefit assessment of different rice farming systems at different locations in the upper VMD. We then explored and analyzed alternative, flood-based options, comparing their profitability to the profitability of intensive rice cultivation. We tested our hypothesis using data from interviews with farmers in low dike and high dike areas in An Giang and Dong Thap provinces, in 2014 and 2016. We combined our interview findings with data from economic farm assessments done by the International Union for Conservation of Nature (IUCN, 2015).

4.2. Material and methods

4.2.1. Study site

An Giang and Dong Thap provinces are located in the upper VMD's two main floodplains: the Long Xuyen Quadrangle and the Plain of Reeds (Figure 4.1). Similar to other floodplains worldwide, such as the ones in Bangladesh studied by Alam et al., (2017) and in Ghana by Tsujimoto et al., (2017), the soil in these floodplain provinces is fertile and suitable for rice production. These provinces therefore have registered the largest expansion of triple rice production in the VMD during the past two decades (Duong et al., 2014). To produce three crops of rice annually, high dikes have been built to protect fields from seasonal flooding. Both provinces have double rice production areas too. These feature low dikes that provide fields some protection from rising floodwaters, allowing two rice crops to be harvested before the floodwaters wash over the dikes and submerge the fields (Kingdom of the Netherlands and The Socialist Republic of Vietnam, 2013). Prior to 2000, low-dike rice farming was dominant throughout the VMD floodplains. However, from 2000 to 2006 there was an intensive effort to heighten dikes, in order to allow triple rice cropping (Sakamoto et al., 2009; Chen et al., 2012). Currently, two thirds of the rice-growing area in An Giang is under triple rice production (Tran and Weger, 2017). In Dong

Thap, triple rice production accounts for one third of the total cultivated area (Tong, 2017). Figure 4.1 presents the survey sites for our research.

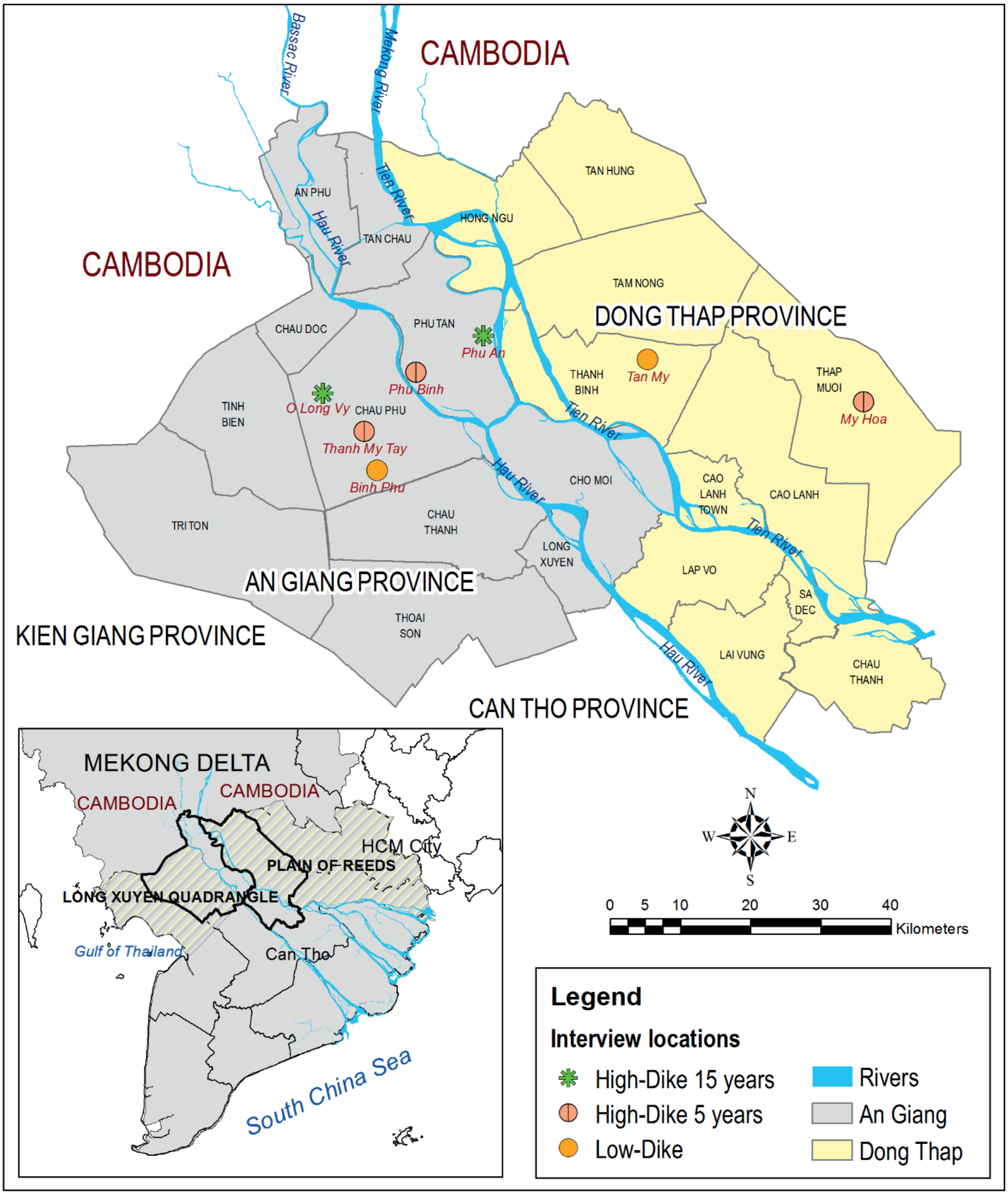

Figure 4.1 Survey sites for our research, in An Giang and Dong Thap provinces

In An Giang Province, our research focused on two districts: Phu Tan and Chau Phu. Phu Tan has a “closed” high-dike system. That means all agricultural fields are completely encircled by primary dike rings, which also provide footing for main roads. Thus, 28 cultivation compartments have been created, and water levels in the fields are regulated according to a schedule, either by pumping or by opening sluice gates (Tran and Weger, 2017). Most fields within the compartments are used for triple rice cropping, but vegetables and maize are also grown. The district of Chau Phu is relatively homogenous in physical characteristics (Kien, 2014). Its main agricultural products are rice, vegetables, orchard fruits and flood-based crops. Aquaculture is found here too. In both these districts, high-dike construction has been implemented over the past two decades.

In Dong Thap Province, our research focused on the districts of Thanh Binh and Thap Muoi. Thanh Binh has both vegetables and upland crops, though most area is under rice. Here triple cropping of rice is increasing, but double rice under low-dike protection is as yet dominant. Similarly, rice is the main agricultural product in Thap Muoi district, though upland crops and orchards are also common, as is aquaculture, including fishery and lotus farming. High-dike production systems have become increasingly prominent in both these districts during the past five years (Table 4.1).

Table 4.1 Characteristics of surveyed districts

District	Construction year of high dike	Area (ha)	Population	Agricultural land (ha)				
				Rice	Maize	Vegetables	Fruit	Aquaculture
Thanh Binh	2011-2014	34,200	156,187	18,542	2,294	1,785	633	503
Thap Muoi	2011-2014	53,000	137,827	38,293	13	736	1,812	338
Chau Phu	2000-2014	45,071	246,268	36,521	100	992	429	490
Phu Tan	1999-2011	31,313	207,698	22,351	643	2,769	317	227

Source: AGO (2015)

4.2.2. Field survey

We conducted two field surveys, in 2014 and 2016, to collect information on the costs and benefits associated with rice-based farming systems. In both surveys, we approached farmers in areas with low dikes and in areas with high dikes. Both "new" and "old" high dikes were represented. "New" high dikes are defined as those completed within the past five years. "Old" high dikes are defined as those in operation for 15 years or more. Most of the farmers in our samples were relatively advanced in age (46 years old on average), and most (97%) were men. More than 90% had a relatively low education, having completed only primary or secondary school.

The first survey was conducted in Phu Tan district, An Giang Province, in October 2014. Farmers were interviewed in two communes: Phu Binh and Phu An. We chose these communes because they had both new and old high dikes. The former, in line with the definition above, had been constructed since 2009, while the latter were built prior to 2000. To explore farming costs and benefits, we interviewed 28 high-dike farmers. They cultivated mainly vegetables and rice (short-grain or long-grain)[12]. The interviews were guided by a semi-structured questionnaire designed to elicit both qualitative data (i.e., on farmers' perspectives and attitudes) and quantitative data (i.e., yields and costs). Although the interviews focused on experiences with high-dike farming systems, some farmers also provided information about costs and benefits of farming before implementation of the high dikes. Six farmers provided information about the three-year payment requested by local authorities to help offset the costs of dike construction. To calculate farm profit, we also included information on earnings from aquaculture and from cultivation of vegetables, such as chili and squash. Our sample was selected using the snowball method. That is, the next farmers to be interviewed were chosen based on recommendations from the farmers previously interviewed. We resorted to this approach because no district-level data was available on farmers and land use. We tested the questionnaire with interviews of two farmers, then refined it before carrying out the bulk of the interviews. Data gathered in the testing phase were not included in the current study's analysis.

In August 2016, we conducted a second survey, this time in Chau Phu district, An Giang Province, and in Thanh Binh district, Dong Thap Province. Fifty-two rice farming households were approached in both low-dike and high-dike areas. Fifteen interviews were conducted in the Tan My commune, and the remainder (37) were done in Binh Phu, Thanh My Tay and O Long Vy communes (Figure 4.1 and Table 4.2). These interviews focused on the costs and benefits associated with farming in the "old" high dike areas of O Long Vy commune and in the "new" high dike areas of Thanh My Tay and Tan My. Interviews in Binh Phu commune explored low-dike farming systems. Two semi-structured questionnaires were drafted for this survey. This elicited general information on the respondents, farm characteristics, yield of each rice crop and production costs. In addition, farmers were asked when the high dikes were built, farm size, rice yields and the selling price of rice. To calculate production costs, farmers were asked about the cost of fertilizer, pesticides and pumping.[13] Triple rice farmers were questioned about the three-year contribution to dike construction as well. Their responses were noted and the interviews recorded. We did not fix the number of interviews in each region in advance; rather we continued to conduct interviews until our information had reached a saturation point (Kumar, 2014). Before the interviews, we tested the questionnaires in a short field survey with eight farmers in An Giang Province. Data from this pilot survey were not included in the current study.

To enrich our analysis, we used secondary data from IUCN (2015). This survey, conducted in April 2015, examined the profitability of different farming systems. It included some 140 farming

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[12] Different varieties of rice, i.e. OM 4218, OM 2514, and IR 50404 etc., are cultivated in the study area of the VMDF. Based on the scope of the study, we classified these rice spices into 3 main groups for data collection, including short-grain rice, long-grain rice and Japonica rice. Details of rice varieties, and type of fertilizer and pesticides referenced from various sources are presented in Supplementary Table C3 and Table C4.

[13] Pumping is needed for both irrigation and drainage. High dike systems have substantially higher pumping costs, as the fields must be kept dry during the wet season. In the dry season, irrigation water is pumped in from canals and rivers.

households in My Hoa commune, Thap Muoi district, Dong Thap Province. Thirty interviews were done with triple rice farmers, and 110 interviews were conducted with households that combined rice farming with lotus and vegetable cultivation, or lotus farming with fishing and tourism. Respondents were selected by random sampling.

To estimate production costs, we considered four main categories: fertilizers, pesticides, pumping and other. It proved rather difficult for farmers to estimate outlays for fertilizer and pesticide, as they applied various types of agrochemicals, and the amounts applied differed by growing period. Interviewers therefore had to elicit this information indirectly. Most farmers could estimate the amount of fertilizer they had used in terms of kilograms or bags, and pesticides in terms of bottles per hectare of cropped land. The price per kilogram of fertilizer and for each bottle of pesticide could then be determined. Regarding pumping, we asked farmers about the cost and duration of the pumping required. There were large differences in these costs, particularly, between the low-dike and high-dike farming systems. Table 4.2 presents characteristics of respondents, farming systems and average farm sizes. Table C1 in the supplementary details production costs associated with the crops investigated.

Table 4.2 Characteristics of interviewees

Commune	Dike type*	N	Age	Gender (%)		Education (%)			Mean farm size (ha)
				M	F	Primary	Secondary	Tertiary	
Tan My	Low	15	51	100	0	53	47	0	2.3
Binh Phu	Low	12	48	100	0	50	50	0	2.8
Thanh My Tay	New	13	42	92	8	50	42	8	2.7
O Long Vy	Old	12	44	100	0	46	54	0	2.0
Phu Binh	Old	14	46	93	7	NA	NA	NA	1.7
Phu An	Low	14	52	100	0	NA	NA	NA	2.2
My Hoa	New	140	41	93	7	43	43	14	NA
Average			**46**	**97**	**3**	**48**	**47**	**8**	**2.3**

**New high dikes are those completed less than five years ago. Old dikes are those in operation for 15 years or more.*
NA: Not Available.
N: Number of interviews.

4.2.3. The cost-benefit analysis calculations

We computed production costs and benefits for rice crops and for alternatives using data from the three field surveys (Figure 4.2). Earnings were calculated by multiplying rice yields by the selling price for each rice crop. Production costs were estimated using the four categories mentioned above: fertilizer, pesticide, pumping and other.[14] Fertilizer costs were approximated based on the number of 50 kg bags used per hectare for each crop ($kg.ha^{-1}$) multiplied by the market price per

[14] The costs consist of land preparation, seeds, harvesting, and transport etc. although another cost of farmers could include a three-year payment of high dike construction.

bag. Pesticide costs were computed similarly, using the number of bottles applied to each crop (bottle.ha^{-1}) and the price per bottle. Pumping costs were calculated by multiplying pumping duration by price per hour. All production costs and earnings were calculated in Vietnamese dong (VND). To facilitate international comparisons, we converted profit amounts into US dollars using the 2017 exchange rate (1 US dollar = 22,700 VND). We then compared the costs and benefits of the different farming systems at the different survey sites. We did gather information on the contributions paid by farmers for dike heightening, however, we excluded these from our production cost calculations, as we lacked analogous data on the low dikes.

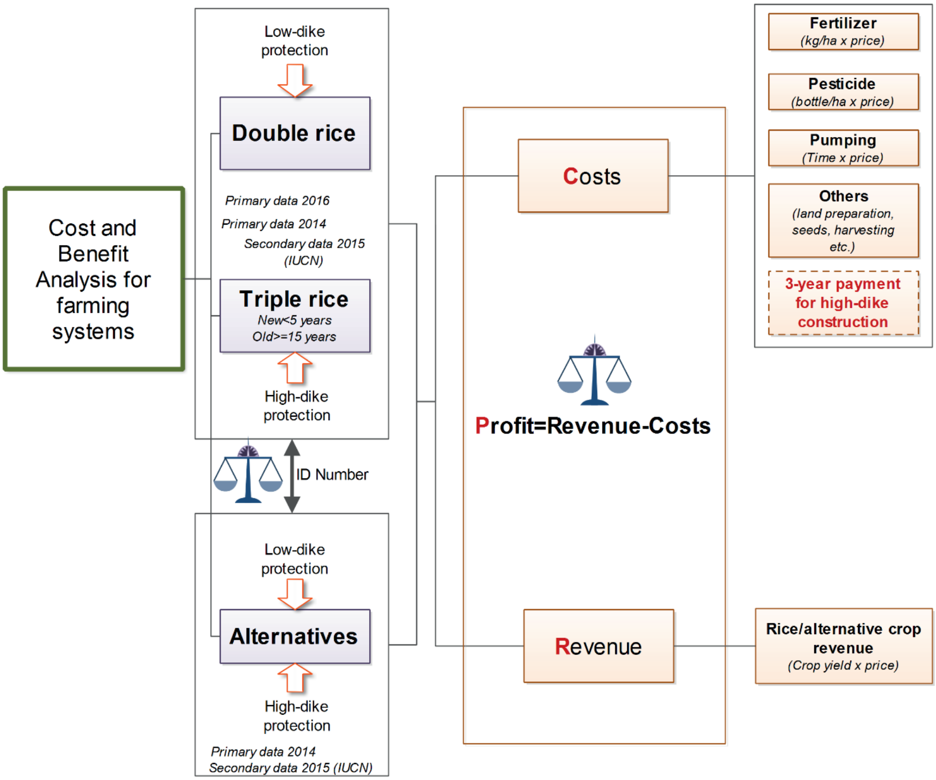

Figure 4.2 Methodology of cost-benefit analysis

For consistency, we compared the production costs and earnings associated with rice cultivation in the different farming systems in the same geographical location. Yet, the systems were not all represented at all survey locations. In Phu Binh, for example, we had data on rice production (short-grain and long-grain) with both low dikes and new high dikes (dikes built within the past 5 years), but there were no data on cultivation under old high dikes (built at least 15 years ago). We therefore assumed an old high-dike production system based on the 2014 interview data from Phu Binh (Table 4.3). Specifically, rice yields were taken to be equal to those from the new high-dike farming system in Phu Binh, with production costs equivalent to those of the old high-dike system in Phu An. In addition, we assigned each farming system an ID number to enable its identification among the proposed alternatives as well as in the results tables.

We assessed alternative farming systems using the 2014 interview data and the secondary data from IUCN (2015). The production costs and earnings associated with each alternative were compared to those of rice cultivated in both low-dike and high-dike systems. In the comparison, rice was assumed to be the main crop in the farming systems (Dung et al, 2018). The farmers interviewed had an average of 2.3 ha rice production area (Table 4.2). Therefore, they could presumably use 2 ha for rice production and devote the remainder of their land to cash crops or fish to supplement their rice income. Due to the high preference of farmers for triple rice production with high dikes and the stable and predictable market for rice, a transformation of the entire area from an intensive rice monoculture to high-value crops is probably unrealistic (Tran and Weger, 2017). Table C2 in the annex presents costs and earnings from each farming system investigated.

4.3. Results

4.3.1. Intensive rice farming systems

Our results show substantially higher rates of agrochemical use for rice production in the triple rice cropping system, particularly in combination with old high dikes, compared to areas with new high dikes and low dikes (Figure 4.3). However, in both triple rice systems, agrochemical application rates rose over time. Compared to the low-dike farming system, mean fertilizer use was 30% higher on average in the new high-dike farming system, corresponding to an extra 100-200 $kg.ha^{-1}$ per crop. Fertilizer use rose even further in the old high-dike farming system, in which some 90% more fertilizer was applied, corresponding to an extra 300-500 $kg.ha^{-1}$ per crop. Mean pesticide use increased by 5% in the new high-dike system, corresponding to an extra 4-12 $bottles.ha^{-1}$ per crop. It then rose further to a 39% increase in the old high-dike farming system, corresponding to an extra 16-25 $bottles.ha^{-1}$ per crop. Thus, after a new high dike was built, farmers spent 54% to 87% more annually on fertilizer than farmers in the low-dike areas. Some 15 years after high dikes were built, farmers spent 133% to 234% more on fertilizer than their low-dike counterparts (Table 4.3). Annual pesticide use rose by 62% in the new high-dike farming system, climbing further to a 118% increase in the old high-dike farming system.

Of the three rice crops in the triple cropping system, the largest increase in agrochemical application occurred in the first crop. Overall, expenditures for agrochemicals rose over years in the high-dike areas. However, fertilizer and pesticide applications varied by location. Farmers in Phu An commune, An Giang Province, used the greatest amounts of fertilizer for each crop. Interestingly, agrochemical use was generally lower in Dong Thap Province than in An Giang Province.

Pumping and other production costs were also higher in the triple rice systems (Table 4.3). Pumping costs in the high-dike systems were double those in the low-dike systems. This was due to the greater expense of the required high-capacity pumps, the fact that pumping was needed more often and the higher volumes of water that had to be pumped out of the fields over a higher head (generally 3-4 m) during the flood season. More time and labor was also required, for land preparation, seeding and transplanting. The lower triple rice production costs found in My Hoa are due to the exclusion of transplanting and spraying costs from the IUCN (2015) data (Table 4.3).

Figure 4.3 Fertilizer and pesticide use for rice production in the low dike and high dike areas

Although production costs were higher in areas with new high dikes, triple rice farmers still made greater profit overall, thanks to the sale of the third crop, compared to farmers cultivating two rice crops with low dikes (Table 4.3). However, triple rice farmers' profits diminished over time. Profit from rice production in first four years of triple cropping was 57%-68% higher than in the low-dike double crop systems; some 15 years later, triple rice profits were still higher, but less so: 6%-13%. Some farmers in the low-dike areas earned more than their counterparts in the old high-dike areas. For example, the 2014 survey showed that profits from triple rice production in the new high-dike system were 13% higher than those in double rice production, but the old high dike system was associated with lower profits (-16%). In the extreme case of low yields and high production costs, as in Phu Binh in 2014, profits fell by almost half (-45%). In general, the higher production costs ate away at the extra profits gained from triple rice farming as the years progressed.

The three-year contributions that farmers paid for high-dike development varied by location and construction year. Payments also depended on the design capacity of the dike (length, height and width) and farm size. According to the 2016 survey and data, farmers paid US $452 ha^{-1} on average over three years in O Long Vy (an old high-dike area), whereas they paid $1,009 ha^{-1} over three years in Thanh My Tay (a new high-dike area) (Figure 4.4). Three farmers in O Long Vy indicated much higher payments than the others. In the new high-dike system of Thanh My Tay, farmers reported similar payments for high-dike construction. In the 2014 survey, farmers in Phu An reported having paid $480 ha^{-1} over three years, and in Phu Binh they reported paying $700 ha^{-1}. These payments can be considered high, as the added profit earned from triple rice production was $1,066 ha^{-1} over three years.

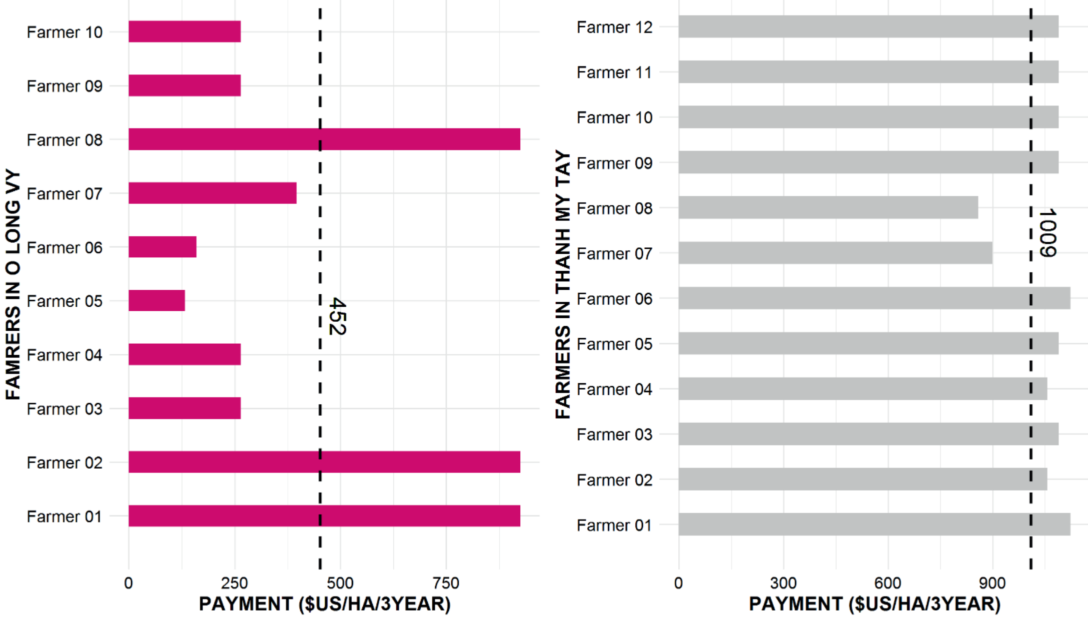

Figure 4.4 Farmer contributions for dike heightening, data from 2016 survey

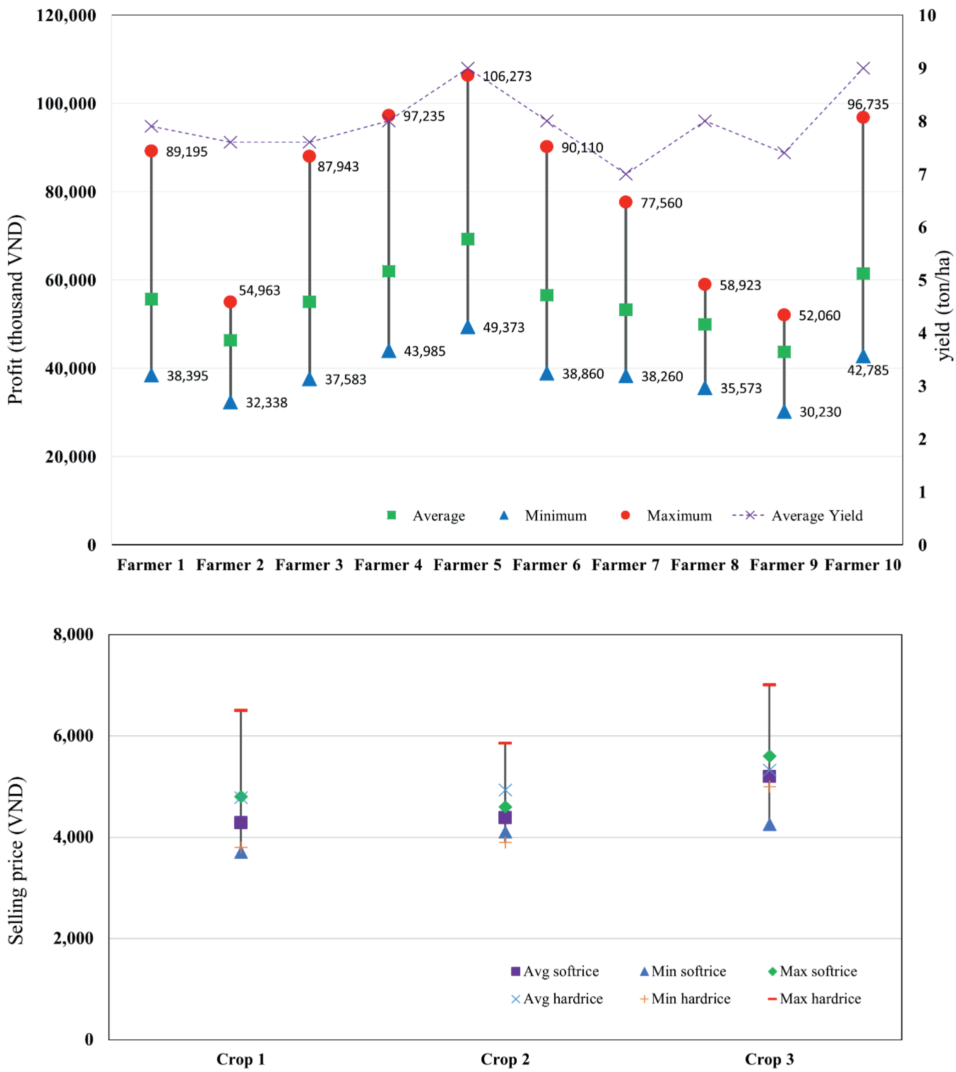

Figure 4.5 Annual profit from triple rice production and rice selling prices compared to yields (above) and selling price of successive crops (below), data from 2014 survey in Phu Binh commune

Earnings from rice production are very sensitive to farm gate prices, which vary according to the type of rice cultivated (short-grain, long-grain or Japonica), the season, the year and yields (Figure 4.5). Particularly for triple rice production, farm earnings are also dependent on production costs. After deducting expenditures for pumping and agrochemicals, we found triple rice production delivered only very small increases in profit (comparing double rice with triple rice). Moreover, this already minimal profit margin diminished over time (comparing production in the first years after high-dike completion to production 15 years later). This is illustrated by the data collected in Phu Binh. In years when the rice market price was low, annual profit from triple rice was sometimes less than the average annual profit from double rice production (30.0-43.9 million VND versus 44.0 million VND, Figure 4.5 and Table 4.3).

