UNIVERSITY OF SOUTHAMPTON

FACULTY OF SOCIAL, HUMAN AND MATHEMATICAL SCIENCES

Geography and Environment

Evaluating an Adaptation: Rice-Sediment Trade-offs in the Vietnamese Mekong Delta

by

Alexander David Chapman

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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EVALUATING AN ADAPTATION: RICE-SEDIMENT TRADE-OFFS IN THE VIETNAMESE MEKONG DELTA

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The exceptional vulnerability of river deltas to climate change and development pressures means there is an urgent need to implement systemic adaptation actions. One of the most important cases is the Vietnamese Mekong Delta (VMD). This thesis performs a novel application of a system dynamics methodology to evaluate the VMD's dyke network as a hard adaptation to changes in the region's hydrological conditions. In doing so it makes a methodological and case study contribution to an emerging research body on the evaluation of adaptation action. Policy analysis and stakeholder consultation are first performed to elucidate the drivers behind the policy to heighten the VMD's dyke network. A farmer survey is then executed within the rice-growing community in order to quantify the socioeconomic impacts of the adaptation. Finally, a system dynamics model is built to explore the dynamics controlling the impacts of the adaptation and the efficacy of alternative policies for the local agricultural system. A key original theme running through this thesis is its consideration of the socioeconomic role of fluvial sediment in the system.

The principle finding, on which both the model and survey agree, is that the switch to high dyke compartments in the VMD (the adaptation) is exacerbating the divide between land-rich and land-poor farmers through the promotion of triple-cropping and sediment exclusion. Factors including the loss of free sediment-bound nutrients for fertilisation, and increasing fertilisation demands, reduce the resilience of poorer farmers to increasing and unpredictable fertiliser prices. The policy currently recommended by the provincial governments to encourage sediment accretion and mitigate the rate of relative sea-level rise is to advocate triennial inundation of paddies. The data presented herein suggest such a policy is sub-optimal, further increasing the risk of debt for smaller-scale farming operations. The testing of various different success criteria weightings did, however, suggest that the less rigid policy of allowing sporadic floodplain inundation and sediment deposition during intense flooding events is preferable to most stakeholder groups.

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List of Accompanying Materials

At the time of going to print two publications had emerged from this thesis, both currently in press:

Chapman and Darby (2016) which constitutes the majority of **Chapters 6** and **7**, barring **Sections 7.4.6** - **7.7**:

Chapman, A.D. & Darby, S.E. (2016) Evaluating sustainable adaptation strategies for vulnerable mega-deltas using system dynamics modelling: Rice agriculture in the Mekong Delta's An Giang Province, Vietnam. Science of the Total Environment, *in press*.

Chapman et al. (2016) which constitutes the entirety of **Chapter 5**:

Chapman, A.D., Darby, S.E., Hồng, H.M, Tompkins, E.L. & Van, P.D.T. (2016) Adaptation and development trade-offs: Fluvial sediment deposition and the sustainability of rice-cropping in An Giang Province, Mekong Delta. Climatic Change, *in press*.

One further publication is planned which will include the material presented in **Sections 7.4.6** - **7.7**.

DECLARATION OF AUTHORSHIP

I, Alexander David Chapman

declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

Evaluating an Adaptation: Rice-Sediment Trade-offs in the Vietnamese Mekong Delta

....

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as: Chapman and Darby, 2016; Chapman et al., 2016 (see list of accompanying materials).

Signed: ....

Date: ....

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My parents, Mrs Joy Chapman and Dr David Chapman, and brother, Mr Vincent Chapman, I thank for the skills, the confidence, the comforts and most importantly the love that has carried me here.

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…and finally, Bob Craven, who would have proof read this thesis, thank you.

Definitions and Abbreviations

CP	Cash Profit
DF	Desired Fertilisation level
GS_q	General Sensitivity degree
MADM	Multi-Attribute Decision Making
MARD	Ministry of Agriculture and Rural Development of the Vietnamese Government
MASL	Metres Above Sea Level
MCDA	Multi-Criteria Decision Analysis
MDP	The Mekong Delta Plan (MDP, 2013)
MNRE	Ministry of Natural Resources and the Environment of the Vietnamese Government
MPI	Ministry of Planning and Investment of the Vietnamese Government
RE	Relative Error
RSLR	Relative Sea-Level Rise
RY	Rice Yield
SDM	System Dynamics Model
SE	Systematic Error
S_q	Sensitivity degree
TE	Technical Efficiency
VMD	Vietnamese Mekong Delta
Vu	(*Vietnamese*) A cropping season
Yielfert	Yield/Fertiliser ratio

Chapter 1: Introduction

"Adaptation and mitigation are the dual challenges of climate change. They stand out among the many environmental problems of the new century. They will challenge you to get involved, and you will be confronted with dynamics that are difficult to understand. May you find system dynamics helpful in building understanding. And may your efforts lead to a better world."