The 2016 data also indicate higher profits for farmers cultivating Japonica rice compared to those producing short-grain and long-grain varieties (US $2,400 versus $1,500). This is because Japonica commands a higher selling price and produces greater yields. The annex presents analogous findings for the other communes.

4.3.2. Alternative farming options

We explored farming alternatives to replace the current double and triple rice cropping pattern, particularly diversification into higher value crops and exploiting the opportunities of the natural flood regime (Table 4.4). For example, small-scale planting of high value crops on rice fields could allow farmers to supplement their incomes.

Our 2014 and 2015 data suggest that some alternative farming systems do return higher profits than double and triple rice production (Table 4.4). In the low-dike areas, farmers' profits increased by 12%-268% with the alternative farming systems. The highest profits were found from combining a 2-ha rice crop with four-season squash and by combining a double intensive lotus crop with tourism. In addition, a flood-based crop, such as lotus or *neptunia oleracea*, combined with wild fish raised rice farmers' income by 14%-70%. Profits could increase by 83% if farmers converted from a double rice monocrop to floating rice combined with vegetables. In the new high-dike areas, farmers' profits increased by 42% and 203%, respectively, when they switched to a 2-ha triple rice crop combined with a fish pond and to a 2-ha triple rice crop combined with four-season squash. In the old high-dike areas, alternatives brought 62%-506% higher profits compared to a triple rice monocrop. In general, farmers could increase their profit by diversifying beyond rice alone, particularly by including a small vegetable or cash crop area, or aquaculture.

In the low-dike areas, alternative farming systems such as double rice with an additional flood-based crop were less profitable than double rice combined with a high-value crop. Based on the 2014 data, these latter farming options brought a profit increase of 12% to 70%, compared to double rice production alone. Farming systems with additional chili or squash raised profit by 59% to 158%. IUCN (2015) found that profit could be increased by 268% with a farming system of intensive lotus and ecotourism services with 1 ha cultivated area. While farming systems with water-based crops did not offer more profit than those with high-value crops, they do exploit the benefits of floodwaters, such as sediment deposition, and thus contribute to reduce land and water degradation.

In the high-dike areas, farmers have seen even their profits from alternatives fall, compared to farmers in the low-dike areas. With three rice crops and a complementary crop, triple rice farmers earned less profit than farmers with two rice crops and a complementary crop. For example, we found the annual profit from a 2 ha triple rice farm with a fish pond to be less than that of a 2 ha double rice farm with flood-based snakehead fish culture ($4,500 versus $5,000). Similarly, for rice complemented by chili production, high-dike farmers earned lower profit than low-dike farmers ($5,500 compared to $6,500). Farmers' profits, moreover, diminished progressively over the 15 years of rice cultivation in the high dike areas.

Table 4.3 Costs and benefits of rice cultivation in low-dike and high-dike areas

Rice production	Variety	ID number	Number of interviews	Crop yield (tons/ha)			Mean price	Mean production costs							Revenue	Profit	
Dike type				Crop 1	Crop 2	Crop 3		Fertilizer (1)		Pesticide (2)		Pumping (3)	Others (4)	Total (1+2+3+4)	x10³ VND.ha⁻¹.yr⁻¹		US $ ha⁻¹.yr⁻¹.
							VND.ton⁻¹	kg.ha⁻¹	x10³ VND.ha⁻¹.yr⁻¹	bottle .ha⁻¹	x10³ VND.ha⁻¹.yr⁻¹		x10³ VND.ha⁻¹.yr⁻¹				
CBA data collection in 2016																	
1. Tan My																	
Low dike	short-/long-grain	L1	12	7.1	5.4		4,950	942	9,400	88	8,800	2,500	15,500	36,200	69,700	33,500	1,476
	Japonica		3	9.2	5.9		5,300						15,500		89,800	53,600	2,361
2. Binh Phu																	
Low dike	short-/long-grain	L2	12	7.6	6.0		4,850	1,140	11,400	95	9,500	2,500	15,500	38,900	74,700	35,800	1,577
3. Thanh My Tay																	
New high dike (4 years old)	short-/long-grain	H1	12	7.6	5.9	5.7	5,100	1,765	17,600	154	15,400	5,100	23,200	61,300	117,600	56,300	2,480
Compared to low dike									*(+54%-+87%)*		*(+62%-+75%)*			*(+58%-+69%)*			*(+57%-+68%)*
4. O Long Vy																	
Old high dike (15 years old)	short-/long-grain	H2	9	7.7	5.5	5.1	5,000	2,189	21,900	192	19,200	5,300	23,200	69,600	107,400	37,800	1,665
	Japonica		4	8.1	5.8	5.7	5,500						23,200		129,800	60,200	2,652
Compared to low dike									*(+92%-+133%)*		*(+102%-+118%)*			*(+79%-+92%)*			*(+6%-+13%)*
CBA data collection in 2014																	
1. Phu Binh																	
Low dike	short-/long-grain	L3	4	8.1	7.0		4,650	900	9,000	79	7,900	2,500	15,500	34,900	78,900	44,000	1,938
New high dike (5 years old)	long-grain	H3	11	7.6	5.9	5.7	5,015	1,990	19,900	156	15,600	5,500	23,200	64,200	113,800	49,600	2,185
Compared to low dike									*(+121%)*		*(+197%)*			*(+84%)*			*(+13%)*
New high dike (5 years old)	short-grain	H4	3	6.9	6.0	5.4	4,620	1,990	19,900	156	15,600	5,500	23,200	64,200	100,300	36,100	1,590
Compared to low dike									*(+121%)*		*(+197%)*			*(+84%)*			*(-18%)*
Old high dike (15 years old)	short-grain	H45[5]	No	6.9	6.0	5.4	4,620	3,005	30,100	180	18,300	4,500	23,200	76,100	100,300	24,200	1,066
Compared to low dike									*(+234%)*		*(+101%)*			*(+91%)*			*(-45%)*
2. Phu An																	
Low dike	short-grain	L4	3	10	8.9		4,330	900	9,000	91	9,100	2,500	15,500	36,100	92,800	56,700	2,498
Old high dike (15 years old)	short-grain	H5	14	9.3	7.0	6.4	4,620	3,005	30,100	180	18,300	4,500	23,200	76,100	123,700	47,600	2,097
Compared to low dike									*(+234%)*		*(+101%)*			*(+91%)*			*(-16%)*
*CBA data collection in 2015**																	
My Hoa																	
New high dike (3 years old)	short-/long-grain	H6	30	7.6	6.1	5.0	5,000	1,554	15,542	121	12,140	3,130	17,900	48,700	93,600	44,900	1,978

(4) "Other" includes land preparation, seeds, planting, spraying pesticides, harvesting and transport. (5) Crop yields are assumed to be the same as those in the five-year dikes (H4) and total production costs are assumed to be equal to those under the 15-year high dike in Phu An (H5) due a lack of data.

** Source: IUCN (2015)*

Exchange rate in 2017: 1 USD=22,700 VND

Table 4.4 Annual household profit under alternative farming systems

Alternative farming system/household	ID number	Annual profit per household		+/-
		x10³ VND	US $	%
A. Low dike				
CBA data collection in 2014				
01. Two short-grain rice crops (2 ha)	L4	92,800	4,088	*0%*
02. Two short-grain rice crops (2 ha) + flood-based giant freshwater prawn (0.1 ha)	L4+L5	104,100	4,586	*12%*
03. Two short-grain rice crops (2 ha) + flood-based snake-head fish (32.73 m^3)	L4+L6	114,900	5,062	*24%*
04. Two short-grain rice crops (2 ha) + two seasons chili (0.2 ha)	L4+L7	147,400	6,493	*59%*
05. Two short-grain rice crops (2 ha) + four seasons squash (0.25 ha)	L4+L8	239,400	10,546	*158%*
05. Two short-grain rice crops (2 ha) + wild fish (flood season)	L4f	105,900	4,665	*14%*
07. Two short-grain rice crops (2 ha) + *Neptunia oleracea* (0.5 ha) + wild fish (flood season)	L4+L9	157,400	6,934	*70%*
*CBA data collection in 2015**				
08. One rice (1 ha) + one lotus (1 ha)	H11+L10	79,350	3,496	*0%*
09. Two-season of lotus (2 ha)	L10	113,800	5,013	*43%*
10. Two-season intensive lotus (1 ha)	L11	117,600	5,181	*48%*
11. Two-season intensive lotus + ecotourism (1 ha)	L12	292,000	12,863	*268%*
12. Two-season intensive lotus + fish (1 ha)	L13	130,400	5,744	*64%*
13. Floating rice + additional cash crops (1 ha)	L14	145,400	6,405	*83%*
B. High dike				
CBA data collection in 2014				
5-year high dike				
01. Three short-grain rice crops (2 ha)	H4	72,200	3,181	*0%*
02. Three short-grain rice crops (2 ha) + eel (10 m^2)	H4+H7	112,200	4,943	*55%*
03. Three short-grain rice crops (2 ha) + fish pond (50 m^2)	H4+H8	102,200	4,502	*42%*
04. Three short-grain rice crops (2 ha) + two seasons chili (0.2 ha)	H4+H9	126,800	5,586	*76%*
05. Three short-grain rice crops (2 ha) + four seasons squash (0.25 ha)	H4+H10	218,800	9,639	*203%*
15-year high dike				
01. Three short-grain rice crops (2 ha)	H45	48,400	2,132	*0%*
02. Three short-grain rice crops (2 ha) + eel (10 m^2)	H45+H7	88,400	3,894	*83%*
03. Three short-grain rice crops (2 ha) + fish pond (50 m^2)	H45+H8	78,400	3,454	*62%*
04. Three short-grain rice crops (2 ha) + two season chili (0.2 ha)	H45+H9	103,000	4,537	*113%*
05. Three short-grain rice crops (2 ha) + four seasons squash (0.25 ha)	H45+H10	195,000	8,590	*303%*
06. Two seasons of chili (0.5 ha)	H9	136,500	6,013	*182%*
07. Four seasons of squash (0.5 ha)	H10	293,100	12,912	*506%*
*CBA data collection in 2015**				
08. Three rice crops (2 ha)	H11	89,800	3,956	*0%*
09. Three rice crops (2 ha) + three sesame (0.2 ha)	H11+H12	110,860	4,884	*23%*

**Source: IUCN (2015)*

Exchange rate in 2017: 1 US dollar=22,700 VND

4.4. Discussion

To understand the sustainability and profitability of triple rice production, its economic and environmental costs and benefits must be analyzed over the longer term. We did this in two provinces in the VMD floodplains, comparing the production costs and benefits of triple rice to those of double rice and various alternatives. Our findings indicate losses, both environmental and economic, from triple rice production over time. From an economic perspective, triple rice profitability fell particularly after the first five years compared to double rice production in low-dike areas. The additional, third rice crop thus brought extra profit for farmers mainly in the initial years after dike heightening. Profits were particularly dampened by increased production costs, especially expenditures for fertilizers and pesticides. In some old high-dike areas, triple rice farmers earned less than double rice farmers, due to the former's significantly higher production costs. Triple rice earnings were even less if the required three-year farmer contributions for high-dike construction were included in the calculations. From an environmental viewpoint, increased fertilizer and pesticide use has degraded soil quality in the triple rice areas. This degradation has been compounded by the lack of fertile sediment deposition from floodwaters (Howie, 2011). Continuation of this cropping pattern in the old high-dike areas will likely exacerbate land degradation further. These findings indicate that triple rice production within high-dike systems may be ineffective in increasing farm profits and livelihoods in the longer term. At the same time, its continuation will worsen environmental degradation, due to rising agrochemical use. Since the surveys were taken from 2014, economic values and environmental impacts could be deviated and more expensive if they are applicable for cost and benefit analysis in the future due to inflation led by economic growth. This could be explicitly explained in our study if considering the higher production costs over time due to the increase in market price and environmental degradation.

Our results confirm the hypothesis that profits from triple rice production decline over time in high-dike areas. It bears noting, however, that our results could have been affected by two factors. First, our data on fertilizer and pesticide use came from a variety of farms and dike compartments. Comparing only farms within a single dike compartment, looking at agrochemical use before and after dike heightening, might have provided a stronger test of our hypothesis. Such an investigation, however, would require other methodologies, as we cannot expect all farmers to recollect full production details over a 15-year period of cultivation with a high dike. Secondly, our findings could be validated by linking soil and water quality indicators to different rice farming systems in the same floodplain over time. This is a promising avenue for future research.

Our study is novel in that it explored the long-term dynamics of profits and production costs over many years of intensive rice production under different dike regimes. Our results are in line with those of several previous studies. For example, Howie (2011), based on interviews with seven triple rice farmers in An Giang Province, found a more than 40% decline in rice output per ton of fertilizer 20 years after dike heightening. Several authors have reported substantial soil degradation after long-term intensive rice production (Chaudhury et al., 2005; Tran Ba et al., 2016). Kien (2014) concluded that low dikes provided more profitable farming systems for local farmers than either no-dike or high-dike systems. Moreover, GIZ (2014) found the highest economic and social benefits could be derived from a floating rice plus vegetable farming system, whereas the high-dike conversion scenario offered the lowest profits. Danh and Mushtaq (2011) recommended land-use policies that exploit rather than prevent floodwater flows on the floodplains. This has been supported by many others (Ahmadvand and Karami, 2009; Caddis et al., 2012; Opperman et al., 2013; Ajwang' Ondiek et al., 2016a; Mirosław-Świątek et al., 2016). Tong (2017) concluded that triple rice farming systems are less profitable and lose out on the many benefits of flooding compared to flood-based farming systems. Moreover, triple rice expansion led to a marked increase in pesticide use in the surrounding low-dike areas as well, which our study did not find. According to Chapman and Darby (2016) and Chapman et al. (2016), dike heightening penalizes poor and landless rice farmers, as it disrupts their access to flood-based livelihoods (i.e., wild fish catches and flood-based crops). These important societal benefits were not included in the current study.

We found fluctuations in farm earnings per ton of rice produced. This was due mainly to the generally low marginal profitability of rice, which varied depending on rice variety and yields. The low marginal profit of rice had a larger impact on triple rice farmers than on double rice farmers. The high dikes were developed to promote triple rice cultivation. However, the large outlays required to embark on triple rice production produced the largest gains in the initial years. This suggests that farm profits and income may be more sustainably increased in other ways, such as diversification into high-value crops. These are crops produced on a small scale -- an area of 0.1 ha to 0.5 ha, next to a 2-ha rice field -- which offer a significantly higher profit margin than rice. Yet, such diversification is more easily achieved in low-dike systems. While high-value crops could certainly be planted as a third season crop, or as a non-rice alternative, within the high-dike areas, farmers in these areas must still contend with losses due to environmental degradation. Higher farm incomes are more readily achieved by diversification into high-value crops in low-dike areas, foregoing the high investment costs and negative impacts of high dikes.

Alternative farming systems, such as intensive lotus or a 2-ha rice field plus a small vegetable or high-value crop area, could increase farm income. Diversification schemes, furthermore, help farmers offset the market risks associated with a rice monocrop (Chambers and Conway, 1992; Berg, 2002; Tsuruta et al., 2011; Phong et al., 2010; Pretty and Bharucha, 2014; Roel et al., 2006). Moreover, conversion of a small rice area to other crops is an easier alternative, in terms of the financial and technological investment required, than a full conversion to a different farming system. After gaining experience and income from their new farming practices, farmers may be more willing to transform larger areas to another system. According to our calculations, alternative flood-based farming systems, such as intensive lotus, return greater profits than rice. These alternatives, which are being developed in the low-dike areas during the flood season, would moreover reduce negative environmental impacts and enhance flood-based ecosystem services (Morris et al., 2008; Gadanakis et al., 2015). Low-dike systems provide other benefits as well, such as fishery and horticulture earnings, which have very limited potential in high-dike areas. Our study indicates benefits potentially provided by a transition from high-dike to low-dike farming systems in terms of environmental or socio-economic improvements because the floodplains are important sources of biodiversity, i.e. rice genetics in floating rice, melaleuca forest, endemic fish and water birds (IUCN&VAWR, 2016). These species have been threatened by the triple rice conversion and may benefit from floodplain restoration.

Although our findings indicate substantial economic and environmental potential of low-dike farming systems, appropriate national policies and strategic floodwater management methods are needed to develop these further. The national policy of promoting triple rice production has successfully increased national rice output and exports, but the tradeoffs of lower farm profitability and environmental degradation have been unfavorable for farmers (Käkönen, 2008). Diminishing profits and increasing environmental degradation suggest that further expansion of high dikes should be halted, and that low-dike farming systems should be explored instead. Overuse of fertilizer in triple rice production, moreover, leads to soil acidification and water pollution across the delta (Zhang and Shan, 2008; Stone and Hornberger, 2016). In addition, conversion of high dikes to low dikes is very costly. Measures have already been implemented to reduce the negative environmental impacts of high-dike systems. For example, in An Giang Province, triple rice farmers are being encouraged to use a 3-3-2 cycle, that is, flooding fields once every three years. This, however, has produced only minimal deposition of fertile sediment (Chapman and Darby, 2016; Chapman et al., 2016). Some developed countries have suggested that instead of constructing large flood structures, adaptation to nature would be a better strategy, exploiting the benefits of the natural cycle of flooding (Fliervoet et al., 2013; Temmerman et al., 2013; Van Wesenbeeck et al., 2014; Van Herk et al., 2015). However, in considering development of flood-based farming systems, two benefits of high dikes cannot be overlooked: (i) the flood safety provided by high dikes to residential areas and (ii) the stable market for rice (Dung et al., 2018b).

The findings of the current research could be applicable to other deltas, especially where measures are being considered to stimulate a transformation from flood-based farming to more intensive farming systems, with or without structural measures like high dikes. For example, the conversion from wetlands to paddy rice fields in Kano floodplain, Kenya is concluded to add provisioning ecosystems services such as rice and fish but the net profit of these benefit is still questionable (Ajwang' Ondiek et al., 2016). In any such transformation, the full, long-term effects of human interventions, such as agricultural intensification, should be considered (Renaud et al., 2013). Farming system innovations are needed that provide for increased farm incomes. But for sustainability, land-use strategies must also offer effective floodwater management, both in the floodplains and across the delta as a whole. In delta floodplains particularly, agricultural intensification must factor in the link between rivers, floodwaters and farmers' fields. Fertile sediment conveyed by floodwaters is a key production resource, as noted in the Mekong Delta Plan (Kingdom of the Netherlands and The Socialist Republic of Vietnam, 2013). Ecosystem services provided by floodwaters underline the need to retain the natural cycle of flooding, to preserve the delta ecosystem (Fliervoet et al., 2013; Opperman et al., 2013; Berg et al., 2017).

Based on a study in Bangladesh, Murshed-E-Jahan and Pemsl (2011) noted that "sustainable intensification often requires external inputs, has negative environmental effects and increases risk". This is in line with our findings. In addition, their study concluded that integrated aquaculture-agriculture production systems could improve farmers' income while having fewer negative impacts on the environment. Our findings furthermore confirm the conclusion of Stone and Hornberger (2016) in Sri Lanka, that fertilizer inputs increase rice yields but also exacerbate nitrogen (N) leaching, which is harmful not only to the environment but to human health as well. Overall, agricultural intensification on the scale of a floodplain must consider economic, social and environmental sustainability criteria, as well as the development needs of the delta as a whole, especially under the impacts of a changing climate.

4.5. Conclusions

The current study provides much overdue information on the short-term and long-term effects of intensive rice cultivation on the VMD floodplains. In sum, farmer's profits declined and environmental degradation increased over time in our study area. Expansion of triple rice production therefore does not appear to be a sustainable livelihood strategy. Alternatives were suggested, however, that could lead to more sustainable and profitable farming systems. These provide food for thought for policymakers in other deltas as well, where a shift is being considered to intensive rice production under high dike protection. Our study offers four urgent messages regarding the economic and environmental impacts of triple rice expansion with large-scale construction of high dikes.

- First, the profitability of triple rice farming declines over the years, while land and water degradation rises due to increased fertilizer and pesticide use.

- Second, further high-dike construction in the VMD floodplains should be discouraged, as the dikes already built have had substantial negative effects on the floodplain ecosystem. There is little potential for profitable crop diversification in the high-dike areas due to the lack of ecosystem services provided by flooding. A transition from high-dike to low-dike farming systems provides benefits to the delta in terms of environmental or socio-economic improvements owing to the important sources of biodiversity offered by the floodplains.
- Third, conversion to high-dike systems should not be undertaken lightly, as a transition back to low-dike, flood-based systems is very difficult and costly.
- Fourth, where stimulation of flood-based farming is being considered, adequate flood protection needs to be provided to ensure residential safety, and the stability of the market for alternative crops needs to be factored in.

CHAPTER 5

Economic assessment of externalities of different dike scenarios at delta scale[15]

Abstract

Intensive rice production has developed across the upstream floodplains of the Vietnamese Mekong Delta (VMD). For this, a dense system of low and high dikes has been built, creating compartmentalized fields where water management can be optimized. Intensive cultivation here has enabled farmers to greatly increase their rice productivity and augment the national food bowl. However, flood-control structures have undermined the water retention capacity of the floodplains, compromising various benefits of natural floodwaters for delta ecosystems. Effects are both internal and external to farming. Negative internal effects are the large investment requirements and higher farming costs. Negative externalities include increased flood damage, reduced sediment flows, saltwater intrusion and riverbank erosion. In this study we assessed the effects of three dike–agricultural system scenarios on delta-level sustainability, considering both internal and external effects. Direct and indirect costs were estimated using various methodologies and the literature. Our findings show that extensive development of high dikes on the floodplains is the least economical and most ecologically risky alternative. In this scenario, accelerated high-dike construction exacted a cost 136% greater than the situation represented by the baseline year of 2011. Externalities in this scenario contributed to rising economic losses in both aquaculture and agriculture. For the scenario in which high dikes were transformed into low-dike systems, reduced water management costs were found, alongside an improved environment and greater capacity to exploit floodwaters' benefits. Our findings provide a useful input for decision-makers considering the unintended economic consequences of existing water management strategies. They support a transition to low-dike farming systems for a more sustainable delta.

Key words: rice production; Mekong; sediment; salinity intrusion; flood damage; sustainability.

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[15] The manuscript corresponding to this chapter was submitted to Journal of Water Resources Management.

5.1. Introduction

In deltas worldwide, downstream areas are influenced by human interventions upstream, particularly where agricultural intensification is paired with extensive infrastructure for flood protection and water management. Large dams on the Yangtze River, for example, have trapped natural sediment within reservoirs, reducing sediment deposition downstream and causing riverbank erosion (Yang et al., 2014). Tessler et al. (2017) estimated the effects of large dams on sediment fluxes for 46 deltas globally. According to their calculations, planned dams would reduce sediment fluxes in the Danube by up to 60% and in the Ganges-Brahmaputra-Meghna by some 21%. In the Danube, Hein et al. (2016) reported on threats to ecosystem services arising from land use changes, river regulation and dam construction over time. For example, increased flooding was observed in various regions of the catchment, alongside increased pollution loads and loss of physical habitat diversity. These outcomes have prompted governments to undertake restoration programs aiming to reconnect floodplains with their main rivers in order to increase nutrient and sediment retention and conserve floodplain ecosystems (McMillan and Noe, 2017). However, the economic cost of such programs is high, partly including cost of environmental degradation from the previous hardware programs (Guida et al., 2016).

Upstream-downstream problems are very evident on the Vietnamese Mekong Delta (VMD). Many studies have found increases in downstream flood damage, salinity intrusion, and riverbank erosion and reduced flows of fertile sediment. This has been attributed to hydropower dam development upstream in the Mekong River, river diversion for irrigation, land subsidence, climate change and sea level rise (Hung, 2012; Kingdom of the Netherlands and The Socialist Republic of Vietnam, 2013; Hung et al., 2014a; Manh et al., 2014, 2015; Hoang et al., 2016; Dung et al., 2018c). These problems have been exacerbated by extensive construction of high dikes to enable triple rice production on the floodplains. Infrastructure such as the dense system of dikes and dams built since the 1990s, alongside the growth of built-up areas, moreover, restricts the space available for floodplain restoration on the VMD (Cosslett and Cosslett, 2014). Environmental degradation is a real risk on the floodplains, which before dike construction functioned as a natural water storage area, mitigating flood damage and providing ecosystem services for a biologically productive and ecologically diverse region (Xuan and Matsui, 1998). To address the current problems and safeguard the delta, effective water management strategies are needed (Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013).

A number of studies have assessed the impacts of upstream hydropower dam development, river diversion for irrigation and climate change on VMD water regimes (e.g., Fredrik, 2011; Hung, 2012; Lauri et al., 2012; Lu et al., 2014; Manh et al., 2014; Richard and Tran, 2014; Hoang et al., 2016). While the upstream impacts have been relatively well covered, the social and economic impacts of delta development processes remain poorly understood. Duong et al. (2014), Dang et al. (2016), Triet et al. (2017) and Dung et al. (2018c) looked at the implications of dike construction for floodwater regimes, but they focused on hydraulic dynamics without considering social and economic influences. Some authors have considered the economic effects of dike construction, but focused on specific locations (see Howie, 2011; Kien, 2014; Dan, 2015). Delta-wide assessments have also been limited by lack of suitable methodologies and data constraints. As a result, externalities visible only at the delta level remain un-quantified, despite their acknowledged importance. To our best knowledge, no study has yet quantified the internal effects (i.e., costs of dike construction and production systems) and external effects (e.g., increase in flood damage) of extensive development of high dikes for triple rice production in the study region. We fill this gap by quantitatively assessing the internal and external effects of three dike–agricultural system scenarios. We use an economic methodology to test our hypothesis that the cost of high-dike construction is greater than the benefits on the delta scale, largely because development of such dikes reduces delta sustainability.

Accelerated high-dike construction for triple rice production has already widely impacted the VMD. Understanding the economic cost of dike-related internalities and externalities is essential not only for formulating effective water management strategies, but also for supporting decision-makers in planning for a prosperous and sustainable delta, as recommended in the Mekong Delta Plan (Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013). In a continuation of our previous work on the costs and benefits of flood protection and agricultural system alternatives at the farm level (Dung et al., 2018a, 2018b), the current study assesses sustainability at the delta level. Our aim was to use cost-benefit analysis to systematically quantify the internal and external impacts of several dike–agricultural system scenarios for the VMD.

5.2. Study area

The VMD spans 45,000 km^2, of which some 39,400 km^2 is in Vietnam. Located in the southernmost part of the river basin, the VMD encompasses 13 provinces and major cities and is home to 18 million inhabitants (Figure 5.1). In our study we divided the VMD into two parts, following the Mekong Delta Plan (Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013): the so-called upstream delta floodplains and the downstream delta, which includes the central and coastal zones.

The VMD plays an important role in the socioeconomic development of the nation. It is considered a strategic region for agriculture. Farming on the VMD contributes 51% of the rice produced nationally and 70% of the country's rice exports. Thanks to its productivity, Vietnam is one of the world's primary rice-exporting nations (Kakonen, 2008). In addition to rice, the delta contributes 65% of Vietnam's aquaculture production and 70% of its fruit production. Since 2005, rice production on the VMD has surpassed 20 million tons per year, and rice exports have reached 8 million tons annually (Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013).

The Long Xuyen Quadrangle (LXQ) and Plain of Reeds (PoR) are the VMD's two primary floodplains (see Figure 5.1). The World Bank (2016) described these floodplains as natural sponges that regulate delta floodwaters by absorbing excess water in the flood season (annually from July/August to November/December) and releasing water back into the main streams in the dry season. However, as noted, areas of double and triple rice production under low and high-dike protection have greatly expanded across these floodplains in the last two decades. This has halved the floodwater retention capacity of the LXQ compared to 2000 (Dung et al., 2018c). Both low dikes and high dikes are found on the floodplains. Low dikes hold back floodwaters long enough to allow production of two rice crops annually, whereas high dikes block floodwaters completely, allowing three three-month rice crops per year (Dung and Jacob, 2017).

Large-scale construction of high dikes, however, poses multiple risks to the delta. In this study, we considered four such risks, all directly related to the floodplains' reduced water retention capacity. The first risk is downstream flooding (Dung et al., 2018c; Triet et al., 2017). The second is reduced flows of fertile sediment across the delta, especially in the LXQ, due to the absence of dynamic interaction between rivers and floodplains during the flood season (Hung et al., 2014a, 2014b; Manh et al., 2015). The third risk is salinity intrusion in the dry season. Though mainly caused by sea level rise and land subsidence, salinity intrusion could be mitigated by the release of water retained within the floodplains (Smajgl et al., 2015; Hoang et al., 2016). The fourth risk is riverbank erosion due to sudden increases in river flows. Such surges have been linked to reduced water retention capacity of the floodplains, as well as to sediment retention by dams, large-scale sand mining in rivers and channels and land subsidence caused by groundwater extraction (Anthony et al., 2015).

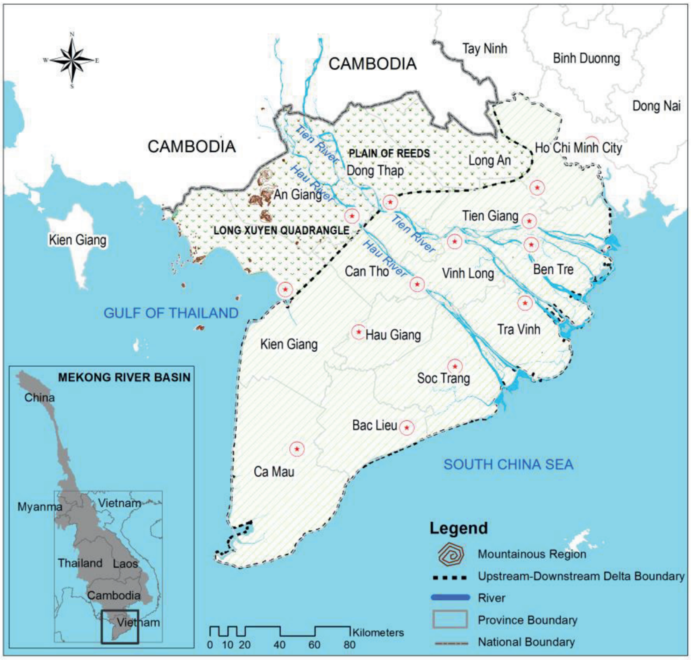


Figure 5.1 Vietnamese Mekong Delta with upstream and downstream boundary indicated.

5.3. Methodology

5.3.1. Assessment of the costs and benefits of dike–agricultural system scenarios

We conducted an integrated assessment of dike–agricultural system scenarios using cost-benefit calculations and hydraulic modeling. Three scenarios were assessed: the baseline, representing the dike system in 2011 (ED2011); full high-dike development in 2030 (HD2030); and full low-dike development in 2030 (LD2030). HD2030 can be considered the business-as-usual case, as it assumes continued expansion of high-dike agricultural systems, particularly for intensive triple rice monoculture and vegetable production. LD2030 represents an alternative development scheme, characterized by a transition toward use of low dikes and floodwater-friendly agriculture production, particularly double rice production and floating crops (e.g., floating rice, lotus, water mimosa and water lily).

For each scenario we calculated (1) investment requirements and operational costs; (2) production costs and revenues from agricultural systems; and (3) externalities. Costs and benefits were derived from a literature review, hydraulic modeling and field-level empirical data. Calculations were done for 1 ha units, then aggregated to the pan-delta level using Arc-GIS.

The sections below describe each step of the assessment.

5.3.2. Developing the scenarios

The baseline scenario represents the dike system of 2011. Flood protection and water management are accomplished with a mix of low and high dikes. The high-dike, triple rice production system is dominant in An Giang province, while the remaining of LXQ and the PoR remains relatively open water with low dikes or no flood protection infrastructure.

The remaining two scenarios represent alternative futures for the VMD in terms of flood protection and water management, and the corresponding agricultural production systems. We inferred these mainly from three sources: historic development trends (1990–2011), national and regional policy documents and development outlooks, and the development strategy presented in the Mekong Delta Plan (Table 5.1).

Table 5.1 Underlying rationales and specifications for future dike–agricultural system scenarios

Farming system	**Historic development trends**	**National and regional development policy**	**Mekong Delta Plan**	**HD2030 specification scenario**	**LD2030 specification scenario**
Triple rice production Flood prevention using high dikes	Shift to triple rice production starting in 1986 (Cosslett and Cosslett, 2014; Xuan and Matsui, 1998; Xuan, 1975)	National food security becomes priority, to be accomplished through triple rice production from economic reform policy in 1986	Enhance flood retention capacity of the floodplains of the Long Xuyen Quadrangle and Plain of Reeds	Convert 464,127 ha of low dikes into high dikes, for a total of 763,089 ha high-dike area	Convert 298,962 ha of high dikes into low dikes
Double production crop with flood-based farming systems and a diversified agricultural portfolio Controlled flooding using low dikes	Smallholder scale dynamics with farming systems freely developed by farmers (Xuan and Matsui, 1998)	No national policy to develop this type of farming system, except several programs conducted by provinces on the floodplains	Single or double rice production alongside flood-based farming systems in the flood season for a sustainable delta	Convert 464,127 ha of low dikes into high dikes, for a total of 763,089 ha high-dike area	Convert 298,962 ha of high dikes into low dikes

In essence, HD2030 represents the current development trend; that is, gradual intensification and expansion of triple rice production by construction of high dikes for flood protection and water management. Under this scenario, high-dike construction spreads to the southwest and northeast. Thus, the natural floodplains of the upper Mekong Delta are increasingly converted to agricultural lands, especially for triple rice monoculture.

LD2030 considers an alternative; that is, a transformative change at the delta level in both flood risk management approach and in the intertwining agricultural production system.

There is a shift away from absolute flood prevention using high dikes. Preferred instead is controlled flooding, which seeks to effectively and safely contain floodwaters within the system by increasing floodplain water retention capacity, thereby reducing flood damage, especially for downstream areas (Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013). In practical terms, this latter option implies a backward transition from high dikes to low dikes and refraining from building new high dikes. VMD agricultural systems would change as well. Instead of a triple rice monoculture, double rice production would be combined with flood-resilient crops during the flood season. Examples of these latter are lotus (*Nelumbo nucifera*) and indigenous floating rice (*Oryza prosative*).

Figure 5.2 visualizes the three scenarios.

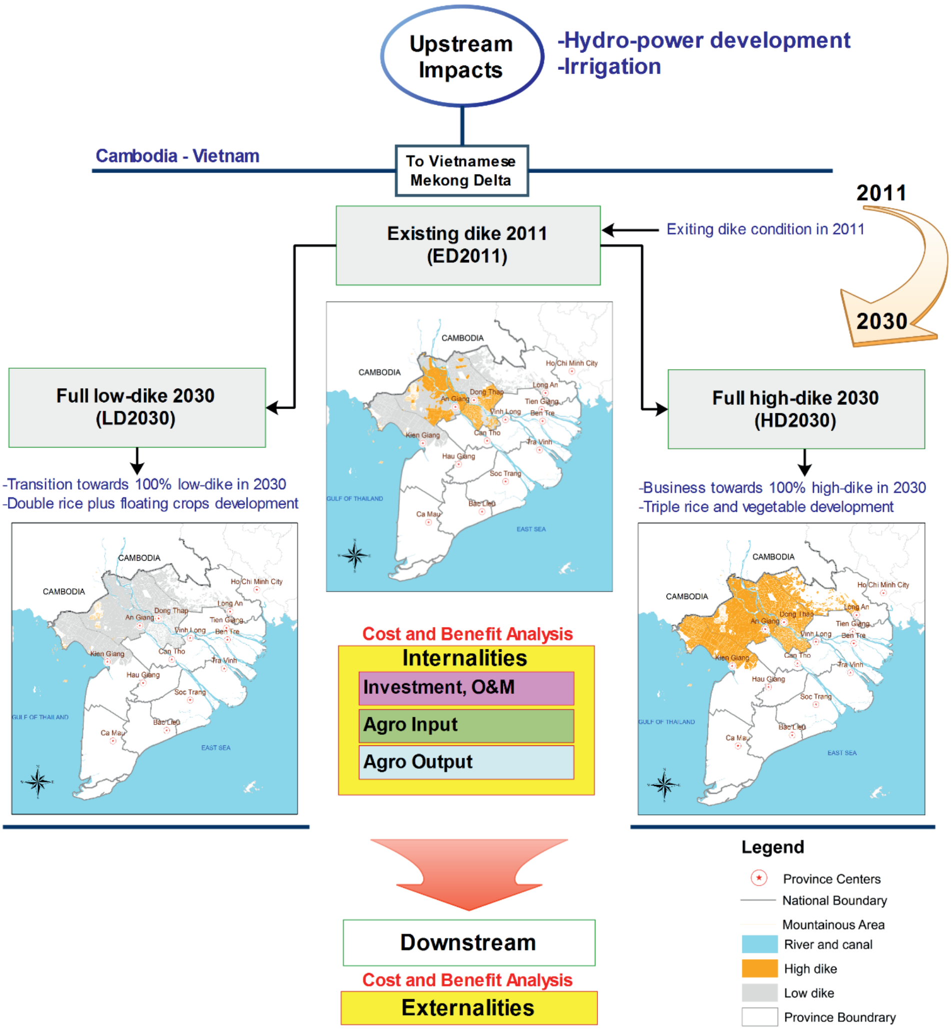


Figure 5.2 Approach to assess dike–agricultural system scenarios.

5.3.3. Calculating investment and operational costs of scenarios

We derived the investment requirements for low and high dikes from recent literature (Dan, 2015, 2015; Dung et al., 2018a; Kien, 2014). For operation and maintenance costs, we referred to Dan (2015). For each cost component, we calculated cross-study averages and used these values for our study. As our aim was to assess delta sustainability, we simplified the calculations of operation and maintenance costs by not taking into account annual discount rates for future scenarios, as the area of annual dike construction could not be quantified. Given that the investment and operational costs were relatively homogeneous across the VMD floodplains, we applied a single cost estimate for all locations on the delta (see Table D1 in the annex).

5.3.4. Calculating production costs and profit of agricultural systems

We computed the production costs and profit of agricultural systems based on typical locations as surveyed by Dung et al. (2018b). These served as proxies for the whole VMD. In particular, costs and profit were estimated for eight main agricultural systems in 117 sampled households at seven locations in An Giang and Dong Thap provinces for the three years from 2014 to 2016.

For each agricultural system, production costs included fertilizer, pesticides, pumping costs and other. This final category being mainly land preparation, seed, planting, spraying, harvesting and transport costs. Farm revenues were estimated using farmers' reported crop yields and market prices, again for the three years from 2014 to 2016. Farm profit was then calculated as farm revenue minus production costs.

For double rice, production costs and revenues averaged, respectively, in the range of US $1,537–$1,713 and $3,070–$4,088. For triple rice, these figures were, respectively, $2,145–$3,352 and $4,123–$5,449. For vegetables, costs and revenues were referenced from calculations for chili and sesame plus floating crops. Table D3 in the supplementary reports these. For more detailed information on the calculation methods and results, see Dung et al. (2018a).

5.3.5. Estimating externalities

Externalities of land use and water management systems are often abundant and multifaceted (Peng et al., 2017). In this study we focused on externalities already observed on the VMD or deemed highly likely in recent impact assessments. In particular, for each scenario the following externalities were considered: changes in flood damage downstream; changes in salinity intrusion in the coastal zone; changes in suspended sediment carried by floodwaters; and changes in riverbank erosion.

Estimating direct monetary costs of externalities under the various scenarios was complicated by the fact that these externalities are not caused only by reduced floodwater retention capacity due to dike construction. Other factors are also at work, such as hydropower development and climate change (Table 5.2). After quantifying the externalities based on data from our studies and the literature, using simplified estimation methods, we assessed the association between these externalities and floodplain water retention capacity (Figure 5.3). For this we drew a proportional relationship between the dike construction area on the VMD floodplains and floodplain water retention capacity (Dung et al., 2018c). The methods used to quantify the externalities are presented below.

Table 5.2 Methodology to quantify externalities from dike–agricultural system scenarios using cost-benefit analysis

Externalities	Indicator	Source	Factors
Flood damage downstream	– Floodwater depth in rivers – Extent of flood >1m	Wijayanti et al. (2017) Dung et al. (2018c)	– Hydropower and irrigation system development upstream – Climate change and sea level rise – Land subsidence
Salinity intrusion	– Areas of increased coastal salinity under the three scenarios, converted into monetary losses from rice production and freshwater aquaculture	Kuiter (2014) Nhan et al. (2012) MARD (2016) Berg et al. (2017)	– Hydropower and irrigation development upstream – Climate change and sea level rise – Land subsidence
Sediment reduction	– Decrease in sediment deposition (intensity) – Increase in fertilizer use for rice production (cost)	Chapman and Darby (2016) Chapman et al. (2016) Hung et al. (2014a, 2014b) Manh et al. (2015) Dung et al. (2018a)	– Hydropower and irrigation development upstream
Riverbank erosion	– Increase in river velocity and discharge	Dung et al. (2018c)	– Hydropower and irrigation development upstream – Climate change and sea level rise – Sediment exploitation and sand mining

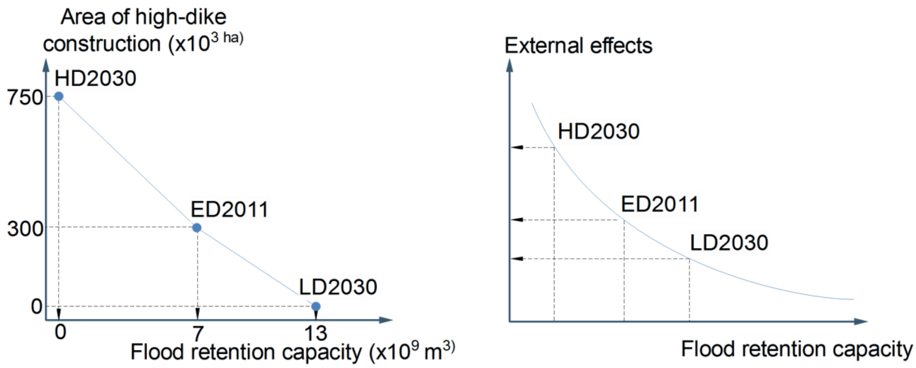


Figure 5.3 Relationship between dike construction area and floodwater retention capacity (left) and between external effects (flood damage downstream, sediment reduction, salinity intrusion, and river bank erosion) and floodwater retention capacity (right) under the three scenarios: ED2011 = baseline, or dike system as in 2011; HD2030 = full high-dike development in 2030; and LD2030 = full low-dike development in 2030.

Flood damage

Complex computational methods are typically used for flood damage assessment (Winsemius et al., 2013). We simplified these, following Wijayanti et al. (2017). Downstream flood damage was thus based on the spatial change in flooded area at various flood depths estimated under the three scenarios. A geographic information system (GIS) was used to interpolate the flooded area under each scenario, with maximum water level data as simulated by a one dimensional–quasi two dimensional (1D-quasi2D) hydraulic model. For model setup and method see Dung et al. (2018c). Results were presented in both tabular and map form.

Flood damage under the HD2030 and LD2030 scenarios was evaluated in relation to the baseline scenario, ED2011. As such, we assessed the impact of dike construction on the downstream flood damage by comparing the sizes of the downstream area flooded at different flood depths. We defined areas as exposed to flood damage only if a flood depth greater than 1 m was registered, as this is the depth at which aquaculture and flood-based agriculture are disrupted (Balica et al., 2014).

Economic costs of flooding were calculated using national statistics on losses in flooded areas in four years of extreme flooding: 2000, 2001, 2002 and 2011. We then estimated economic losses from flooding for the HD2030 and LD2030 scenarios based on the percentage increase or decrease in flooded area compared to available data for the baseline year of 2011.

Salinity intrusion

The VMD's two main rivers, the Tien and Hau, empty into the South China Sea. These rivers deliver large amounts floodwater to the floodplains via branches that can be diverted for irrigation and to flush away saltwater intrusion downstream in the dry season. Reduced flood retention capacity of the floodplains due to high-dike construction could diminish this flushing capacity, worsening salinity intrusion.

We estimated the cost of salinity intrusion using rice yield reductions in a number of production areas affected in the extreme drought year of 2016. For the affected rice production area, we referenced data from MARD (2016). For yield reductions in rice, which is a crop very sensitive to salinity, we referenced Nhan et al. (2012). We calculated the economic losses by multiplying the economic loss for 1 ha by the affected rice production area (ha). Of which, the 1-ha loss was computed by multiplying the average rate of rice yield reduction (%) with the net profit from 1 ha rice. The 1-ha rice profit was provided by Berg et al. (2017) in their study in Tien Giang, a coastal province of the VMD (presented in Table 5.5 in the Result section).

The reduction in rice yield is proportional to the salinity concentration (see Figure D1 in Supplementary D). The higher the salt concentration is, the lower yields will be. In the VMD, areas affected by salinity intrusion and salinity concentrations vary over the years. We mapped salinity intrusion using contour lines provided by the Southern Institute for Water Resources Research (SIWRR) for the year 2008 and for 1998, 2010, 2015 and 2016, and the means for these years, as provided by the Southern Institute for Water Resources Planning (SIWRP). The salinity data for 2008 were calibrated and verified by the SIWRR using hydraulic modeling with an advection-dispersion (AD) module, while those of SIWRP were drawn using observed data.

Sediment loss

Various studies have examined sediment load on the floodplains as well as across the VMD. For example, Hung et al. (2014a) measured fluvial sediment inside and outside dike compartments in Dong Thap Province. Manh et al. (2015) used hydraulic modeling to simulate sedimentation, attributing reduced sediment load to hydropower dams and hydraulic works upstream. Dung et al. (2018a) found that fertilizer use had to be increased in rice farming systems under high-dike protection compared to those in low-dike areas.

To estimate the cost of reduced sedimentation, we referred to Chapman et al. (2016). These authors conducted a household survey, interviewing 195 farmers in An Giang Province.

They computed the value of sediment using a set of components including the amount of fertilizer applied, the average cost of fertilizer, the cost efficiency gain per centimeter of sediment, the average depth of sediment, number of crops per year and area in production. The annual value loss was then found by subtracting the annual value of sediment in low-dike farming systems from that in high-dike farming systems. Using the annual value loss, we computed economic losses due to reduced sediment load in our three scenarios by multiplying the average 1 ha sediment loss (US$.year^{-1}) by the high-dike area (ha).

Riverbank erosion

Riverbank erosion is caused by human activities such as construction of upstream hydropower dams which change the flow of rivers and sand mining (Anthony et al., 2015). Riverbanks can also erode due to increased river discharges attributed to dike construction. We sought to quantify the impact of dike construction by analyzing changes in river discharge on the floodplains under the three scenarios. For this we used the same 1D-quasi2D hydraulic modeling simulations as applied in our flood damage estimates.

5.4. Results

5.4.1. Internal cost and revenue of scenarios

Compared to our baseline (ED2011), HD2030 with its greatly expanded high-dike area has the greatest dike construction cost (Table 5.3). LD2030 with its low dikes presents the lowest cost. Specifically, HD2030 implies a 136% greater investment and operational cost than ED2011 ($0.99×10^9$ versus $0.42×10^9$). Investment and operational cost is much lower for the LD2030 scenario ($0.05×10^9$). For the high dikes in general, investment and operational cost increases in proportion to the size of the high-dike area.

Regarding farm production, HD2030 generates the lowest profit from both rice and vegetable production, compared to ED2011 and LD2030. Specifically, the profit derived by converting all area to triple rice production, as in HD2030, is US $0.81×10^9$; profit from triple vegetable production is $3.54×10^9$. Both these estimates are lower than the profits calculated for ED2011 ($1.55×10^9$ for rice and $4.33×10^9$ for vegetables). The profit from LD2030 is greater than that for HD2030, as $2.02×10^9$ in profit can be gained from double rice production or $4.83×10^9$ from double vegetable production combined with a floating crop. The main reason why HD2030 returns such low profits lies in the increasing production costs of intensive farming systems over time (e.g., due to rising need for fertilizer and pesticides) leading to lower revenues compared to the other scenarios (see also Dung et al., 2018a).

For rice production, the total cost, including dike construction investment and operational costs and farming inputs, is highest for HD2030 (\$$4.34\times10^9$), compared to ED2011 (\$$2.50\times10^9$) and LD2030 (\$$1.32\times10^9$). We found the most costly agricultural system to be vegetables if the entire area is developed with low dikes, as in LD2030 (\$$10.38\times10^9$ compared to \$$7.95\times10^9$ and \$$1.32\times10^9$). However, the total net profit is still highest for this full low-dike scenario considering a double cropping cycle with vegetable production (\$$4.75\times10^9$). Remarkably, the total net profit of HD2030 is lowest for production of both triple rice (\$$-0.97\times10^9$) and vegetables (\$$1.76\times10^9$), compared to ED2011 (respectively, \$$0.8\times10^9$ and \$$3.57\times10^9$) and LD2030 (\$$1.93\times10^9$ and \$$4.75\times10^9$).

Table 5.3 Internal cost and revenue of dike–agricultural system scenarios.

Scenario	Crop	Protected area (ha)		Dike construction cost* (US 10^9) (a)			Farm production (US 10^9)			Total (US 10^9)	
		Low dike	High dike	Investment	Maintenance	Management	Cost (b)	Revenue	Profit	Cost (a+b)	Net profit
ED2011	Rice	464,127	298,962	0.42	0.22	0.11	1.75	3.30	1.55	2.50	0.80
	Vegetables						7.20	11.52	4.33	7.95	3.57
HD2030	Rice	0	763,089	0.99	0.52	0.28	2.56	3.37	0.81	4.34	−0.97
	Vegetables						2.39	5.93	3.54	4.17	1.76
LD2030	Rice	763,089	0	0.05	0.04	0	1.23	3.25	2.02	1.32	1.93
	Vegetables						10.29	15.13	4.83	10.38	4.75

Exchange rate in 2017: US $1=22,700 VND.

** Present value in 2012 (Dan, 2015).*

5.4.2. Externalities

Flood damage

Results from the hydraulic modeling indicate greater risk of downstream flooding if high dikes are built on a large scale up to 2030. Both area and depth of flooding increase under HD2030, but are generally reduced under LD2030, compared to ED2011, which represents the situation in 2011 (Figure 5.4, Table 5.4). More specifically, under HD2030, the area flooded to a depth of 1–2 m, 2–3 m and >3 m increases by, respectively, 8%, 3% and 8% compared to ED2011. In contrast, under LD2030, the area flooded to a depth of 1–2 m increases by 5%, but it decreases by 14% at the depths greater than 2 m, compared to ED2011.

Regarding economic losses due to flooding, under ED2011, losses due to flooding are $\$0.194\times10^9$. These increase by 19%, to $\$0.231\times10^9$, under the full high-dike development scenario, HD2030. Under LD2030, representing full implementation of low dikes, economic losses are reduced by 9%, to $\$0.177\times10^9$, compared to the baseline (Figure 5.5).

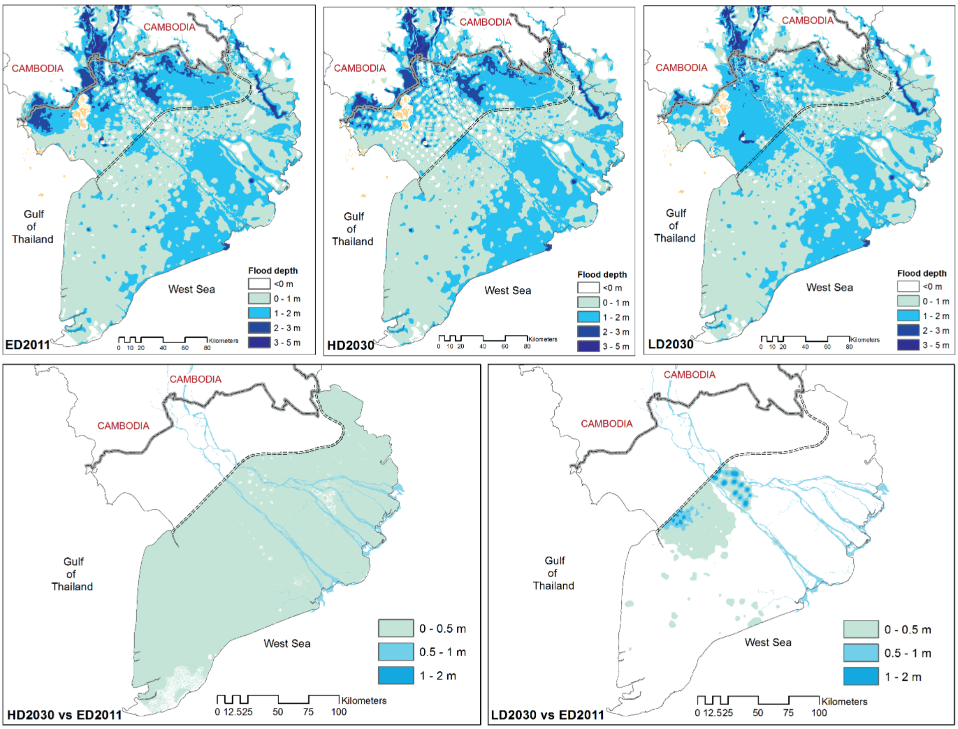


Figure 5.4 Maps of flood extent and depth downstream under three dike construction scenarios.

Table 5.4 Flood extent and depth under three dike construction scenarios

Water depth (m)	Flooded area (ha)			Differences (ha)		Difference (%)	
	ED2011 (1)	HD2030 (2)	LD2030 (3)	(2)–(1)	(3)–(1)	(2)–(1)	(3)–(1)
0–1	1,967,338	1,902,175	1,927,180	–65,163	–40,158	–3%	–2%
1–2	820,415	884,578	862,286	64,163	41,871	8%	5%
2–3	21,803	22,526	20,345	724	–1,458	3%	–7%
>3	3,682	3,958	3,426	277	–255	8%	–7%
Flood damage (>1 m)						19%	–9%

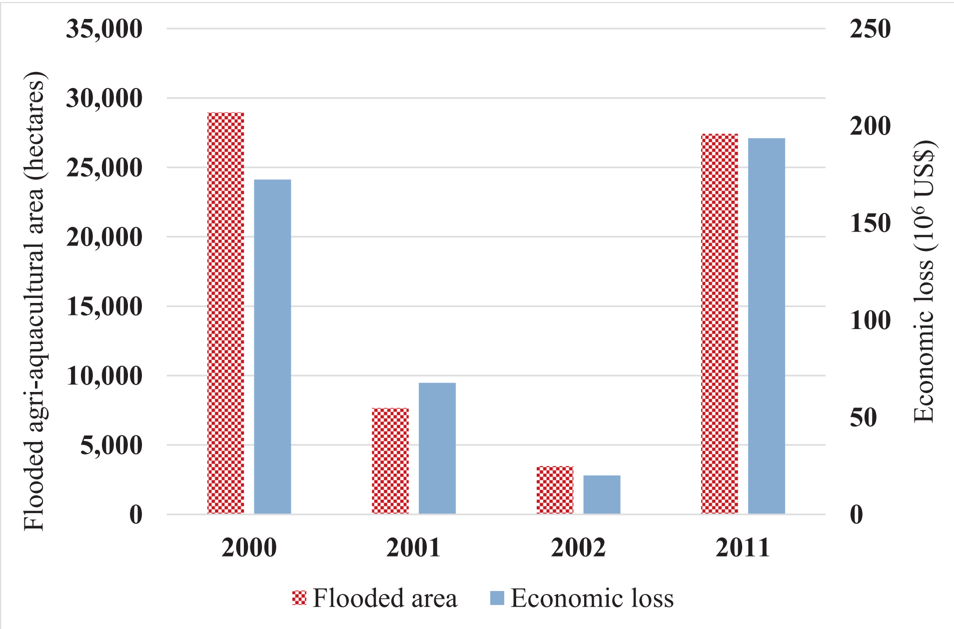


Figure 5.5 Economic losses to aquaculture and agriculture caused by flooding over the whole Vietnamese Mekong Delta

Salinity intrusion

We estimated economic losses due to salinity intrusion by its direct impact in reducing rice yields for the area affected (Table 5.5). Figure 5.6 maps areas affected by salinity intrusion. The baseline scenario, ED2011, presents a loss of \$0.148×10^9. The loss under HD2030 is 10% higher, due to increased salinity intrusion caused by reduced floodwater retention capacity of the floodplains (\$0.163×10^9). Under LD2030, losses due to salinity intrusion are 10% less than in the baseline scenario, that is, \$0.133×10^9 compared to \$0.148×10^9.

Table 5.5 Potential economic losses due to salinity intrusion for rice production in coastal areas.

No	Indicator	Function	Value	Source
1	Agricultural areas affected by saltwater intrusion in 2016 (ha)	A	224,479	MARD decision (2016)
2	Yield reduction (%)	B	50%*	Nhan et al. (2012)
3	Mean rice yield in Cai Be, Tien Giang Province (ton.ha^{-1}.crop^{-1})		7.6	Berg et al. (2017)
4	1 ha rice production cost in Cai Be, Tien Giang Province (10^6 VND.ha^{-1}.crop^{-1})	C	11.9	Berg et al. (2017)
5	1 ha profit from rice in Cai Be, Tien Giang Province (10^9 VND.ha^{-1}.crop^{-1})	D	0.036	Berg et al. (2017)
6	Economic loss estimated for 1 ha of rice affected by the 2016 salinity intrusion (10^9 VND.ha^{-1}.crop^{-1})	E=B×D	0.018	Calculation
7	Economic loss in delta rice production due to salinity intrusion in 2016 10^9 VND	F=E×A	4,007	Calculation
	US $\$10^9$		0. 148	Calculation

In 2017, US $1=22,700 VND

** This number is necessarily a mean estimate due to the varying dynamics of the coastal areas affected by salinity intrusion on the VMD (see also Figure 5.6). Figure D1 in Supplementary depicts a sensitive relationship between the paddy rice yields and salinity concentration. The authors took 50% as the average reduction rate of paddy rice yield, though the actual figure could be larger or smaller.*

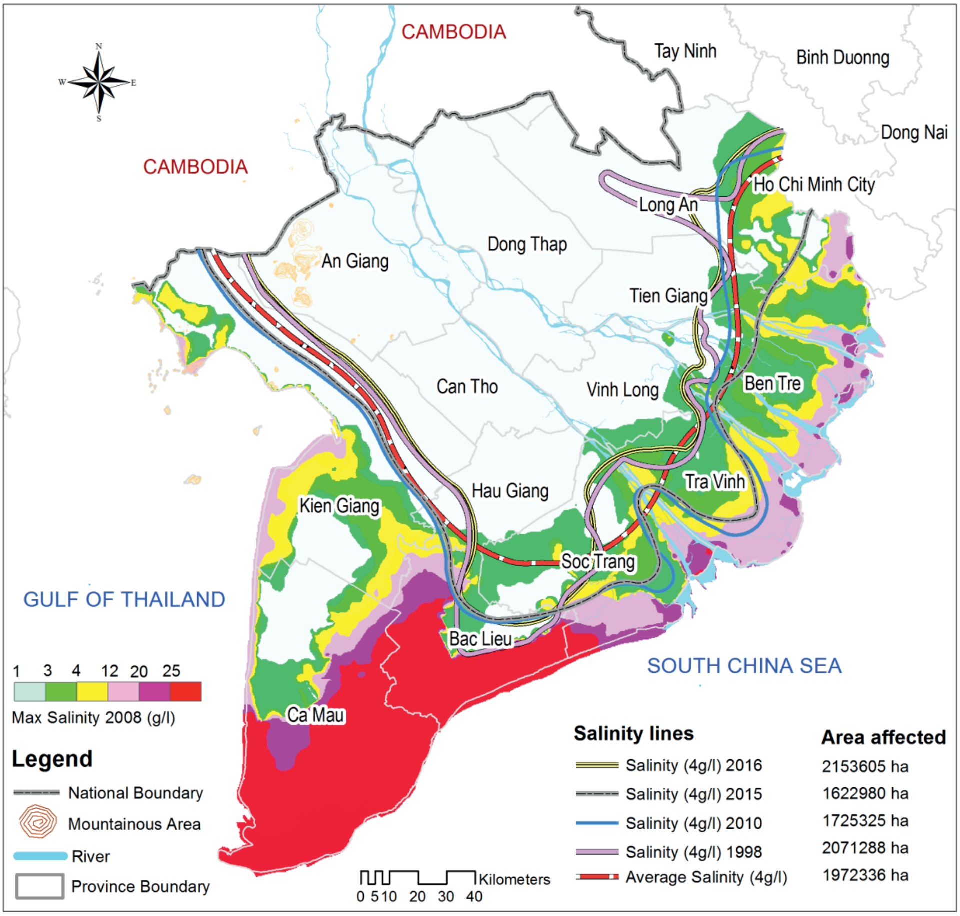


Figure 5.6 Coastal areas of the Vietnamese Mekong Delta affected by saltwater intrusion in the dry season of selected years. Data from SIWRP, map by authors.

Sediment loss

Diminished sediment load results in a potential economic loss of about US $110 for each hectare of agricultural land under high-dike protection (Table 5.6). Compared to the baseline scenario of ED2011, the economic loss due to reduced sedimentation increases by 155% under HD2030, from $\$0.033\times10^9$ to $\$0.084\times10^9$. Under LD2030, the low-dike scenario, this loss is reduced by 70%, from $\$0.033\times10^9$ to $\$0.010\times10^9$.

Table 5.6 Potential economic loss due to diminished sediment loss caused by high-dike construction

No	Indicator	Value	Source	Other potential causes
1	Amount of fertilizer used for rice production in low-dike area (kg.ha^{-1}.year^{-1})	900–1,100	Dung et al. (2018a)	Hydropower and irrigation development upstream
2	Fertilizer used for rice production in high-dike area (kg.ha^{-1}.year^{-1})	1,500–3,000	Dung et al. (2018a)	
3	Sediment deposited in low-dike area	Increase	Manh et al. (2015)	
4	Sediment deposited in high-dike area	Decrease	Manh et al. (2015)	
5	Annual sediment loss due to high dikes (135,755 ha) in An Giang Province (10^6 US$.year^{-1})	15 (±5)	Chapman et al. (2016)	
6	Average sediment loss per year from 1 ha high-dike area (US$.year^{-1})	110	Chapman et al. (2016)	

Riverbank and dike erosion

Compared to ED2011, the average discharge of delta rivers changes under HD2030 and LD2030 (Figure 5.7). HD2030 presents the greatest increase in river discharge, whereas river discharge decreases under LD2030.

The flood retention capacity of the floodplains is reduced under HD2030, raising floodwater discharge on the Plain of Reeds and most of the LXQ. In the Tien and Hau rivers, discharge increases by 0.1%–0.6%, rising also by 0.1%–64% in the rivers along the boundaries of the LXQ and Plain of Reeds floodplains. In some LXQ rivers, increases in flood discharge are caused by changes in floodwater distribution due to dike construction.

In contrast, under LD2030, flood discharge decreases in most rivers thanks to the restoration of the water retention capacity of the floodplains. Here discharges of the main rivers decrease by 1%–27%. In the rivers along the LXQ boundaries, flood discharges increase by 2%–326% due to greater floodwater volumes from the floodplains being released into the Gulf of Thailand.

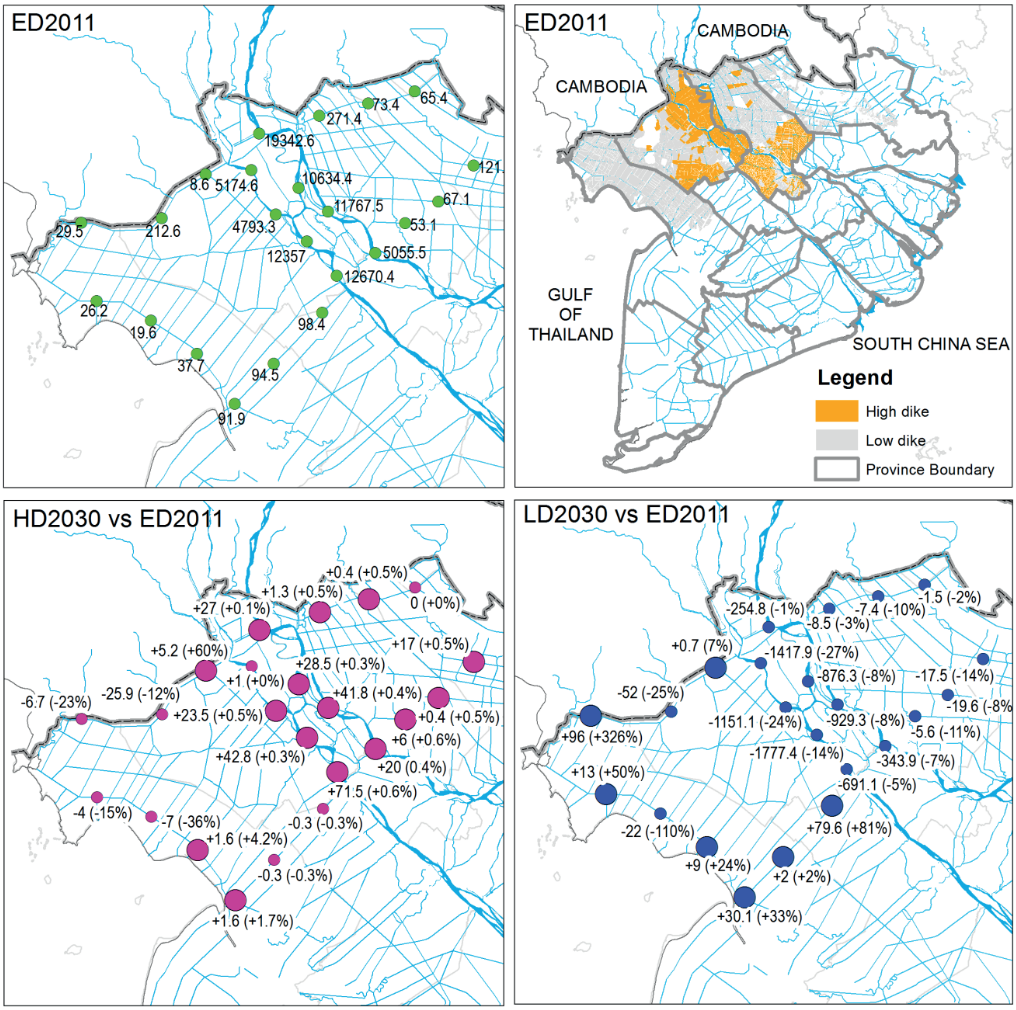


Figure 5.7 Changes in discharges ($m^3.s^{-1}$) as a potential cause of riverbank erosion under the three dike scenarios. Map by authors.

Table 5.7 Cumulative potential economic losses from externalities under the three dike construction scenarios.

Scenario	Cost (US $\$10^9$)				
	Flood damage downstream	Salinity intrusion*	Sediment loss	Riverbank erosion	Total
ED2011 (baseline)	0.194	0.148	0.033		**0.375**
HD2030	0.231 *(+19%)*	0.163 *(+10% to +20%)*	0.084 *(+155%)*	Increased risk	**0.478**
LD2030	0. 177 *(–9%)*	0.133 *(–10% to –20%)*	0.01 *(–70%)*	Decreased risk	**0.320**

In italics: % compared to the baseline, ED2011. *Sensitivity calculation.

5.5. Discussion

We implemented a systematic cost-benefit analysis of three VMD dike–agricultural system scenarios, demonstrating significant and differentiated hydrological and economic impacts for each. While considerable recent literature has been dedicated to assessing, and to some extent, quantifying costs and benefits of land use and water management interventions, our aim was to contribute a missing piece of the puzzle. That is, we sought to bring the delta-wide and multidimensional implications of interventions into focus. This section discusses our main findings and their implications for long-term delta management and sustainability. It then reflects on some limitations of the current study and recommendations for future research.

5.5.1. Main findings

First, we found that a land and water management strategy geared predominantly to flood prevention, as represented by the HD2030 scenario, is not economically and hydrologically feasible for the VMD in the long run. Our study found large-scale high-dike construction to be a costly option with dubious benefits in the long run. Upgrading the current situation to a full high-dike system was found to be 136% more costly than the baseline, 2011 dike system (US $\$0.99\times10^9$ versus $\$0.42\times10^9$). This is equivalent to 11% of the agricultural earnings from the whole VMD region in 2010 (SIWRP, 2012). In terms of farm production, HD2030 returns the lowest profit, and sometimes even resulted in losses, for both rice and vegetables, due to increasing production costs over time in addition to the considerable initial investment required for dike construction. Externalities are also prominent in the HD2030 scenario, with the potential to cause economic losses of $\$0.478\times10^9$, equivalent to -50% to 25% the net profit gained from intensified rice to vegetable production (see Tables 5.3 and 5.7). Other externalities that exact a high price under this scenario are the higher flood damage downstream and the reduction of natural sedimentation of the floodplains. All in all, these findings suggest a need to reconsider plans to expand high-dike development in the future.

Second, sediment load was the externality most affected in our scenarios (though with the smallest impact in absolute terms), compared to the other externalities considered (i.e., downstream flood damage, salinity intrusion and riverbank erosion). Multiple studies have found that hydropower development upstream on the Mekong River and expansion of high-dike agricultural systems have led to reduced sediment in delta floodwaters (Kummu and Varis, 2007; Hung, 2012; Hung et al., 2014b; Manh et al., 2014, 2015). Diminished inflows of fertile sediment with annual floodwaters reduces crop yields and productivity, which represents a substantial economic loss for the delta. Extensive construction of high dikes for intensive crop production thus seems certain to diminish farm incomes and the delta economy.

Lastly, our study found a close relationship between the reduced flood retention capacity of the VMD floodplains and large-scale high-dike construction for rice production. Though floodplain water retention capacity is key to mitigate flood damage downstream, and to reduce other unwanted externalities such as losses of sedimentation and mounting salinity intrusion, there is an increasing trend toward high-dike construction to enable triple rice production on the VMD floodplains (MARD, 2015). In recent decades, various countries have recognized floodwater control infrastructures as being at odds with sustainable development goals, for economic, social and environmental reasons. Multiple projects have been initiated to restore floodplains by replacing the concrete infrastructures built in years past with more environmentally appropriate systems (Vis et al., 2003; Temmerman et al., 2013; Van Staveren et al., 2014; Roth and Winnubst, 2014). This, again, suggests that in Vietnam construction of high dikes should be reconsidered in light of the current findings, particularly the high long-term costs demonstrated in the present study.

5.5.2. Implications for sustainable VMD management

Findings from this study are relevant for sustainable land and water management in the VMD in several ways. At the farm level, our calculated costs of salinity intrusion and sediment reduction (see Table 5.7) reveal the direct financial consequences of high-dike development for rice production. These externalities, which result in increasing production costs over time, suggest that intensive rice production on the VMD floodplains under high-dike protection is financially unfeasible and unsustainable in the long run. Indeed, farmers will likely need to increasingly use fertilizers to compensate for reduced sedimentation, while salinization, too, will likely increasingly affect rice yields. Future planning and development of rice production systems would do well to consider such costs, to ensure the longer term sustainability of farm earnings and delta livelihoods.

At the delta level, this study found that the flood retention capacity of the VMD has been rapidly reduced due to dike construction. Previous studies, such as Dung et al. (2018c) and Kingdom of the Netherlands and the Socialist Republic of Vietnam (2013), found that a large amount of water storage on the floodplains, especially in the LXQ, has already been lost due to dike construction. The present study furthermore identified an increased flood damage due to extensive dike construction. Based on these findings, we recommend careful conservation of the current floodwater retention capacity of the VMD floodplains, to avoid any further rise in flood damage downstream as well as consequences such as reduced sediment load, increased salinity intrusion and worsening riverbank erosion. We propose that dike construction, particularly construction of high dikes, be ceased in floodplain areas. Where high-dike construction is deemed necessary for protection of residents and built-up areas, the infrastructure should be designed to store at least the same amount of water as the floodwater naturally retained in that area, so as to maintain flood regimes within the regions as well as in the surrounding areas.

Our findings furthermore point to the advantages of an alternative dike–agricultural system approach; that is, controlled flooding, which uses low dikes and alternative farming systems. A transition from the current high-dike intensive production system to such low-dike systems could increase agricultural revenues by reducing the need for substantial direct investment and minimizing unwanted externalities, particularly flood damage, salinity intrusion and sedimentation losses. Our analyses indicate that such a transition (the LD2030 scenario) could reduce economic losses considerably: for flooding by 9%, for salinity intrusion by 15%, and for sediment reduction by 70%. Compared to the HD2030 scenario, the total losses due to externalities are reduced significantly under the LD2030 scenario (\$$0.478\times10^9$compared to \$$0.320\times10^9$). These indicative benefits from transforming land use and water management warrant initiation of experimentation and pilot projects at the farm and local levels, to pave the way for a large-scale transformation.

5.5.3. Limitations and ways forward

This study faced several limitations. The first regards the methodology used to assign monetary values to externalities. To estimate the economic costs of downstream flooding we used estimates of floodwater depth and area flooded as simulated by a hydraulic model, alongside available national data on economic losses. Though flood duration is considered a key indicator of flood damage in agriculture, our hydraulic model simulations were unstable when running scenarios at long time intervals. In addition, we estimated the cost of riverbank erosion based on flood discharge dynamics provided by modeling. Yet, the values derived by our study for the economic cost of large-scale delta-wide dike construction are subject to error due to data aggregation and price fluctuations over time. We therefore recommend more detailed analyses to improve estimates of dike construction and operation costs, for example, with better sampling of investment costs for different locations and different time periods.

Using our multidimensional economic assessment method, based on the literature and hydraulic modeling, we were able to quantify several cost and benefit components. However, this method raised some uncertainties as well. The largest of these regards our calculations for the 2030 scenarios. Specifically, these omitted annual interest and inflation rates from the yearly economic estimates of dike construction costs, with an average value used instead. In terms of cost and profit calculations for farm production, actual figures could be very different from our findings, if different areas of rice and vegetable production are realized. Moreover, our calculations of the economic impacts of flood damage and salinity intrusion could be affected by the reliability of the economic loss data provided in national statistics. In addition, extensive dike construction is a factor in two of our externalities, that is, flood damage downstream and sedimentation losses. Therefore the cost of these externalities can be expected to be related to dike construction area.

Finally, though this study sought to derive the delta-wide cost of dike–agricultural system scenarios, our method for scaling up from calculations per hectare to the whole VMD might mask interesting findings at the local level. Local-level assessments could thus add valuable details to these analyses and further verify and strengthen our findings.

5.6. Conclusions

This study presents a multidimensional assessment of two alternatives for land use and water management on the VMD. We assessed delta-wide costs and benefits of (1) continuing the long-established flood prevention approach by means of high-dike construction and (2) transitioning to a controlled-flooding system, which uses low dikes and flood-compatible agricultural systems. Our main conclusions are three:

First, large-scale high-dike development has indicated surpassed economic costs that are set to increasingly outstrip benefits over time. This is mainly due to very high externalities, a high initial investment cost and reduced revenue from the associated triple crop production system.

Second, a transition to a flood-tolerant water management approach would benefit VMD sustainability, both on the delta scale, as presented in this study, and at the farm level, as presented in Dung et al. (2018a, 2018b). Flood protection can be achieved by measures to increase the floodplains' water retention capacity. Such a strategy has benefits for common pool resources, while mitigating externalities. However, it requires a major shift from the current water management approach and the corresponding agricultural system. In essence, future delta management should refrain from high-dike construction, and pursue instead floodwater retention using low dikes and increased floodwater storage areas, while developing flood-resilient farming systems.

Third, the alternative delta management approach suggested here has important advantages over the existing approach, including lower investment costs, higher agricultural revenues and greater flood protection. Adapting the current delta management approach could therefore be highly promising for the long-term safety and sustainability of the VMD. This study can be construed as an initial attempt to assess the delta-wide costs and benefits of alternative management approaches. This is a complex topic requiring refined economic methods, which can be improved upon in future work.

CHAPTER 6

Synthesis

6.1. Introduction

The Vietnamese Mekong Delta, or VMD, was the central object of research in this thesis. The main aim of the research was to assess the implications of agricultural land-use dynamics on floodwater regimes and livelihoods on the delta, as extensive development of high dikes across the floodplains in recent decades has raised concerns about environmental and economic consequences and sustainability. Considering the many environmental, social and economic factors at work, both internal and external, I considered it essential to explore the merits of adaptation measures, in the form of alternative farming systems and land and water management strategies, alongside their potential to contribute to a sustainable delta.

Indeed, a growing body of research calls for new, softer approaches to land and water management. Specifically, these should be designed to improve the upstream floodwater storage capacity of the floodplains and to reduce the downstream flood risk in the long term. This study sought to contribute to this field of study by addressing two objectives:

1) to identify the hydrodynamic impacts of agricultural land-use dynamics on floodwater regimes on the delta, regional and local scale; and
2) to explore and analyze the potential of adaptation measures, in both farming systems and agricultural land use, to contribute to a sustainable delta.

Based on these research objectives, four research questions were explored in chapters 2 through 5. Chapter 2 evaluated changes in peak floodwater levels upstream and downstream on the delta, based on four dike construction scenarios, using a 1D-quasi2D hydrodynamic model. Floodwater distribution was also analyzed, with water balance calculations applied to trace where the floodwaters went under the different scenarios. Chapter 3 brought in the perspectives of farmers and experts on alternative flood-based farming systems using multi-criteria analysis with analytic hierarchy process and a sustainable livelihood perspective. In Chapter 4, cost-benefit analysis was used to identify farming system options that could maximize farm-level livelihood sustainability. Chapter 5 then further elaborated on the cost-benefit analysis on the delta scale. It assessed the internal and external consequences of three dike–agricultural system scenarios, exploring which appeared most suitable for the delta in the long term, from a sustainability perspective.

The current chapter reviews the main findings of the research (section 6.2). It then outlines the study's overall contributions to the literature (section 6.3). The methodological strengths and limitations are discussed (section 6.4), and finally, recommendations for future research are presented (section 6.5).

6.2. Main findings

6.2.1. The research questions answered

The main findings of this study are summarized in relation to the four research questions posed in the introduction. Question 1, addressed in chapter 2, was as follows: *How do agricultural land-use dynamics impact floodwater regimes across the delta?* Our analyses showed that extensive high dike construction on the Long Xuyen Quadrangle floodplain severely reduced the floodplain's floodwater storage capacity. Peak water levels have increased substantially, and floodwater distributions changed across the floodplain and upper delta. However, hydrodynamic impacts were found to be relatively small in the downstream regions, explained also by results from the water balance calculation indicated substantial loss of water outside the delta's floodplain. In addition, the impacts were found to be significant only over the period from 2000 to 2011, when the high-dike systems were being extensively built. However, this last result could have been a function of the modeling approach used, as this presented some limitations in simulating variability in water levels upstream and downstream.

Question 2, addressed in chapter 3, asked the following: *What alternative farming systems are assessed most favorably by stakeholders, adopting a sustainable livelihood perspective?* This research found that from a sustainable livelihood perspective, farmers and experts favored the alternative flood-based farming systems under low-dike protection over farming systems protected by high dikes. In contrast, most of the farmers who were interviewed indicated a preference for high-dike farming systems, mainly due to the advantage high dikes offered in protecting built up areas against flooding and the stability of the market for rice.

Question 3, addressed in chapter 4, was the following: *What is the profitability of alternative farming systems compared to intensive rice production according to environmental and economic analyses?* Our cost-benefit analyses indicate that profits from triple rice farming systems decreased over time within the high-dike areas due to progressively increasing production costs. Diversified farming systems within low-dike areas were found to be more advantageous than intensive rice monoculture systems, in both environmental and economic terms.

Lastly, question 4, addressed in chapter 5, asked the following: *What are sustainable agricultural land-use management strategies for the delta according to an economic assessment?* The findings indicate that the delta would be more sustainable with flood-based and low-dike farming systems due to the smaller monetary outlays required for low dike construction and maintenance, as well as the significant external social and environmental impacts of the high-dike systems, particularly triple rice production.

All in all, this study found significant hydrodynamic consequences of the extensive dike construction on the delta floodplains which has spurred rapid expansion of triple rice production. Additionally, the study demonstrated that alternatives are thinkable. Some of these alternatives were found to be more profitable and more sustainable in the long term. Below, we reflect on the main study findings in relation to the two research objectives.

6.2.2. Research objective 1

The first research objective was to identify the hydrodynamic impacts of agricultural land-use dynamics on flood regimes on the delta, regional and local scale. Chapter 2 demonstrated substantial changes in peak floodwater levels upstream on the delta and on the delta floodplains. These changes could be attributed to the impacts of dike construction and the associated agricultural land uses. The modeling results showed the largest hydrodynamic impacts from high dike construction to be in the upper delta from 2000 to 2011. During this period multitudes of high-dike cultivation compartments were built on the Long Xuyen Quadrangle floodplain. However, impacts of further large-scale high dike construction from the baseline year of 2011 were found to be minor. This means that construction of high dikes in the period prior to 2011 already reduced interactions between the region's floodplains and its main rivers, to the extent of changing floodwater regimes across the delta and raising the flood risk downstream.

Rapid expansion of the high-dike areas in the 2000-2011 period severely reduced the flood retention capacity of the floodplains. Thus, dike construction produced radical changes in the water balance and flow distribution by reducing the volumes of floodwater reaching the Long Xuyen Quadrangle. Water balance calculations for four dike construction scenarios indicate that reduction of floodwater inflows to the Quadrangle were higher than the loss retention volume due to dike construction. My study, further, explicitly mapped floodwater flows under the different dike construction scenarios, finding that flood volumes varied considerably between the scenarios.

Whereas dike expansion substantially affected floodwater levels and distributions in the upper delta, impacts were much less marked in the downstream regions. Though the model results indicate relatively small impacts on floodwater regimes downstream, the flood risk downstream may nonetheless be found to have increased if the multiple driving forces at work and their interactions are considered, including not least, climate change and development of hydropower dams upstream in the Mekong River.

6.2.3. Research objective 2

The second research objective was to explore and analyze the potential of adaptation measures, in both farming systems and agricultural land uses, to contribute to a sustainable delta This study explored and assessed adaptation measures across spatial and temporal scales to determine land and water management strategies that could lead to a sustainable VMD. Chapters 3 through 5 presented the results of multi-criteria analysis and cost-benefit analysis. These highlighted the benefits of flood-based adaptation measures. Thus, alternative farming systems and agricultural land uses that exploit the benefits of flooding, rather than seeking to prevent flooding, were found to be most advantageous in the long term. Flood-based adaptation measures increased the flood retention capacity of the floodplains and made the most of the benefits of the floodwaters.

Results of multi-criteria analysis, presented in chapter 3, indicated that rice farmers were most concerned about the environmental degradation associated with triple rice production in high-dike farming systems, above other livelihood and floodwater management issues. Their concern for the environment even outweighed that expressed by the experts. Rice farmers observed that the detrimental effects of soil and water degradation on their livelihoods and income had increased over time in the triple rice production system. They thus felt that production of triple rice posed a threat to the sustainability of their livelihoods in the long term.

Using a sustainable livelihood perspective to assess alternative farming systems, both farmers and experts indicated a strong preference for flood-based alternatives and diversification to higher value crops, away from rice with its lower economic returns. Stakeholders demonstrated appreciation of the advantages of floodwaters and of the need for farming systems that balance environmental, social and economic factors. In contrast, intensive rice farming systems under high-dike protection were considered unsustainable, due to their low profitability and the environmental degradation they caused. However, a clear challenge was to transfer the benefits of the stable market for rice and the flood protection provided by the high dikes to life and homestead to more diversified, flood-based livelihood systems. This was foremost in the minds of many of the farmers interviewed, as reflected in the preference they expressed for the high-dike farming systems, based on the interview results.

Applying cost-benefit analysis at the local level, chapter 4 found a declining profitability of triple rice production over the years, during which time land and water degradation rose due to the increased need for fertilizer and pesticides in this farming system. These results imply that continuation of national policies promoting maximum rice production on the floodplains should be reconsidered. Recommended alternatives to intensive rice monocrop farming systems are more varied low dike, flood-based farming systems, as these latter bring not only economic benefits, but are environmentally advantageous as well. Additionally promising are alternative farming systems that entail diversification into higher value crops and exploitation of the advantages of the natural flooding regime. However, as earlier noted, flood-based farming systems must be developed in such a way that adequate flood protection is provided to ensure residential safety. Furthermore, access to stable markets for agricultural products is a key consideration among most high-dike farmers.

Applying cost-benefit analysis on the delta scale, chapter 5 concluded that the costs of large-scale high dike construction would surpass the benefits over time. High externalities, large investment requirements and falling revenues were found to be associated with the triple rice production system. In sum, my findings indicate that flood-tolerant management approaches have the highest potential to achieve a sustainable delta, increasing floodplains' water retention capacity and offering benefits in the form of common pool resources. Flood-tolerant management was also found to reduce negative externalities, such as greater flood damage downstream, interruption of sediment inflows, salinity intrusion and riverbank erosion.

6.3. Methodological strengths and limitations

6.3.1. Combination of modeling techniques with social assessment tools

A major strength of this research was its combination of modeling techniques with the use of social assessment tools to explore the implications of dike construction on floodwater regimes and livelihood sustainability on the delta. The social assessment analyses entailed qualitative and quantitative elements, among others, interviews with farmers and experts and focus group discussions, using multi-criteria analysis and cost-benefit analysis and addressing a range of spatial and temporal scales.

6.3.2. Scenario-based modeling of floodwater dynamics

A specific strength of this study regards the 1D-quasi2D hydrodynamic model applied to assess the changes in floodwater regimes and flow volumes under multiple dike construction scenarios. To simulate the effects of dike construction on the floodplains, a quasi2D approach had to be embedded into the 1D models, as these latter neglected key spatial variability features of floodplain hydraulics and oversimplified floodplain flows. After model calibration and validation returned good performance, the model was used to simulate peak water levels under various dike construction scenarios, reflecting different agricultural land-use dynamics. While many previous studies have focused on the impacts of historical dike development (Duong et al., 2014b; Hoa et al., 2007; V. P. D. Tri et al., 2012b), this is one of the first studies to assess the possible impacts of future dike development on the Mekong Delta.

The modeling analyses, however, could not shed light explicitly on where the floodwaters went under the different scenarios. The addition of water balance calculations provided a better understanding of the mechanisms underlying the changes in flood dynamics due to dike construction. This study thus presented an advanced modeling approach for assessing the impacts of land-use dynamics across spatial scales (local, regional and delta) and temporal dimensions (the 2000, 2011, 2013 floods and the land-use scenario of 2030).

A limitation of the study was the performance of the model in simulating the floodwater regimes downstream in the delta. The limited variability found in water levels downstream may have been caused by uncertainty in the model, the use of downstream data from the coastal areas of the delta for model calibration and validation, and other decisions made during the calibration process. Regarding the spatial distribution of floodwater volumes, too, the model results could have been influenced by the way the model was calibrated. The hydrodynamic modeling approach applied could also have influenced the accuracy of flood simulation and water balance equations. Two-dimensional and three-dimensional hydrodynamic models (2D and 3D) may be better than quasi2D modeling for simulating flood dynamics on a complex floodplain. Nonetheless, at present 2D and 3D approaches are difficult to apply in an area as large as the Mekong Delta, due to the detailed data and large computational capacity required (Soumendra et al., 2010; Dung et al., 2011).

6.3.3. Multidisciplinary method for evaluating adaptation measures

This study developed and applied a multidisciplinary method, including both qualitative and quantitative elements, to explore and evaluate adaptation measures to maximize VMD sustainability. First, alternative farming systems were investigated using qualitative assessments with multi-criteria analysis. Thus, chapter 3 presented the perceptions of farmers and experts on various farming systems from a sustainable livelihood perspective. Chapter 4 added an economic and environmental assessment of these alternatives at the local level, after which chapter 5 scaled up the assessment to the delta level. Additionally, modeling aspects presented in chapter 2 were embedded in the analyses conducted in chapter 5. These served, for example, to quantify the hydraulic impacts of the different dike scenarios, to obtain their economic costs. Without this combination of steps, the research questions could not have been answered adequately. This research thus presented a coherent and logical story based on a combined methodology, with clear links between the elements. All in all, the combination of modeling with social assessment tools represents a major strength of the research. Indeed, Wada et al. (2017) underlined the advantages of incorporating socio-economic assessment into hydrological modeling and suggested this as a promising line of future research.

A multidisciplinary method was used to assess adaptation measures across spatial and temporal scales considering three dimensions of sustainability: hydro-environmental, social and economic. This approach yielded a conceptual framework suitable for addressing similar problems in different social contexts and economic sectors. In chapter 2, modeling was used to evaluate changes in peak floodwater levels across the delta under different dike construction scenarios and over a period of time extending from 2000 to 2013. In chapter 5, the hydrodynamic impacts were assessed for a 2030 land-use planning scenario, to estimate the costs associated with that scenario. In chapters 3 and 4, farming systems and alternatives were economically and environmentally evaluated on different spatial scales over time, based on the views of farmers and experts. In sum, the multidisciplinary method applied, including the three assessment dimensions, proved a major asset in answering the research questions.

My study used multidimensional economic assessment to quantify several cost and benefit components of internalities and externalities of dike construction (chapter 5). An estimate of the economic costs and benefits associated with external and internal factors at the delta level was derived by combining a literature review with findings from farm-level cost-benefit analyses. This method presented some limitations however. The economic data had to be simplified (e.g., discount rate and inflation rate) due to the socio-economic complexity of future dike–agricultural system scenarios. Although great effort was put into estimating the delta-wide cost of the different scenarios, the method used to scale up the calculations from units per hectare to the whole Mekong Delta might have masked interesting findings at the local level (see chapters 3 and 4). Though the findings were clear, the assessment nonetheless represents a simplification of the complex social context of the VMD.

6.4. Scientific contributions

6.4.1. Contributions regarding the multidisciplinary methodology

My study used a multidisciplinary methodology to assess the impacts of agricultural land-use dynamics and adaptation measures across spatial and temporal scales, considering three assessment dimensions: hydro-environmental, social and economic. Integration of different approaches helped to answer the research questions, representing a procedure typical of research addressing complex social problems and assessing multiple impacts of a natural phenomenon while exploring adaptation measures. The findings from my study should therefore help others tackle similar issues in the future, while also helping Vietnam choose priority actions on the issues examined.

This study builds on and expands the scientific literature concerning floodwater management on delta floodplains. The study advances the debate on whether existing strategies, often featuring development of hard infrastructure for land and floodwater management, are sustainable for a delta as a whole. In view of the repercussions of the extensive dike construction scenario associated with agricultural intensification, new strategies are clearly needed, offering sustainable adaptation measures for the delta system. Chapters 2 through 5 demonstrated many negative impacts of the existing land and floodwater management strategy, from the local to the delta level. A recommended alternative is more flood-friendly farming systems with low-dike protection where needed, to exploit the benefits of floodwaters and retain floodwaters on the delta floodplains.

The methodology and conceptual framework used in the current study could be adapted for use on other deltas, such as in Bangladesh and Myanmar, as these face similar problems of agricultural intensification, especially on floodplains. With different cultures, socio-economic developments as well as physical conditions, the studies could be comparative based on the findings from the same methodology and conceptual framework applied. In addition, the conceptual framework, based on assessment of adaption measures considering the three dimensions of sustainability (hydro-environmental, social and economic) could be applied to assess adaptation measures in other fields. Clearly, this study in itself will thus contribute to comparative research in the future.

Application in the current research of the three-dimensional method across both spatial and temporal scales also constitutes a comprehensively referenced addition to this research tradition. Our application to the assessment over time and scale is yielding important insights. Over the temporal scale, the economic costs-benefits and environmental impacts of rice intensification were assessed since environmental degradation is a slow progressive process that affects cost benefits at farm level over time. This research on the assessment of different dike conversion periods has been instrumental in this regard. Over the spatial scale, water balance were assessed across scales to explain where the floodwater goes. This is also crucial to understand how the 1D-quasi2D modeling approach can return stable water flows in changing conditions by diverting water elsewhere. Cost and benefit were spatially evaluated from farm to delta scales, as local benefits may be off-set by external costs and impacts at the delta level. These are difficult to assess, but provide a scientific insight in delta-scale dynamics and perspectives, and my research indicates that these should be accounted for in delta policies.

The study contributes to the scientific knowledge base developed for the Mekong Delta Plan (2013). In that plan, Dutch experts proposed four scenarios for development of a safe, prosperous and sustainable delta. The overall strategy recommended is the use of no-regret measures and prioritization of short-term and long-term interventions for three delta regions: the Upper Delta, the Middle Delta and the Coastal Zone. However, the general measures recommended have not been expanded with, for example, case studies involving community perspectives. The research presented here explored adaptive measures for the Upper Delta, thus contributing case study-based knowledge to actions proposed within the Mekong Delta Plan. In particular, my findings provide a reference for the strategy, "coping with increased seasonal fluvial floods and enhancing the water retention capacity through adapted land and water use" recommended by Mekong Delta Plan for the upper floodplains. In the most promising scenario for a sustainable delta, so-called "agro-based industrialization" proposed by the Dutch experts, land-use policies are to be implemented that enhance seasonal flood-based agriculture within the floodplains. This is in line with my study's findings.

6.4.2. Contributions regarding the conceptual framework

From a hydrodynamic perspective, this research contributes valuable knowledge on the hydrodynamic impacts of land-use changes associated with extensive construction of high dikes on the floodplains of a major delta. These impacts have been a topic of debate in recent decades. My findings shed light explicitly on where floodwaters go under the influence of land-use changes, based on water balance calculations. Furthermore, the limitations of 1D-quasi2D modeling in simulating floodwater dynamics were explored and a recommendation was made to develop a 2D or 3D hydrodynamic model for the delta.

From a social perspective, my research helps people, especially decision makers and scientists, to better understand farmer perspectives on their livelihood systems and on various flood protection scenarios, both low dike and high dike. My research also explored alternative farming systems and assessed these based on the views expressed by farmers and experts, using a sustainable livelihood perspective. Additionally, the environmental implications of various farming systems were presented, alongside the impacts of these on farmers' livelihoods in the long term.

From an economic perspective, the research showed that triple rice is not profitable over the long term and that it results in unsustainable livelihoods for rice farmers. Moreover, various scenario-based land-use development strategies were evaluated using cost-benefit analysis at the delta level. These economic evaluations will be useful for scientists and decision makers seeking strategies for sustainable development of the delta in the long term.

6.5. Future outlook

6.5.1. Inclusion of additional factors and developments

The current research raised some issues and questions to be addressed in future work. First, climate change has a major impact on the floodwater regime of the VMD. This study initially considered including the effects of climate change, but this proved onerous. In addition, VMD floodwater regimes are strongly influenced by the development of hydropower dams upstream. This factor, though excluded from the current research, cannot be disregarded as an important element affecting the socio-economic development of the delta. These exclusions were due to the complexity they imposed. Introducing these factors in the hydrodynamic modeling would have rendered the study unfeasible and led to high uncertainties in the 1D-quasi2D simulations of flood risk downstream. The focus of the current research was, ultimately, to explore and assess adaptation measures under the impact of extensive dike construction, particularly impacts on floodwater regimes and livelihoods. Future research could seek ways to combine the abovementioned factors, that is, hydropower development and climate change, in modeling with the intensive dike construction scenarios and use of social assessment methods, to assess their cumulative impacts.

In many farming systems, low dike and high dike, farmers' livelihoods are being rendered unsustainable by the impacts of agricultural intensification facilitated by hard measures for flood protection. This study explored and assessed adaptation measures to cope with these impacts. The assessments focused on three dimensions, based on the conceptual framework presented. This same conceptual framework could be applied to other deltas where intensive agriculture has been developed. In addition, evaluating socio-economic impacts (chapter 5) is very complex and sensitive in practice, though it was simplified in this research. Future research could elaborate on issues facing individual farms and farmers.

6.5.2. Further applications of the conceptual framework

From a hydrodynamic perspective, the results of the 1D-quasi2D hydrodynamic model could be improved upon by using 2D or 3D models to represent the complex interactions between the floodplains and the whole river system. With the 1D-quasi2D method, the accuracy of the representation of some of the interactions may still be questioned. Currently, it is very difficult to pursue 2D and 3D modeling for the whole Mekong Delta due to limited availability of data and high computational demands. In addition, monitoring data are needed for model calibration, especially for the West and East Sea.

From a social perspective, further studies could survey the surrounding provinces of Dong Thap, Kien Giang and Can Tho on the floodplains of the Long Xuyen Quadrangle and Plain of Reeds. In this research, farmer interviews and focus groups were conducted in only one floodplain province (An Giang) and a commune in Dong Thap Province. Expansion of the study area would provide data to compare with the findings of the current research, to confirm the reliability of the findings and support their use by decision makers and scientists. Similarly, water and soil quality data could be measured in both low-dike and high-dike areas over a long time period to test my study's findings.

From an economic perspective, the assessment of land-use strategies (chapter 5) could be expanded upon using new methods to quantify the externalities and detailed estimations of monetary terms. New methods would enable a more accurate evaluation of the costs and benefits associated with each external factor affected by high dike construction. Those factors addressed in the current study were changes in flood damage downstream, sediment load, salinity intrusion and riverbank erosion. More detailed evaluations of such external factors would yield a more reliable and comprehensive assessment.

Supplementary information A

The 1D-quasi2D modelled river network

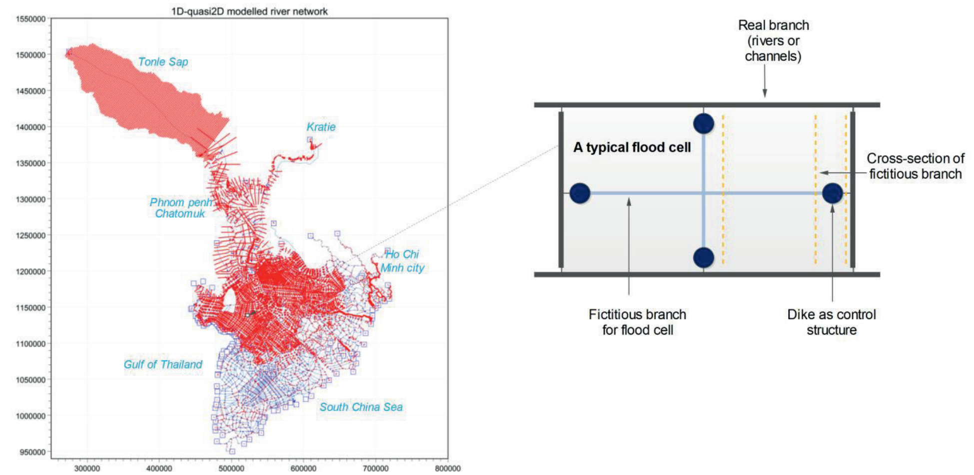


Figure A1 The left figure describes the 1D-quasi2D modelled river network of the VMD and the right figure shows a representative typical floodplain compartment. The approach is from Dung et al. (2011).

Reference

Dung, N.V., Merz, B., BĂ¡rdossy, A., Thang, T.D., Apel, H., 2011. Multi-objective automatic calibration of hydrodynamic models utilizing inundation maps and gauge data. Hydrology and Earth System Sciences 15, 1339-1354. https://doi.org/10.5194/hess-15-1339-2011.

Graphs of correlation and Nash–Sutcliffe efficiency 2011 and Time series of daily simulated and observed flows in 2013

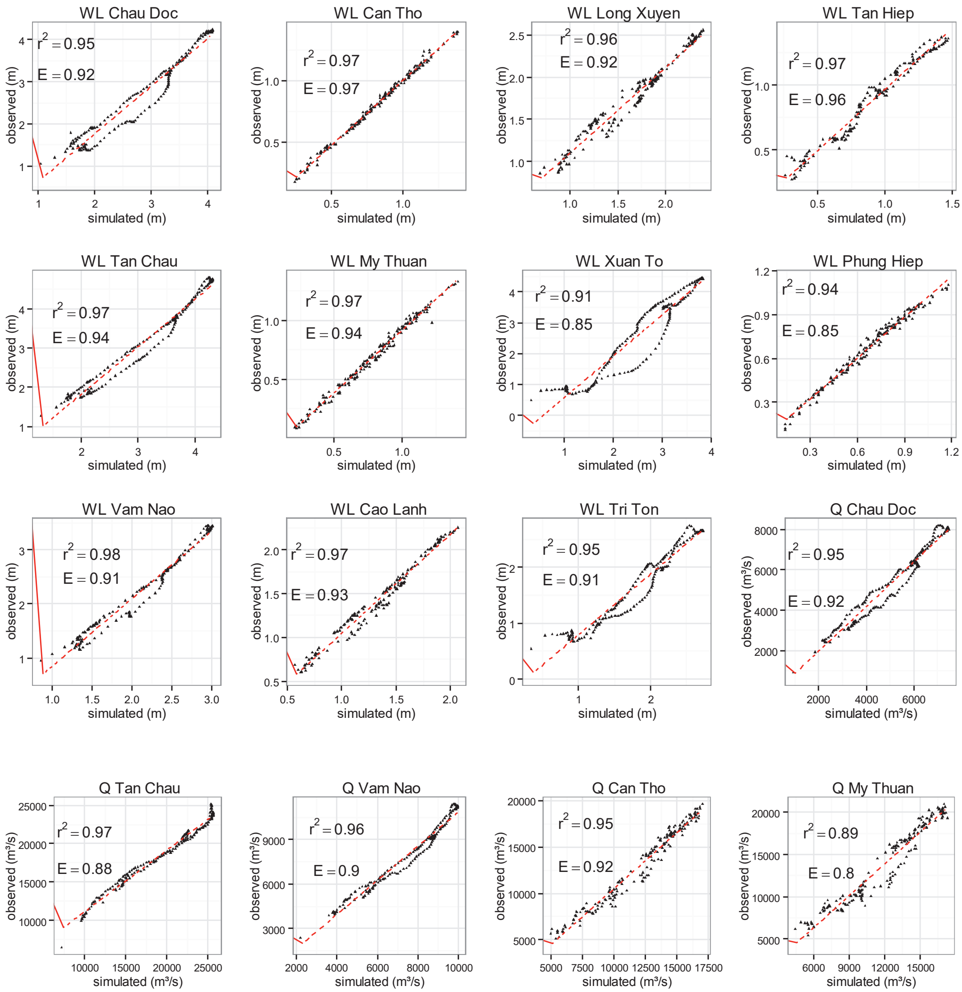


Figure A2 Graphs of correlation and Nash–Sutcliffe efficiency of daily simulated and observed flows in 2011 at all stations used for model calibration

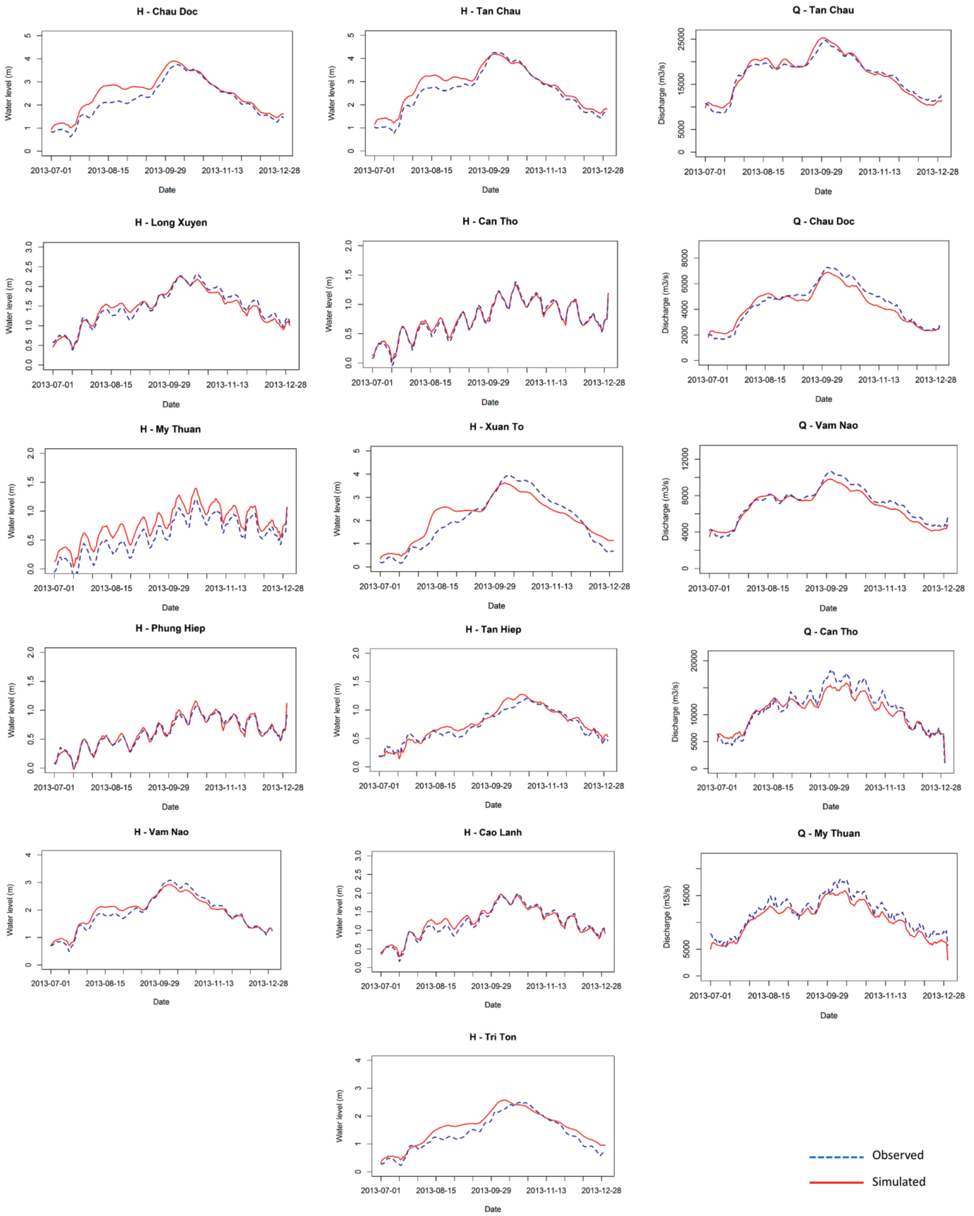


Figure A3 Time series of daily simulated and observed flows in 2013 at all stations used for model calibration

Table A1 Paired sample test for water level time series along the Hau River in 2011

Scenario and Difference	N	Mean	Peak	Peak Time	Std. Deviation	95% Confidence interval of the difference		t-value	df	p-value
						Lower	Upper			
Paired Sample Test for water level (m) time series at Chau Doc										
S1	4393	2.567	3.486	12/10/2011	0.669					
S2	4393	2.908	4.152	12/10/2011	0.882					
S3	4393	2.912	4.166	12/10/2011	0.885					
S4	4393	2.920	4.179	12/10/2011	0.890					
Pair S1-S2						-0.374	-0.308	-20.415	8188	0.000
Pair S1-S3						-0.377	-0.311	-20.569	8175	0.000
Pair S1-S4						-0.385	-0.319	-20.968	8153	0.000
Paired Sample Test for water level (m) time series at Vam Nao										
S1	4393	1.937	2.664	13/10/2011	0.521					
S2	4393	2.030	2.943	26/10/2011	0.583					
S3	4393	2.035	2.963	26/10/2011	0.588					
S4	4393	2.040	2.975	26/10/2011	0.593					
Pair S1-S2						-0.116	-0.070	-7.914	8674	0.000
Pair S1-S3						-0.122	-0.075	-8.304	8656	0.000
Pair S1-S4						-0.127	-0.081	-8.726	8640	0.000
Paired Sample Test for water level (m) time series at Long Xuyen										
S1	4393	1.654	2.431	27/10/2011	0.499					
S2	4393	1.653	2.593	27/10/2011	0.509					
S3	4393	1.658	2.614	26/10/2011	0.514					
S4	4393	1.664	2.625	26/10/2011	0.519					
Pair S1-S2						-0.020	0.022	0.083	8780	0.934
Pair S1-S3						-0.025	0.017	-0.370	8776	0.711
Pair S1-S4						-0.031	0.012	-0.862	8771	0.389
Paired Sample Test for water level (m) time series at Can Tho										
S1	4393	0.843	2.054	27/10/2011	0.480					
S2	4393	0.829	2.098	27/10/2011	0.499					
S3	4393	0.830	2.102	27/10/2011	0.499					
S4	4393	0.832	2.106	27/10/2011	0.500					
Pair S1-S2						-0.006	0.035	1.368	8771	0.172
Pair S1-S3						-0.008	0.033	1.197	8770	0.231
Pair S1-S4						-0.010	0.031	1.008	8770	0.314

Supplementary information B

Questionnaire

Introduction (High dike area)

I am a student from Wageningen University and Vietnamese National University and is doing PhD thesis research in Irrigation & Water Resources Management.
Our research mainly focus on exploring the impacts of floods on livelihoods of farmer. With this research, I hope to gain more insight about the flood-based farming systems. Our aim is to help farmers maximise production and income to increase the sustainability of livelihoods of farmers in An Giang province as well as the Mekong Delta. The interview takes place by asking several questions, which take about 45 minutes.
For ethical issues, please state that the interviewees have the right to stop/withdraw from the interview at any time if they are not comfortable with or for any reasons. The identity/personal information of the interviewees is also kept confidential.
Please feel free to contact me via email address dung.ductran@wur.nl or phone's number +84 902 007 905 if you have further questions or discussions.
Is there any question before we start with the interview?

Interview guide

1. Date: .... 2. Interviewer: ....
3. District: .... 4. Commune: ....

SECTION 1: GENERAL INFORMATION

5. Name of interviewee: ....
6. Relationship with household head: ....
7. Information of household head:
   a. Name .... b. Age ....
   c. Sex: Male ☐ Female ☐ d. Education..
8. Number of household members: .... (person)
9. Number of family labours: .... (person)
10. Phone number: ....

SECTION 2: CHARACTERISTICS OF FARMS

11. How many year were the high dikes constructed in your area?
    ....
12. How many hectare/1000m² do you have for agricultural production activities?
    ....
13. What are characteristics of your farming system?

No	Type of crop	Area (*1000m²*)	# of crop per year	Month of cultivation
1				
2				
3				
4				
5				

14. What are your rice crop yields and price?
    a. Winter-Spring season, yield .... (tonnes/ha), price .... (VND/kg)
    b. Spring-Autumn season, yield .... (tonnes/ha), price .... (VND/kg)
    c. Autumn-Winter season, yield .... (tonnes/ha), price .... (VND/kg)
15. What are your vegetable/fruit tree yields and price?
    a. Winter-Spring season, yield .... (tonnes/ha), price .... (VND/kg)
    b. Spring-Autumn season, yield .... (tonnes/ha), price .... (VND/kg)
    c. Autumn-Winter season, yield .... (tonnes/ha), price .... (VND/kg)
16. What is the amount of fertilizer applied per season?
    a. Winter-Spring season, fertilizer .... (kg/ha), price .... (VND/kg)
    b. Spring-Autumn season, fertilizer .... (kg/ha), price .... (VND/kg)

c. Autumn-Winter season, fertilizer .... (kg/ha), price .... (VND/kg)

17. What is the amount of pesticides applied per season?
    a. Winter-Spring season, ...(bottle/1000m^2), price .... (VND/bottle)
    b. Spring-Autumn season, ...(bottle/1000m^2), price .... (VND/bottle)
    c. Autumn-Winter season, ...(bottle/1000m^2), price .... (VND/bottle)
18. How much do you have to pay for pumping for irrigation over season?
    a. Winter-Spring season, time of pumping .... (time), price .... (VND/time)
    b. Spring-Autumn season, time of pumping.................................. (time), price .... (VND/time)
    c. Autumn-Winter season, time of pumping................................. (time), price .... (VND/time)
19. What are your net agricultural incomes in each crop excluding production costs?
    a. Winter-Spring season...(VND/1000m^2)
    b. Spring-Autumn season...(VND/1000m^2)
    c. Autumn-Winter season ....(VND/1000m^2)
20. How much money did you must pay when high dikes were constructed? And how long did you pay?
    a. Amount of payment ....(VND/1000m^2/crop)
    b. Number of years (time)..
21. How many labor and hour per day you used to work in the field?
    ....
22. What are you doing besides cropping practices to increase your income?
    ....
23. How often have your fields flooded? And how do you flood your fields?
    ....

SECTION 3: ADVANTAGES OF HIGH DIKES

24. What are the advantages of high dikes in general?
    a. Less dike maintenance every year like august dikes
    b. Safety for inhabitant, especially children in the flood season
    c. Better living conditions compared to before high dike constructions
    d. Convenient transportation and market connection
    e. Others ....
25. What are the advantages of high dikes with your specific agricultural activities?
    a. Third crop
    b. Good to raise pourtry and cattle around year
    c. More options for crops (vegetable, fruit trees) without flooded inundation
    d. Increase labour time in the flood season to avoid leisure time with social problems
    e. Others ....
26. Do you think high dikes can increase your incomes in agricultural production compared to august dikes or no dikes?
    ① Not agree ② Agree ③ Strongly agree
27. Do you think high dike can create more job for farmers compared to august dikes or no dikes?
    ① Not agree ② Agree ③ Strongly agree
28. Do you think your crop products is stable with the market?
    ① Not agree ② Agree ③ Strongly agree
29. What are levels of advantage in cultivation in high dike areas compared to the time before high dike implementation?
    ① More advantage ② Normal ③ More difficult
    Specific advantages..

SECTION 4: DISADVANTAGES OF HIGH DIKES

30. What are the disadvantages of high dikes with your specific agricultural activities?
    a. Reducing a considerable number of natural fish to land fields
    b. Reducing soil fertility by not bringing fertile sediment into fields
    c. Reducing crop yields
    d. Increasing production costs such as pumping, pesticide, and fertilizers
    e. Increasing maintenance and operation costs
    f. Others ....
31. What are the level of the effects of high dike constructions on natural fish sources beneficial from floods after 5 years?
    ① Not affect ② Affect ③ Strongly affect
    Specific effects..
32. What are the level of the effects of high dike constructions on the fertility of soil after 5 years?
    ① Not affect ② Affect ③ Strongly affect
    Specific effects..
33. What is your opinion about "the high dikes reduce your crop yields after some years compared to august dikes"?
    ① Not agree ② Agree ③ Strongly agree
    Specific effects..
34. What is your opinion about "the high dikes increase your production costs (fertilizer used, pesticide used, and pumping costs) compared to those in august dikes"?
    ① Not agree ② Agree ③ Strongly agree
    Specific effects..

35. Do you think high dikes decrease the flood water retention (water storage) and this impacts biodiversity conservation (explain more about the natural species loss) and causes flood risks downstream?
① Not agree ② Agree ③ Strongly agree
Specific effects..

36. Do high dikes increase the maintenance and operation costs for dike heightening compared to august dikes?
① Not agree ② Agree ③ Strongly agree
Specific effects..

37. Do you worry that floods break the high dikes? What will you do if the problem happens?
① Not worry ② Worry ③ Strongly worry
What will do...

SECTION 5: ALTERNATIVES FOR FARMING SYSTEMS IN HIGH DIKES

38. How many crop and which crops do you want to do with your farming system in future?
....

39. Which crop season do you think you get less benefit? Why?
Crop seasons with the least benefit/profit..
Reasons..

40. Do you want to stop cultivating the crop with less benefit?
① Not agree ② Agree ③ Strongly agree

41. Do you want to reduce the number of crops inside the high dikes?
① Not agree ② Agree ③ Strongly agree
Specific reasons...

42. Flood waters are good for soil fertility. Do you want flood waters flowing to the fields to improve the soil quality in the flood season?
① Not agree ② Agree ③ Strongly agree
Specific reasons...

43. What alternatives you want to do in future to increase the income in agriculture inside the high dike systems?
....

44. Crop diversification has been introduced as a good solution to increase the sustainability of livelihoods in high dike areas. What do you think if you can diversify by using a part of your cropland for cash crops or aquaculture?
....

45. Do you know any successful household with productive farming system over many years in the high dike areas? Do you think their farming systems are stable?
....

46. Do you think your crops are more sustainable than those in august dikes or no dikes?
① Not agree ② Agree ③ Strongly agree
Specific reasons...

47. Flood waters are good for your land fields. What is your opinion if the government wants to get flood waters by making temporary openings along high dikes?
....

48. Do you want to change your current crops into higher value crops?
If yes. Reasons..
If no. Reasons..

49. Do you want to change your current crops into higher value crops if the government supports loans, technology, and ensures a sustainable consumption in the market?
....

50. If you have a good and stable income from the two first crops, do you agree if the government requires free fields for flooded in the third crop?
....

51. Do you know program no.31 issued by An Giang province about "Productions and cultural living with floods in the floating seasons"? Did you join the program and what were its benefits?
....

52. What farming systems in the high dike area you can modify in the list below? Which successful farming systems that can increase income and be good for environment for a sustainable livelihood?
a. 3 rice crops
b. 2 rice crop + vegetable
c. 2 rice crops
d. 2 rice crops + fish in rice fields
e. 1 rice crop + 2 vegetables
f. 1 rice crop + 1 vegetables + fruit tree
g. Other system:
1) ....
2) ....
3) ....

Introduction (Low/August dike area)

Interview guide

1. Date: .... 2. Interviewer: ....
3. District: .... 4. Commune: ....

SECTION 1: GENERAL INFORMATION

5. Name of interviewee: ....
6. Relationship with household head: ....
7. Information of household head:
   a. Name .... b. Age ....
   c. Sex: Male ☐ Female ☐ d. Education..
8. Number of household members: .... (person)
9. Number of family labours:... (person)
10. Phone number:...

SECTION 2: CHARACTERISTICS OF FARMS

11. How many hectare/1000m² do you have for agricultural production activities?
    ....
12. What are characteristics of your farming system?

No	Type of crop	Area (*1000m²*)	# of crop per year	Month of cultivation
1				
2				
3				
4				
5				

13. What are your rice crop yields and price?
    a. Winter-Spring season, yield .... (tonnes/ha), price .... (VND/kg)
    b. Spring-Autumn season, yield... (tonnes/ha), price .... (VND/kg)
    c. Autumn-Winter season, yield .... (tonnes/ha), price .... (VND/kg)
14. What are your vegetable/fruit tree yields and price?
    a. Winter-Spring season, yield .... (tonnes/ha), price .... (VND/kg)
    b. Spring-Autumn season, yield... (tonnes/ha), price .... (VND/kg)
    c. Autumn-Winter season, yield .... (tonnes/ha), price .... (VND/kg)
15. What is the amount of fertilizer applied per season?
    a. Winter-Spring season, fertilizer.. (kg/ha), price .... (VND/kg)
    b. Spring-Autumn season, fertilizer .... (kg/ha), price .... (VND/kg)
    c. Autumn-Winter season, fertilizer .... (kg/ha), price .... (VND/kg)
16. What is the amount of pesticides applied per season?
    a. Winter-Spring season,.. (spray/1000m²), price .... (VND/spray)
    b. Spring-Autumn season, ... (spray/1000m²), price .... (VND/spray)
    c. Autumn-Winter season, ... (spray/1000m²), price .... (VND/spray)
17. How much do you have to pay for pumping for irrigation over season?
    a. Winter-Spring season, time of pumping .... (time), price .... (VND/time)
    b. Spring-Autumn season, time of pumping.................................. (time), price .... (VND/time)
    c. Autumn-Winter season, time of pumping .... (time), price .... (VND/time)

18. What are your net agricultural incomes in each crop excluding production costs?
    a. Winter-Spring season..(VND/1000m²)
    b. Spring-Autumn season ....(VND/1000m²)
19. How many labor and hour per day you used to work in the field?
    ....
20. What are you doing besides cropping practices to increase your income?
    ....

SECTION 3: CHARACTERISTICS OF FLOOD-BASED FARMS

21. Which main crops/number of crops do you cultivate in flood seasons before and after the construction of august dikes?
    Before..
    After ....
22. Why do you choose these crops in flood seasons?

a. Easy to cultivate/carry out
b. Do not know any better crop
c. Bring more profit
d. Imitate other farmers in the area
e. Recommendation of local government
f. Other reason:..

23. What are your benefits from the crops in flood seasons?
    a. Increase income
    b. For daily food
    c. More work to do to avoid leisure time for wine drinking
    d. No benefit
    e. Other reason:..
24. What are main constraints/barriers in cultivating your farms in flood seasons?
    a. Dangerous
    b. Do not have means for cultivation (i.e. boat, net, floating etc.)
    c. Flood wave is too strong
    d. Do not know which crops are suitable
    e. Have no skill/technology
    f. Difficult to sell the production
    g. Do not have labour
    h. Other reason:..
25. The benefits of floodwater that can bring fertile sediments and fish to farmers. What are these benefits to your crop production?
    ....
26. Do you really want to cultivate/work in the flood season?
    If no, reasons:..
    If yes, what kind of work or crop do you want to do? ....
27. What is your perception about the effect of high dikes on crop production? What do you think if the government wants to upgrade your dike system into high dikes?
    ....

SECTION 4: ALTERNATIVES FOR FLOOD BASED FARMING SYSTEMS IN AUGUST DIKES

28. Do you know any alternative in farming systems to increase the income in flood seasons? Where can you know these alternatives? How can they do that?
    ....
29. Will you apply these alternatives in future?
    ....
30. What are the benefits from these alternatives in farming systems?
    ....
31. Do you know program no.31 issued by An Giang province about "Productions and cultural living with floods in the floating seasons"? Did you join the program and what were its benefits?
    ....
32. What farming systems in the august dike area you can modify in the list below? Which successful farming systems that can increase income, get benefits from floodwater and be good for environment for a sustainable livelihood?
    a. 2 rice crops + fish cage/floating rice/floating vegetable
    b. 1 rice crop + cash crop + fish cage/floating rice/floating vegetable
    c. 1 cash crop + fish cage/floating rice/floating vegetable
    d. Other system:
       1) ....
       2) ....
       3) ....

Multi-criteria analysis

To start the MCA questionnaire, please let me know your professional background.
Scientist/Academic: ☐ **Government Official:** ☐ **Technical advisor/consultant:** ☐
Social advisor/consutltant: ☐ **Other, namely:** ....

Scale

1	3	5	7	9
Equal	Moderate importance	Importance	Strong importance	Extreme importance

A1. Based on the above scale, please compare the importance of <u>criteria</u>

Livelihood: "means of securing the basic necessities -food, water, shelter and clothing- of life". Our study aims to explore alternatives in farming systems to maximize livelihood's sustainability of farmers.

Flood water management: "aims to provide better, more sustainable management of flood risk for people, homes and businesses, help safeguard community groups from unaffordable rises in surface water, drainage charges and protect water supplies to the consumer". Both at local scale and the scale of the Mekong Delta. Livelihood of famers in An Giang is mainly based on farming systems under low dike (flood retention) and high dike protections (local flood protection & risks, flood costs at delta level).

Environmental sustainability in land and water: Farmers' livelihood is sustainable if their farming systems are mixed in a sustainable environment in terms of land and water – e.g soil quality (fertility, acidity, and chemical pollution), water quality.

Weights of criteria

A	B	More important (A or B)	Intensity (Scale 1 to 9)
Livelihood	Flood water management		
Livelihood	Environmental sustainability in land and water		
Flood water management	Environmental sustainability in land and water		

A2. Please put your points for the importance of criteria, based on the total point of 100

Weights of criteria

Livelihood	Flood water management	Environmental sustainability in land and water	Total
……………..…points	……………..…points	……………..…..points	100 points

B1. Based on the above scale, please compare the importance of <u>sub-criteria</u>

Concept
1. Profitability: Net income from agricultural production (total crops/fish per year). Value=Production benefit (total selling products)-Production cost (pumping, seed, pesticide, fertilizer, labor, etc) **2. Employment opportunities:** degree of direct (on-farm) and in-direct (of-farm, processing, labour etc) employment provided throughout the year/season; (contrast: no-employment opportunities in flood season) **3. Market stability:** Livelihood of farmers is better if their products from the farming systems could be sold with stable and good price. **4. Opportunities for the poor farmers:** In rural area, livelihood of farmers is better if the living condition of the poor is improved over years. (livelihood opportunities for the landless, and small holders) **5. Infrastructure and public works:** include houses, hospital, schools, transportation systems .etc. which could improve well-being of farmers.

Weights of sub-criteria in **LIVELIHOOD**

A	**B**	**More important (A or B)**	**Intensity (Scale 1 to 9)**
Profitability	Employment opportunities		
Profitability	Market stability		
Profitability	Opportunities for the poor farmers		
Profitability	Infrastructure and public works		
Employment opportunities	Market stability		
Employment opportunities	Opportunities for the poor farmers		
Employment opportunities	Infrastructure and public works		
Market stability	Opportunities for the poor farmers		
Market stability	Infrastructure and public works		
Opportunities for the poor farmers	Infrastructure and public works		

B2. Please put your points for the importance of sub-criteria, based on the total point of 100

Weights of sub-criteria in LIVELIHOOD

Profitability	**Employment opportunities**	**Market stability**	**Opportunities for the poor farmers**	**Infrastructure and public works**	**Total**
…………points	..……..….points	……..…..points	……..….points	………..points	100 points

C1. Based on the above scale, please compare the importance of <u>sub-criteria</u>

Concept
1. Flood protection: Local flood protection in for farming systems An Giang are mainly based on low dikes, high dikes, sluide gates. High dikes protect better for people, farms against floodings but are potentially extremely damaged if fail. Low dikes less protect farms than high dikes; however, low dikes allow floodwater with fertile sediment and natural fish entering the fields to improve soil fertility. **2. Complexity in operation:** Water is flowed in and out the farming systems by structures such as canals, sluice gates, and pumps or gravity pipes etc. Structural operations in high dikes are very costly (operation and maintenance costs) and complex than those in low dikes. **3. Exploitability of flood benefits:** Floodwater plays an important role in An Giang because it brings common pool resources such as fertile sediment and natural fish (Howie, 2011) which are beneficial for farmers' livelihood based on farms. Low dikes exploit floodwater benefits than high dikes. **4. Internalities:** Costs (impacts) potentially caused by flood water mangement for the farming systems at local scale. I.e. High dikes increase flood peaks on local rivers, reduce flood retention capacity, and very costly if fail. Low dikes need to be maintained after floods but are cheap. **5. Externalities:** Costs (impacts) potentially caused by flood water mangement for the farming systems at regional and delta scale. I.e. High dike constructions at large scale may cause flood risks downstream.

Weights of sub-criteria in **FLOOD WATER MANAGEMENT**

A	**B**	**More important (A or B)**	**Intensity (Scale 1 to 9)**
Flood protection	Complexity in operation		
Flood protection	Exploitability of flood benefits		
Flood protection	Internalities		
Flood protection	Externalities		
Complexity in operation	Exploitability of flood benefits		
Complexity in operation	Internalities		
Complexity in operation	Externalities		
Exploitability of flood benefits	Internalities		
Exploitability of flood benefits	Externalities		
Internalities	Externalities		

C2. Please put your points for the importance of <u>sub-criteria</u>, based on the total point of 100

Weights of sub-criteria in FLOOD WATER MANAGEMENT

Flood protection	**Complexity in operation**	**Exploitability of flood benefits**	**Internalities**	**Externalities**	**Total**
……..…..points	…………..points	……..…..points	………..….points	…………..points	100 points

D1. Based on the above scale, please compare the importance of sub-criteria

Concept
1. Water pollution: Water pollution is impacted by the usage of pesticide and fertilizers from farms, and sulfidiication & acidification of SAS. **2. Soil fertility:** Soil fertility would be strongly reduced by an intensity in crop cultivations on farms, due to an increase of fertilizer use. **3. Water storage capacity:** ability of the system to store wet season flood water for dry season use (locally & system). **4. Biodiversity conservation:** "Biodiversity is the variety of all species on earth. It is the different plants, animals and micro-organisms, their genes, and the terrestrial, marine and freshwater ecosystems of which they are a part" i.e. in An Giang natural fish, bird, plants .etc

Weights of sub-criteria in **ENVIRONMENTAL SUSTAINABILITY IN LAND AND WATER**			
A	**B**	**More important (A or B)**	**Intensity (Scale 1 to 9)**
Water pollution	Soil fertility		
Water pollution	Water storage capacity		
Water pollution	Biodiversity conservation		
Soil fertility	Water storage capacity		
Soil fertility	Biodiversity conservation		
Water storage capacity	Biodiversity conservation		

D2. Based on the above scale, please compare the importance of sub-criteria

Weights of sub-criteria in ENVIROMENTAL SUSTAINABILITY IN LAND AND WATER				
Water pollution	**Soil fertility**	**Water storage capacity**	**Biodiversity conservation**	**Total**
…….…..points	…………points	……..…..points	………..….points	100 points

MCA SCRORING CARDS FOR ALTERNATIVES BASED ON EVALUATION CRITERA

Scale of 5

1	2	3	4	5
Low	**Below average**	**Average**	**Above average**	**High**

Scale of 3

1	2	3
Low	**Average**	**High**

Please check the number on each cell of the tables below based on the scale of 1-3 and 1-5. Complete all cells each column (10 alternatives) before moving to next columns.

Table E1

LIVELIHOOD		**1.Profitability**	**2. Employment opportunities**	**3. Market stability**		**4. Opportunities for the poor farmers**	**5. Infrastructure and public works**
No	**Alternatives in farming systems**	1.1. Net farm income	2.1 High employment rate annually	3.1. High market price over years	3.2. High Saleability	4.1. Employment for the poor in the flood seasons	5.1. Better living condition i.e house, transportation, hospital, school .etc
1	LD1 Double rice + floating crops	① ② ③ ④ ⑤	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③
2	LD2 Double mixed crops + floating crops	① ② ③ ④ ⑤	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③
3	LD3 Double vegetable + floating crops	① ② ③ ④ ⑤	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③
4	LD4 Double vegetable + flooded fields	① ② ③ ④ ⑤	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③
5	LD5 Eel feeding + straw mushroom	① ② ③ ④ ⑤	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③
6	HD1 8 rice crops in 3 years	① ② ③ ④ ⑤	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③
7	HD2 Double rice + vegetable	① ② ③ ④ ⑤	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③
8	HD3 Triple mixed crops (rice is main crop)	① ② ③ ④ ⑤	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③
9	HD4 Mixed crops (rice+pond)+poultry or cattle	① ② ③ ④ ⑤	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③
10	HD5 Fruit tree	① ② ③ ④ ⑤	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③

Table E2

FLOOD WATER MANAGEMENT		1.Flood protection		2.Complexity in operation	3.Exploitability of flood benefits		4. Internalities			5.Externalities	
No	**Alternatives in farming systems**	1.1. People and property protection	1.2. Land protection	2.1. Requirement in structural operation (pumps sluice gates .etc)	3.1.Higher fertile sediment and wild fish	3.2. Higher ability in cleaning fields	4.1. Flood peak increase on local rivers and canal	4.2. Dike broken and river bank erosion	4.3. Reduction in flood retention capacity	5.1. Increase in flood risks downstream	5.2. In crease in saltwater intrusion downstream
1	LD1 Double rice + floating crops	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③
2	LD2 Double mixed crops + floating crops	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③
3	LD3 Double vegetable + floating crops	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③
4	LD4 Double vegetable + flooded fields	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③
5	LD5 Eel feeding + straw mushroom	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③
6	HD1 8 rice crops in 3 years	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③
7	HD2 Double rice + vegetable	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③
8	HD3 Triple mixed crops (rice is main crop)	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③
9	HD4 Mixed crops (rice+pond)+pourtry or cattle	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③
10	HD5 Fruit tree	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③	① ② ③

Table E3

ENVIRONMENTAL SUSTAINABILITY IN LAND AND WATER		**1. Water pollution**		**2. Soil quality/fertility**		**3. Water storage capacity**		**4. Biodiversity conservation**		
No	**Alternatives in farming systems**	1.1. Affected by pesticide	1.2. Affected by fertilizer	2.1. Pesticide use (kg ha^{-1})	2.2. Fertilizer use (litre ha^{-1})	3.1. Higher water saving in irrigation in the dry season	3.2. Surface and ground water storages	4.1. Natural species (fishes, birds etc.)	4.2. Pesticide use intensity (kg ha^{-1})	4.3. Crop diversity
1	LD1 Double rice + floating crops	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤
2	LD2 Double mixed crops + floating crops	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤
3	LD3 Double vegetable + floating crops	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤
4	LD4 Double vegetable + flooded fields	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤
5	LD5 Eel feeding + straw mushroom	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤
6	HD1 8 rice crops in 3 years	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤
7	HD2 Double rice + vegetable	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤
8	HD3 Triple mixed crops (rice is main crop)	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤
9	HD4 Mixed crops (rice+pond)+pourtry or cattle	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤
10	HD5 Fruit tree	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③	① ② ③	① ② ③ ④ ⑤	① ② ③ ④ ⑤	① ② ③ ④ ⑤

Supplementary information C

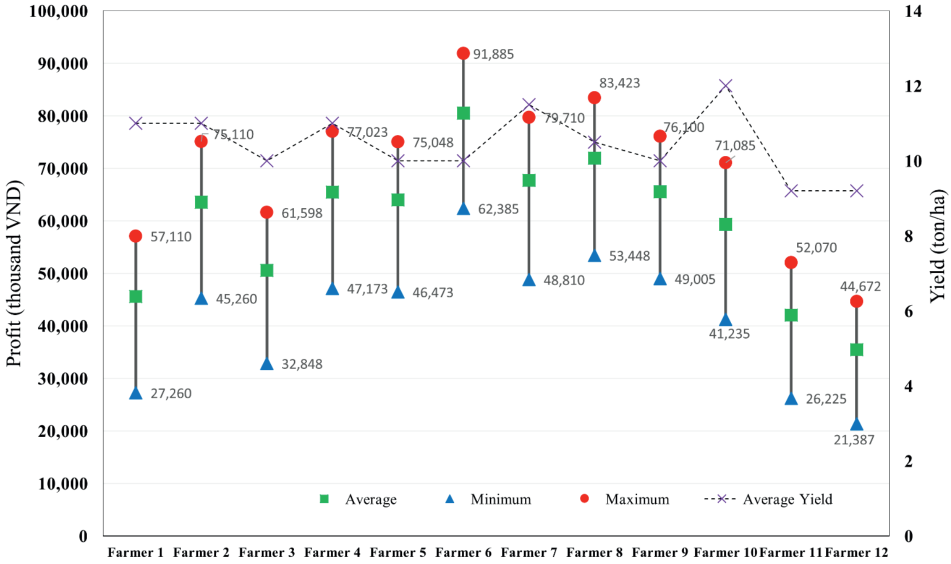
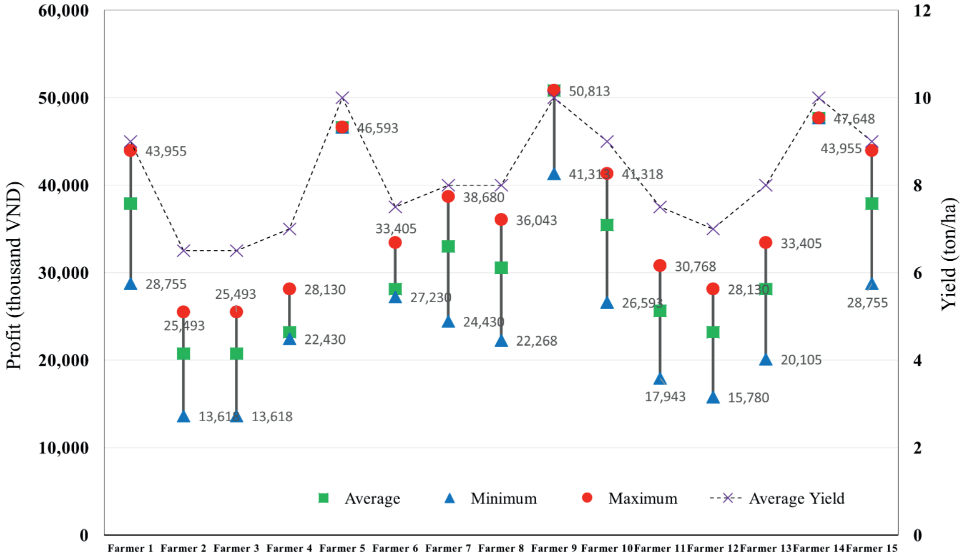


Figure C1 Variation of annual triple rice profits affected by selling price compared with yield from the survey data at Phu An commune in 2014



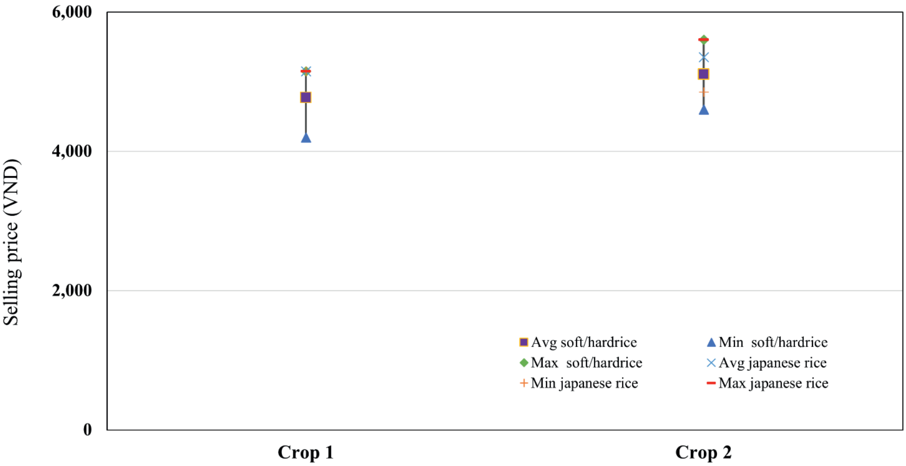


Figure C2 Variation of annual triple rice profits affected by selling price compared with yield (upper plot), and variation of selling price based on rice variety (lower plot) from the survey data at Tan My commune in 2016

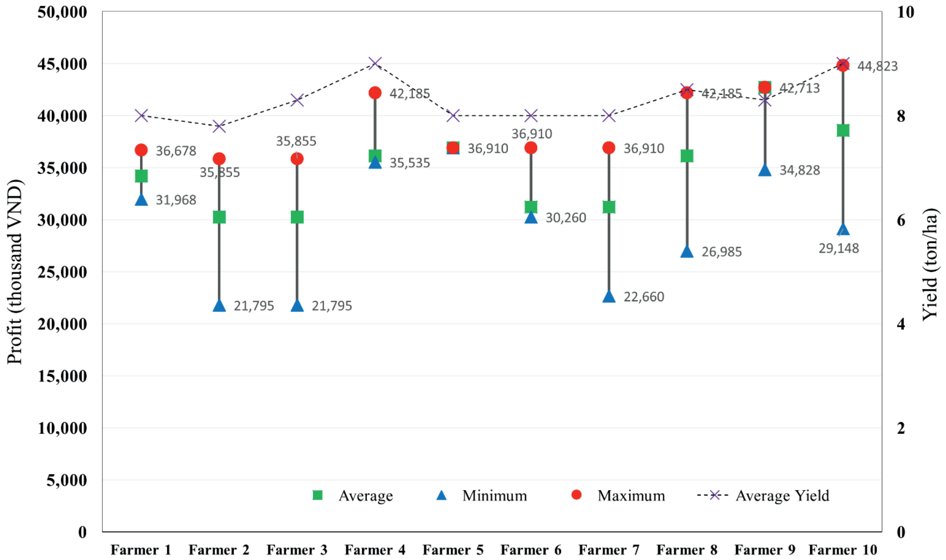


Figure C3 Variation of annual triple rice profits affected by selling price compared with yield from the survey data at Binh Phu commune in 2016

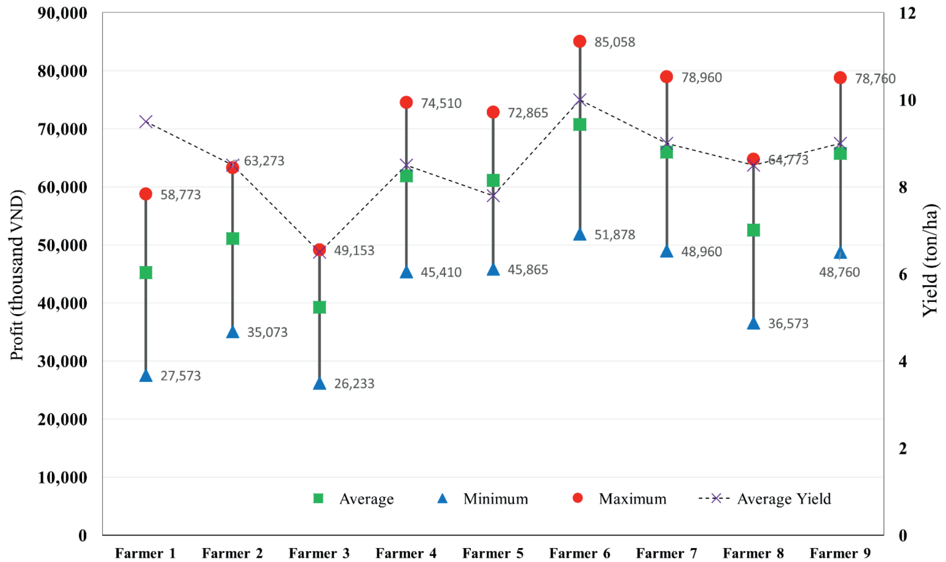


Figure C4 Variation of annual triple rice profits affected by selling price compared with yield from the survey data at O Long Vy commune in 2016

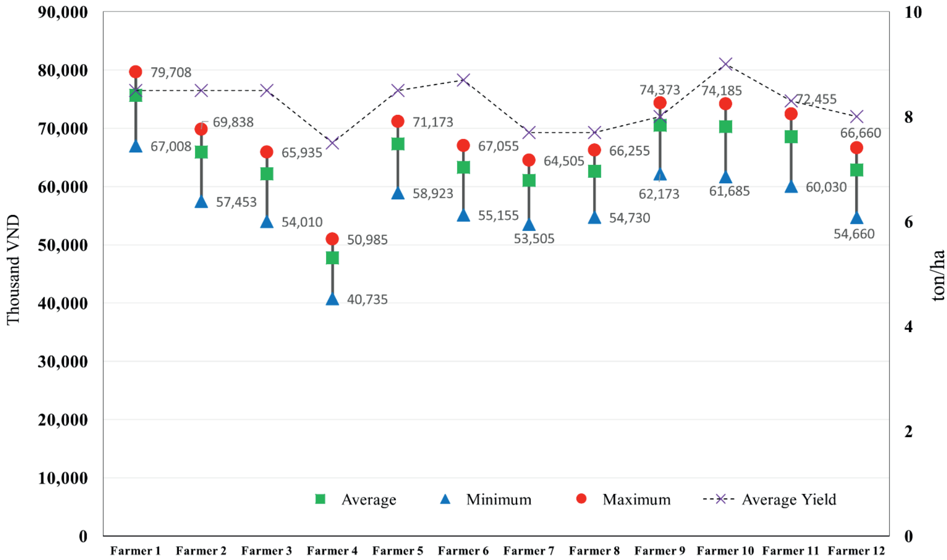


Figure C5 Variation of annual triple rice profits affected by selling price compared with yield from the survey data at Thanh My Tay commune in 2016

Table C1 Details of costs and benefits of some types of crop

Crop type	Unit	Amount	Revenue VND.ha^{-1}.year^{-1}	Profit	
				VND.ha^{-1}.year^{-1}	US \$.ha^{-1}.year^{-1}
Chili (5-6 months.season^{-1}, 2 seasons.year^{-1})					
Crop yield	tons.ha^{-1}	10-20			
Benefits			450,000,000	272,916,000	12,023
Production costs			177,084,000		
Other costs			105,384,000		
Fertilizer	kg.ha^{-1}.season	3500-4900	36,000,000		
Pesticides			30,000,000		
Collective pumping			700000		
Individual pumping			5,000,000		
Squash (2-3 months.season^{-1}, 4 seasons.year^{-1})					
Crop yield	tons^{-1}.ha	4-5			
Benefits			990,000,000	586,228,000	25,825
Production costs			403,772,000		
Other costs			250,600,000		
Fertilizer	kg.ha^{-1}.season	3300	120,000,000		
Pesticides			18,400,000		
Collective pumping			5200000		
Individual pumping			9,572,000		
Lotus (4-5 months/crop, around year)					
Benefits			78,487,360	56,915,260	2,507
Production costs			21,572,100		
Land preparation			846,840		
Pesticides			1,630,520		
Fertilizers			12,906,320		
Water pumping			1,193,150		
Harvest			6,368,940		
Intensive lotus (4-5 months/crop, around year)					
Benefits			166,924,080	117,619,580	5,181

Crop type	Unit	Amount	Revenue VND.ha^{-1}.year^{-1}	Profit	
				VND.ha^{-1}.year^{-1}	US \$.ha^{-1}.year^{-1}
Production costs			46,068,010		
Land preparation			1,425,260		
Pesticides			3,433,090		
Fertilizers			25,814,420		
Water pumping			2,390,830		
Harvest			13,004,410		
Rice-lotus (4-5 months/crop, around year)					
Benefits			120,680,190	84,352,810	3,716
Production costs			36,327,380		
Land preparation			2,194,440		
Varieties			2,538,090		
Pesticides			6,575,300		
Fertilizers			11,508,270		
Water pumping			2,169,160		
Harvest			11,342,120		
Intensive lotus-ecotourism (year-round)					
Benefits			610,615,000	292,000,000	12,863
Total costs without family labor			215,538,000		
Production costs (1+2)			318,615,000		
Eating and drinking business/lotus farm tourism (1)			*301,995,000*		
Commodity cost			145,786,000		
Water			1,766,000		
Gas			10,714,000		
Coal			291,000		
Electricity			5,580,000		
Depreciation			12,900,000		
Labor			87,771,000		

Crop type	Unit	Amount	Revenue VND.ha^{-1}.year^{-1}	Profit	
				VND.ha^{-1}.year^{-1}	US \$.ha^{-1}.year^{-1}
Lotus cultivation cost (2)			*16,620,000*		
Land hiring			286,000		
Land preparation			2,521,000		
Pesticides			160,000		
Fertilizers			1,405,000		
Water pumping			98,000		
Harvest			12,150,000		
Sesame (3-4 months/crop)					
Benefits			176,386,650	105,302,100	4,639
Production costs			71,084,550		
Land preparation			4,387,320		
Seeds			3,364,980		
Fertilizers			17,451,660		
Agrochemicals			8,723,310		
Harvest			20,858,640		
Water pumping			1,003,560		
Land hiring			30,750,000		

Table C2 Costs and benefits of existing 1-hectare/household farming systems under low dike and high dike protection

Existing alternative farming systems	ID number	Crop calendar			Cost	Revenue	Annual profit			
		Nov-Feb	Mar-Jun	Jul-Nov	x10³ VND.ha⁻¹		x10³ VND.ha⁻¹	x10³ VND.household⁻¹	US $.ha⁻¹	US $ household⁻¹
		Crop 1	Crop 2	Crop 3						
A. Low dike										
CBA data collection in 2014										
01. Two short-grain rice crops	L4				50,200	96,600	46,400		2,044	
02. Flood-based giant freshwater prawn	L5						113,000		4,978	
03. Flood-based snake-head fish (3 units of 32.7 m³)	L6				170,100	236,300		66,200		2,916
04. Two-season chili	L7				177,100	450,000	272,900		12,022	
05. Four-season squash	L8				403,800	990,000	586,200		25,824	
06. *Neptunia oleracea* + wild fish (flood season)	L9						129,100		5,687	
*CBA data collection in 2015**										
07. Two-season lotus	L10				21,600	78,500	56,900		2,507	
08. Two-season intensive lotus	L11				46,100	166,900	117,600		5,181	
10. Two-season intensive lotus + ecotourism	L12				318,600	610,600	292,000		12,863	
11. Two-season intensive lotus + fish	L13				49,000	179,400	130,400		5,744	
12. Floating rice + additional cash crops	L14				144,100	289,500	145,400		6,405	
B. High dike										
CBA data collection in 2014										
01. Three short-grain rice crops 5 years	H4				64,200	100,300	36,100		1,590	
02. Three short-grain rice crops 15 years	H45				76,100	100,300	24,200		1,066	
03. One season of eel (3 units of 10 m²)	H7							120,000		5,286
04. Fish pond (3 unit of 50m²)	H8							90,000		3,965
05. Two-season chili	H9				177,100	450,000	272,900		12,022	
06. Four-season squash	H10				403,800	990,000	586,200		25,824	
*CBA data collection in 2015**										
07. Three rice crops	H11				48,700	93,600	44,900		1,978	
08. Three seasons of sesame	H12				71,100	176,400	105,300		4,639	

** Source: IUCN (2015)*   *Exchange rate in 2017: 1 USD=22,700 VND*

Table C3 Popular high-yield varieties of rice in the VMD Floodplains

Variety name	Classification	Duration (days)	Mean annual yield *(tons.ha^{-1}.$crop^{-1}$)
OM 4218	Long-grain, soft	90	6-8
OM 2514	Long-grain, soft	95	6-8
OM 1490	Long-grain, soft	90	6-8
Jasmine	Long-grain, soft	90	6-8
OM 2517	Long-grain, hard	85-90	6-8
IR 50404	Short-grain, hard	90-95	6-8
OM 5472	Long-grain, sticky	90-95	6-8
OMCS2000	Long-grain, soft	90-95	6-8
	Long/short-grain, sticky		6-8
Sticky rice (*Nếp*)	Japonica	95	

Sources: Department of Agricultural and Rural Development of An Giang Province
AGGSO, (2014): average yield of three rice crops per year for the whole province*

Table C4 Some popular types of pesticide and fertilizer applied for rice production in the VMD Floodplains

Pesticide-Brand	Chemical components	Fertilizer-Brand	Chemical components
Accenta 50CC	Fipronil 35g/l + 15g/l Lambda-cyhalothrin	Humic acid powder	Axit humic: 95% (Humidity: 5%)
Peran 50EC	Permethrin 50%	Magnesium Sulphate	MgO 25%, S 20%
Match 050EC	50g/l Lufenuron	Heptahydrate 99%	MgO 16.3%; Mg 9.8%; S 13%
Actimax 50WG	Emamectin benzoate (50g/kg)	Super Humic	Acid Humic 70% (Humidity: 20%)
Lilacter 0.3SL	Eugenol (3g/l)	NPK 25.25.5	N: 25%, P2O5: 25%, Kali (K2O): 5%
		NPK 23.23.0	N: 23%, P2O5: 23%
		NPK 20.20.0	N: 20%, P2O5: 20%
		NPK 20-20-15+TE	N: 20%, P2O5: 20%, Kali (K2O): 15%
		NPK 16-16-8-13	N: 16%, P2O5: 16%, Kali (K2O): 13%

Sources: Official national news (http://baoangiang.com.vn)

Supplementary information D

Table D1 Direct and indirect costs and benefits of dike construction scenarios.

No	Factors	Data indicator
Direct		
1	**Construction costs**	
1.1	Low dike	10^3 VND.ha^{-1}
1.2	High dike	10^3 VND.ha^{-1}
2	**Maintenance costs**	
2.1	Low dike	10^3 VND.ha^{-1}
2.2	High dike	10^3 VND.ha^{-1}
3	**Management costs**	
3.1	Low dike	10^3 VND.ha^{-1}
3.2	High dike	10^3 VND.ha^{-1}
Indirect		
4	**Production costs**	
4.1	Low dike (rice)	Farm inputs (seed, fertilizer, pesticides, etc.)
4.2	Low dike (vegetable-chili)	
4.3	Triple rice (rice)	
4.4	High dike (vegetable-sesame)	
5	**Profits**	
5.1	Low dike (rice)	Farm output (profits = revenue – production costs)
5.2	Low dike (vegetable)	
5.3	Triple rice (rice)	
5.4	High dike (vegetable)	

Table D2 Costs estimated for each hectare dike construction.

No	Factors	Data indicator	Information type	Value (US$)	Source(s)
1	**Construction costs**				
1.1	Low dike	Investment cost per hectare	Literature	69	Joep (2015)
1.2	High-dike	Investment cost per hectare	Literature	1,299	Dan (2015)
2	**Maintenance costs**				
2.1	Low dike	Maintenance cost per hectare	Literature	46	Joep (2015)
2.2	High dike	Maintenance cost per hectare	Literature	675	Dan (2015)
3	**Management costs**				
3.1	Low dike	Management cost per hectare	Literature	0	
3.2	High dike	Management cost per hectare	Literature	362	Dan (2015)

Exchange rate in 2017: US $1 = 22,700 VND.

Table D3 Production costs and revenues for rice and vegetable production estimated per hectare.

No	Factors	Production cost	Revenue	Source
		US $.ha^{-1}.year^{-1}	US $ ha^{-1}.year^{-1}	
Low dike				
1.1	Double rice	1,625	3,579	Dung et al. (2018a)
1.2	Two vegetable crops (chili) and floating crop	13,489	19,824	Dung et al. (2018a)
High dike				
1.3	Triple rice	2,749	4,786	Dung et al. (2018a)
1.4	Triple vegetable (sesame)	3,132	7,771	Dung et al. (2018a)

Exchange rate in 2017: US $1 = 22,700 VND.

Table D4 Flooded areas in depth affected by dike construction scenarios

Year	No. of people killed by flooding	No. of houses submerged and damaged	Schools submerged and damaged (rooms)	Paddy area inundated and damaged (ha)	Fruit trees and vegetable damaged (ha)	Roads damaged (km)	Fish and shrimp raising areas destroyed (ha)	Source	Cost ($$10^6$)
1995		28,431	127	24,525		1,425	870	Pham Cong Huu DAAD (2009)	
1996	15	136,213	1,464	14,034	8,358	2,220	2,064		
2000	32	114,526	1,299	28,964	909	1,927	1,833		172
2001	31	24,670	254	7,667	294	781	575		68
2002	9	38,789	345	3,481	7,039	979	378		20
2004	2	7,805	45	351	3,198	205	516		
2005		5,420	20	9,565	1,741	115	509		
2006	10	496			315	31			
2007		6,050	13		2,871	162	1		
2011	89	176,588	1,268	27,418	70,244	870	7,305	MRC, (2011)	194

Exchange rate in 2017: US $1 = 22,700 VND.

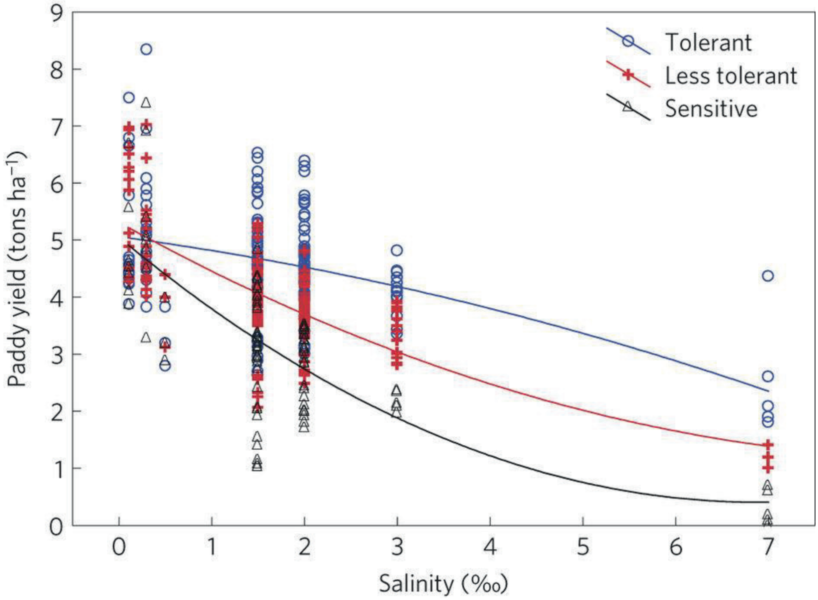


Figure D1 Paddy yield in the coastal areas of the Vietnamese Mekong Delta in relation to salinity (Nhan et al., 2012).

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Summary

Due to intensified rice production, induced by national food security policy, the floodplains in the upper parts of the Vietnamese Mekong Delta have changed in agro-ecology from a seasonal floodplain into a highly intensified rice production area. To enable intensified rice production, large-scale flood-control infrastructure has been built, particularly low dikes and high dikes, to control the water entering agricultural fields. As a result, the delta has become a primary contributor to Vietnam's food security, and the delta's high production has made Vietnam one of the world's foremost rice exporters. However, this transformation has reduced the flood retention capacity of the delta, degraded land and water quality, and undermined delta ecosystem services.

The main aims of the research presented in this thesis were two: to identify the impacts of extensive construction of flood-control infrastructure on the flood dynamics of the delta and to explore adaptation options to maximize livelihood sustainability and ecological sustainability on the delta. An available 1D-quasi2D hydrodynamic model was developed for the delta system as a whole to simulate flood discharges and river water levels, considering four dike construction scenarios. Using a sustainable livelihood perspective, alternative farming systems were explored using multi-criteria analysis and cost-benefit analysis on the local scale, relying on multiple interviews with stakeholders operating under different types of dikes and at different locations on the floodplains. The next step was to elaborate on costs and benefits while shifting the focus to the delta scale, also considering various future flood-control scenarios.

This thesis has an article-based structure, meaning that the individual chapters (chapters 2-5) were drafted in the form of articles for submission to peer-reviewed academic journals. Chapter 1 provides background, a problem statement, the conceptual framework, methodologies used and the objectives of the research. Chapter 6 revisits the research questions and objectives, synthesizing and reflecting on the findings from the individual chapters.

Chapter 2 analyzes the impacts of the extensive flood-control infrastructure constructed on the upper Vietnamese Mekong Delta, mainly in the form of low dikes and high dikes. The analyses show, particularly, that high dike construction on the Long Xuyen Quadrangle floodplain has severely reduced the floodplain's water storage capacity. Peak water levels have increased substantially, and water balance calculations indicate changes in floodwater distributions, especially across the floodplains and upper delta. In addition, the impacts turned out to be significant only over the period from 2000 to 2011, when most of the existing high dikes were built. However, hydrodynamic impacts were found to be relatively small downstream. This last result could be a function of the modeling approach used, as this presented some limitations in simulating variability in water levels downstream.

Chapter 3 brings in the perspectives of farmers and experts on alternative flood-based farming systems using multi-criteria analysis with analytic hierarchy process and a sustainable livelihood perspective. The stakeholders participating in the ranking favored the alternative flood-based farming systems under low-dike protection over farming systems protected by high dikes. In contrast, high-dike farming systems were more appreciated by the interviewed double and triple rice farmers, mainly due to the advantages the high dikes offered in protecting built up areas against flooding, alongside the stability of the market for rice.

Chapter 4 presents an analysis of the costs and benefits of high-dike farming systems and flood-based alternatives on a local scale. Here, farming systems under low-dike protection were found to be more sustainable in both economic and environmental terms, whereas profits from farming systems under high-dike protection diminished over time, due to the high monetary outlays required for production (i.e. fertilizer and pesticides). Results show that costs of agro-inputs has been rising over years due to the degradation of soil with triple-rice farming systems under the protection of high-dikes.

Chapter 5 also elaborates on costs and benefits, shifting the focus to the delta scale. Values were derived for the impacts of internal and external factors under future land-use scenarios associated with different dike construction schemes. Results indicate that the development scenario of upgrading all low-dike farming systems to high-dike farming systems across the floodplains would greatly increase both internal costs (construction, maintenance and operation) and external costs (particularly, flood risk, sediment loss, salinity intrusion and river bank erosion).

All in all, this study found significant hydrodynamic implications of the extensive dike construction on the delta floodplains that has spurred rapid expansion of triple rice production in recent decades. Additionally, the study demonstrates that alternatives are feasible. Some of these alternatives were found to be more profitable and more sustainable in the long term.

As such, this study advances knowledge on the impacts of extensive flood-control infrastructure on hydrodynamic patterns and flood risk upstream and downstream in delta systems. The findings of this study suggest a need to develop flood-based land and water management strategies and farming systems, instead of continued expansion of high-dike infrastructure and related farming systems. Indeed, this study found higher economic and environmental returns to the low-dike farming systems in the long run. However, certain advantages of the high-dike systems must be recognized, such as their protection of built up areas and farmers' ready access to the stable market for rice.

Tóm tắt nghiên cứu

Nhằm đảm bảo an ninh lương thực quốc gia, Việt Nam phát triển mạnh sản xuất lúa tăng vụ trên vùng trữ lũ Tứ Giác Long Xuyên và Đồng Tháp Mười thượng lưu Đồng bằng sông Cửu Long (ĐBSCL). Sự phát triển đã thay đổi vùng sinh thái nông nghiệp sinh kế nhờ lũ trở thành vùng chuyên canh lúa hai vụ và ba vụ được bảo vệ ngăn nước lũ vào đồng ruộng bằng các hệ thống đê bao cao và đê bao tháng tám. Nhờ chính sách này, vùng ĐBSCL trở thành một trong những vùng kinh tế lớn đóng góp chính cho vị thế hàng đầu của quốc gia trên thế giới về xuất khẩu khẩu gạo. Tuy nhiên, chính sự phát triển này đã và đang làm giảm khả năng trữ lũ của vùng đồng bằng, làm suy thoái đất và chất lượng nước, đe dọa hệ thống sinh thái của vùng.

Luận văn nghiên cứu theo mục tiêu được chia làm hai phần: đánh giá tác động của việc phát triển đê bao lên dòng chảy và cơ chế lũ, đồng thời nghiên cứu xác định các giải pháp thích ứng nhằm gia tăng tối đa bền vững sinh kế và bền vững sinh thái cho nông dân nông thôn trên cơ sở xem xét phát triển toàn diện toàn bộ vùng đồng bằng. Nghiên cứu đã phát triển các kịch bản xây dựng đê bao dựa trên mô hình thủy lực một chiều-giả định hai chiều nhằm mô phỏng mực nước và dòng chảy lũ. Sau đó, nghiên cứu đánh giá và đề xuất các hệ thống canh tác nông nghiệp sinh kế bằng công cụ phân tích đa tiêu chí và phân tích lợi ích-chi phí dựa trên quan điểm phát triển sinh kế bền vững. Các đánh giá sinh kế bền vững cho được thực hiện bằng cách phỏng vấn nông dân ở các vùng đê bao khác nhau trong vùng nghiên cứu và thảo luận nhóm cùng nhiều chuyên gia nông nghiệp. Các kết quả đánh giá sau đó được sử dụng để đánh giá lợi ích chi phí cho toàn vùng đồng bằng dưới các kịch bản phát triển đê bao tương lai.

Luận văn có cấu trúc gồm các chương là từng bài báo đã và sẽ gửi xuất bản cho các tạp chí quốc tế có phản biện. Chương 1 giới thiệu nội dung cơ bản về lý do nghiên cứu, khung khái niệm, các phương pháp khoa học được sử dụng, và mục tiêu nghiên cứu. Chương 6 khái quát lại các câu hỏi và mục tiêu nghiên cứu trước khi tóm tắt và thảo luận chung các kết quả dưới góc độ đánh giá toàn bộ thông điệp và đóng góp khoa học của nghiên cứu.

Chương 2 phân tích tác động của đê bao lên dòng chảy lũ vùng ngập lũ và toàn hạ lưu đồng bằng dựa trên các kịch bản phát triển đê bao tháng tám và đê bao cao. Các phân tích cho thấy việc xây dựng đê bao cao vùng Tứ Giác Long Xuyên đã làm suy giảm nghiêm trọng khả năng trữ lũ của vùng rốn lũ. Mực nước trên sông và kết quả tính toán phân phối dòng chảy cân bằng cho thấy vùng rốn lũ gia tăng khá nhiều dưới do việc phát triển đê bao, đặc biệt là giai đoạn từ năm 2000 đến 2011, thời điểm phát triển mạnh đê bao cao bảo vệ canh tác lúa vụ ba. Mặc dù mô hình thủy lực cho thấy ít tác động lên dòng chảy ở vùng sông hạ lưu, điều mà nghiên cứu cũng chỉ ra là do các giới hạn của mô hình một chiều giả định hai chiều, phương pháp cân chỉnh và sự thiếu dữ liệu đo đạc để kiểm định toàn diện cho toàn bộ vùng đồng bằng.

Chương 3 tập trung đánh giá phân tích đa tiêu chí các mô hình canh tác thay thế triển vọng bền vững sinh kế dựa trên nhận thức của nông dân và chuyên gia. Trong đó, các nông dân và chuyên gia cho trọng số và đánh giá mức độ bền vững theo các tiêu chí bền vững sinh kế cho các mô hình canh tác có thể khai thác lợi ích từ lũ bảo vệ bởi đê bao tháng tám cao hơn so với các mô hình canh tác được bảo vệ bởi đê bao cao. Ngược lại, kết quả từ các cuộc phỏng vấn nông dân cho thấy đê cao vẫn được đánh giá cao hơn đê tháng tám nhờ hai lợi thế chính là bảo vệ tài sản và tính mạng cho con người, và bảo đảm canh tác lúa vụ ba nhờ vào thị trường bền vững của loại nông sản lâu đời này.

Chương 4 trình bày kết quả phân tích lợi ích chi phí của các hệ thống canh tác nông nghiệp vùng đê cao so với các mô hình thay thế dựa vào lợi ích từ nước lũ. Trong đó, các mô hình canh tác trong vùng đê bao tháng tám được đánh giá là bền vững hơn về mặt kinh tế và môi trường so với các mô hình trong vùng đê bao cao. Trong vùng được bảo vệ bởi đê bao cao, lợi nhuận canh tác ngày càng giảm do chi phí sản xuất ngày càng tăng cao (như thuốc trừ sâu và phân bón gia tăng). Kết quả nghiên cứu của chương này cho thấy chi phí nông nghiệp đã và đang tăng tỷ lệ thuận với số năm canh tác chính là hậu của của việc đất canh tác bị suy thoái do canh tác lúa ba vụ mà được bảo vệ bởi đê bao cao.

Chương 5 đi sâu phân tích lợi ích chi phí các kịch bản phát triển đê bao tương lai ở cấp độ toàn vùng đồng bằng. Tác động của các kịch bản xây dựng đê bao theo giả thiết bảo vệ các hoạt động canh tác nông nghiệp cho vùng lũ gây ra những tác động nội vùng và ngoại vùng được tính toán theo các giá trị quy đổi thành tiền. Kết quả cho thấy các kịch bản nếu phát triển toàn bộ đê bao tháng tám thành đê bao cao cho toàn bộ vùng rốn lũ thì sẽ làm tăng chi phí nội vùng và cả ngoại vùng (rủi lo lũ gia tăng hạ lưu, giảm lượng bùn cát, xâm nhập mặn, và sạt lở bờ sông).

Nhìn chung, nghiên cứu này giúp xác định những tác động to lớn của đê bao lên vùng lũ vùng đồng bằng, được xây dựng nhằm bảo vệ canh tác lúa ba vụ trong những thập niên vừa qua. Hơn nữa, nghiên cứu cũng cho thấy các giải pháp là hoàn toàn khả thi. Một số giải pháp canh tác được xác định trong nghiên cứu cho thấy có thể mang lại nhiều lợi ích và bền vững.

Như vậy, nghiên cứu này nâng cao kiến thức về những tác động của các hệ thống đê bao và công trình thủy lợi lên chế độ thủy lực và những thay đổi dòng chảy mùa lũ hạ lưu và thượng lưu vùng đồng bằng. Kết quả nghiên cứu đề xuất việc cần thiết phải phát triển các chiến lược quản lý đất và nước, và các mô hình canh tác nông nghiệp dựa trên việc khai thác song song những lợi ích từ nước lũ, thay vì nhắm vào việc phát triển đê bao cao chỉ có lợi cho canh tác lúa ba vụ. Nghiên cứu này cho thấy những lợi ích lâu dài về mặt kinh tế và môi trường của các hệ thống canh tác trong vùng đê bao tháng tám, nơi để đất nghỉ ngơi trong vụ ba để đồng ruộng ngập lũ. Tuy nhiên, để phát triển canh tác các hệ thống nông nghiệp trong vùng đê bao tháng tám, những lợi ích của đê bao cao về mặt bảo vệ tính mạng và tài sản con người và thị trường bền vững cho các mặt hàng nông sản cần được chú trọng.

Samenvatting

Het gebruik van de uiterwaarden in de noordelijkste gebieden van de Vietnamese Mekongdelta is de afgelopen decennia sterk veranderd. Ingegeven door nationaal voedselzekerheidsbeleid heeft hoogintensieve rijstbouw de plaats ingenomen van landbouwactiviteiten die afgestemd waren op de (overstromings)seizoenen. Om deze intensieve rijstbouw mogelijk te maken is in de delta op grote schaal waterbouwkundige infrastructuur aangelegd, met name lage en hoge dijken, om waterstromen zoveel mogelijk te controleren. Toegenomen voedselproductie heeft er vervolgens toe geleid dat de Mekongdelta een zeer belangrijke bijdrage levert aan de nationale voedselzekerheid, en dat Vietnam één van de grootste rijstexporterende landen ter wereld is. Op hetzelfde moment heeft deze transformatie geleid tot een gereduceerde capaciteit om overstromingspieken op te kunnen vangen, tot verarmd land en een verlaagde waterkwaliteit, en zijn de unieke ecosystemen in de delta onder druk komen te staan.

De twee belangrijkste doelen van het onderzoek dat wordt gepresenteerd in deze dissertatie zijn: het identificeren van de gevolgen van de wijdverspreide aanleg van overstromingsinfrastructuur op waterdynamieken in de delta, en het verkennen van adaptatiemogelijkheden om de duurzaamheid van zowel het levensonderhoud van communities als de ecologie in de delta te verbeteren. Een reed beschikbaar 1D-quasi2D hydrodynamisch model is verder ontwikkeld om overstromingsdebieten en rivierwaterstanden te simuleren op de schaal van de Mekongdelta. Hierbij zijn 4 verschillende scenario's van dijkinfrastructuur gebruikt. Vanuit het perspectief van duurzaam levensonderhoud zijn alternatieve landbouwsystemen onderzocht, gebruik makend van multi-criteria en kosten-baten analyses op lokaal niveau. Hiervoor zijn ook interviews gevoerd, waarbij met belanghebbenden is gesproken over verschillende manieren om met dijksystemen en waterbeheersing om te gaan, in verschillende delen van de uiterwaarden. De volgende stap was het verder in kaart brengen van kosten en baten op de schaal van de hele delta, waarbij ook verschillende toekomstscenario's in overweging zijn genomen.

De structuur van deze dissertatie is gebaseerd op wetenschappelijke artikelen, wat betekent dat de individuele kernhoofdstukken (hoofdstukken 2-5) bestaan uit artikelen die zijn ingediend en/of gepubliceerd door peer-review wetenschappelijke tijdschriften. Hoofdstuk 1 geeft algemene achtergrond en presenteert het de probleemstelling, het conceptuele raamwerk, methodologie en de onderzoeksdoelstellingen. Hoofdstuk 6 blikt terug op de onderzoeksvragen en –doelstellingen, en reflecteert op de onderzoeksresultaten zoals gepresenteerd in de individuele hoofdstukken.

Hoofdstuk 2 analyseert de gevolgen van de wijdverspreide aanleg van overstromingsinfrastructuur in de noordelijkste gebieden van de Vietnamese Mekongdelta. Het betreft hier met name de aanleg van lage en hoge dijksystemen. De analyses laten zien dat het aanleggen van een systeem van hoge dijken in de Long Xuyen Quadrangle de capaciteit om overstromingswater ter plaatse op te kunnen vangen, sterk gereduceerd is. Verder zijn pieken in waterafvoerniveaus sterk gestegen, en berekeningen van de waterbalans laten zien dat het overstromingswater zich op een andere manier over het gebied verspreidt dan voorheen. Echter, de hydrodynamische gevolgen zijn relatief gezien beperkt voor de gebieden verder stroomafwaarts. Daarnaast gaven de resultaten aan vooral significant te zijn voor de periode 200-2011, in de tijd dat de meeste hoge dijken zijn aangelegd. Dit laatste punt zou een uitkomst kunnen zijn van de onderzoeksmethodologie, omdat er beperkingen waren bij het simuleren van veranderingen in de waterniveaus stroomafwaarts.

Hoofdstuk 3 brengt het perspectief van boeren en experts op alternatieve, overstromingsgebaseerde landbouwsystemen naar voren. Hiervoor zijn wederom multi-criteria analyses en perspectieven op duurzaam levensonderhoud van communities in de delta gehanteerd. De belanghebbenden die hieraan deelnamen hadden een voorkeur voor landbouwsystemen gebaseerd op bescherming door lage dijken, in plaats van landbouwsystemen gebaseerd op hoge dijken. Boeren die echter al twee of drie rijstoogsten per jaar produceerden, hadden een voorkeur voor de al aanwezige hogere dijksystemen. Hoge dijken maken deze oogsten mogelijk en beschermen stedelijke gebieden tegen overstromingen. Ook de stabiele rijstmarkt is een belangrijke factor.

Hoofdstuk 4 presenteert een kosten-baten analyse van hoge dijksystemen en overstromingsgebaseerde alternatieven op lokaal niveau. Landbouwmethoden gebaseerd op lage dijksystemen werden duurzamer bevonden in zowel economische als milieutechnische zin. De direct voordelen van landbouwmethoden onder hoge dijksystemen worden in de loop der tijd minder, omdat intensieve productie ook meer landbouw inputs (kunstmest en pesticiden) vereist. De resultaten laten zien dat de kosten van benodigde landbouw inputs in gebieden met hoge dijksystem en drie rijstoogsten per jaar de afgelopen jaren zijn gestegen, omdat er sprake is van een verminderde bodemkwaliteit.

Hoofdstuk 5 werkt de kosten-baten analyse verder uit, maar met een focus op de schaal van de hele delta. Daarbij zijn waarden bepaald voor zowel interne als externe factoren die invloed uitoefenen op toekomstige landgebruikscenario's en dijksystemen. De resultaten laten zien dat het verhogen van alle lage dijksystemen tot hoge dijksystemen langs uiterwaarden en rivieren tot grote interne (constructie, gebruik, onderhoud) en externe (toename potentiële schade van overstromingen, en tegengaan van sedimentatie, zoutindringing en oevererosie) kosten zou leiden.

Dit onderzoek heeft aangetoond dat de wijdverspreide aanleg van dijkeninfrastructuur ten behoeve van intensieve rijstproductie in de afgelopen tientallen jaren significante gevolgen heeft op waterdynamieken in de delta. Daarnaast laat het onderzoek zien dat alternatieve vormen van landbouw mogelijk zijn. Sommige van deze alternatieven zijn kosteneffectiever en ook duurzamer op de lange termijn.

Hiermee draagt het onderzoek bij aan het vergroten van de kennisbasis rondom de gevolgen van het aanleggen van overstromingsinfrastructuur op waterdynamieken en overstromingsrisico's in zowel bovenstroomse als benedenstroomse gebieden in delta's. De uitkomsten van het onderzoek roepen op tot het ontwikkelen van watermanagementbeleid en landbouwsystemen gebaseerd op overstromingen, in plaats van het verder uitbreiden van hoge dijksystemen en de hieraan gerelateerde landbouwbenaderingen. Systemen met lage dijken hebben hogere economische en milieuwinsten op een langere termijn. Op hetzelfde moment moeten ook de voordelen van hoge dijksystemen, zoals het beschermen van de gebouwde omgeving en steden, niet vergeten worden, en is ook de stabiele rijstmarkt een factor van belang.

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Wageningen, the Netherlands

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Curriculum Vitae

Dung Duc Tran was born in 1982 in Nghe An, a province located in the Central North of Vietnam.

He did bachelor of Irrigation and Water Resources Management in 2000 at Water Resources University in Ho Chi Minh City, Vietnam. After the successful bachelor graduation in 2005, he worked as a water-engineering researcher at Southern Institure for Watere Resources Planning (SIWRP) in Ho Chi Minh City until 2014. During his time at the SIWRP, Dung successfully applied for a scholarship of Vietnamese Ministry of Agriculture and Rural Development sponsored by World Bank. By the opportunity offered in 2008, he conducted the MSc program in April 2009 at UNESCO-IHE, the Netherlands in Hydrology and Water Resources Specialisation. He achieved the MSc degree in 2011 and continued his work for SIWRP. In 2014, Dung Duc Tran pursued his PhD at Wageningen University, the Netherlands funded by NUFFIC/NICHE VNM 104 project which contained cooperation between the Netherlands and Vietnam governments. The PhD defence was in November 2018.

After completion of his PhD, Dung continues working as a key researcher in Center of Water Management and Climate Change, Ho Chi Minh National University. In addition, he will work for ASEAN fellow program based on 1-year contract awarded to17 talented young scientists from 10 ASEAN countries. The fellowship, sponsored by the US-ASEAN Foundation, aims to help young scientists build capacity in developing scientific works in support of decision making process in ASEAN countries.

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- Techniques for writing and presenting a Scientific Paper (2014)
- R and Big Data (2017)
- Bayesian Statistics (2017)
- Research in context activity: 'Co-organizing and participating in research field trips in the Netherlands (2014) and Vietnam (2016), and reporting on these experiences in lively internet blogs' (2017)

Other PhD and Advanced MSc Courses

- Cost-benefit analysis and environmental valuation, Wageningen University (2014)
- Scientific writing, Wageningen Graduate Schools (2017)
- Presenting with impact, Wageningen Graduate Schools (2017)

External training at a foreign research institute

- Resilience and adaptation to climate change for sustainable management of tidal area, Working group on Sustainable, National Cheng Kung University, Taiwan (2016)

Management and Didactic Skills Training

- Supervising MSc student with thesis entitled 'Flood control in Vietnamese Mekong Delta, A case study research the high dike system of Phu Tan district.' (2014)
- Supervising BSc student with thesis entitled 'Decision-making of smallholder farmers on crop variety in Cho Moi, Vietnam' (2016)

Selection of Oral Presentations

- *Research proposal and results: on the implication of dike constructions on flood regimes in the Mekong Delta.* Seminar Workshop in Centre of Water Resources And Climate
- *Panel member on alternative farming systems.* International Workshop "Appropriate Technology Solutions for Water, Energy and Land Management in the Mekong Delta", 14-17 June 2016, Can Tho, Vietnam
- *Multi-criteria analysis for alternatives in flood-based farming systems to contribute a sustainable livelihood in Vietnamese Mekong Delta, a case study: An Giang Province*. International Conference on Water Resource and Environment (WRE), 23-26 July 2017 Shanghai, China

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