– Andrew Ford (2010, p. 314)

1.1 Positioning of this thesis

Climate change is happening and has been documented in the oceans, the atmosphere, and on every one of Earth's continents (Hansen and Cramer, 2015). Around the globe the impacts of these changes are being documented (Smith et al., 2014). In many such instances the pressures brought by climate change are inseparable from other natural and anthropogenic pressures on society (O'Brien and Leichenko, 2000). As the intensity and frequency of environmental pressures on social-ecological systems increases, the importance of implementing adaptation strategies to cope with those pressures also grows. Large investments have, and will, be made into fundamental alterations to earth's environment, in the name of both climate change adaptation and mitigation (Chambwera et al., 2014). Past experiences suggest that extreme caution should be applied when humans intervene to manage earth's natural cycles, as the unintended consequences can be wide-ranging and irreversible (Steffen et al., 2007). Unintended consequences are a particular feature of the current epoch, informally termed the *anthropocene*, during which humans have been the dominant influence over the processes controlling earth's systems (Syvitski and Kettner, 2011). Any mistakes made in the adaptation process, (termed *maladaptations* by Barnett and O'Neill, 2010), will only serve to worsen an already precarious situation for global ecosystems and the most vulnerable members of our society (MEA, 2005). The latest IPCC report warns that misunderstandings, conflicting objectives, and short-term thinking may bring *emergent risks*; defined as those negative outcomes which result from the systemic interactions of concurrent mitigation, adaptation, and development actions (Oppenheimer et al., 2014).

An optimist's stand-point might be that it is in fact possible to design successful adaptations, i.e. interventions capable of alleviating undesirable impacts without unintended consequences (Doria et al., 2009). But, others would contend that in systems of high complexity, and given the normative nature of how success is defined, such interventions are unlikely (McDowell et al., 2014). A more pragmatic position is that adaptations must be evaluated to identify their weaknesses and implicit trade-offs (Suckall et al., 2014b) and, if negative side-effects are either unavoidable or only perceived post-action, further action (*second-order adaptation*) is carried out in order to alleviate them (Birkmann, 2011). It is in the areas of first and second-order adaptation evaluation, and particularly the evaluation of their potential to create emergent risks when they interact with other human objectives, that empirical research is only just beginning to emerge. There are currently a low number of methodologies, applicable only to specific contexts, and particularly a low number of practical examples (Bours et al., 2013). This thesis makes a contribution to this methodological knowledge gap, evaluating an important and topical case study adaptation utilising a novel, tailored, version of a system dynamics methodology.

1.2 The Mekong Delta as a case study

River deltas are archetypal examples of systems that are extremely sensitive to anthropogenic and environmental pressures. Over past centuries humans have driven dramatic changes in their physical characteristics, and their sensitivity now makes them particularly vulnerable to the impacts of climate change (Syvitski and Kettner, 2011). However, deltas' sensitivity to change not only makes them vulnerable to climate change but also brings with it potential for maladaptation and emergent risk. As development hotspots, populated to ten times the global average, and making a major contribution to global food security, there is a particularly strong case for the analysis and evaluation of any action taking place in these regions (Ericson et al., 2006). Especially, with the growing threat of delta drowning (Syvitski et al., 2009), the growing problem of anthropogenic influences accelerating the rate of *relative sea-level rise* (RSLR - the net sea-level change when all factors including terrestrial drivers such as land subsidence are accounted for). The Vietnamese Mekong delta (VMD), shown in **Figure 1.1**, lies at only 5m or less above current sea-level (Van et al., 2012) and faces 6 mm of relative sea-level rise every year (Syvitski et al., 2009). This threat in particular gives the delta's 18 million inhabitants, and their substantial agricultural exports, extreme vulnerability to climate change (Nicholls et al., 2007). Further challenges related to climate change include the increased frequency and intensity of storms, droughts and fluvial flooding (Collins et al. 2013).

A significant process which acts to mitigate RSLR and both temporary and permanent inundation is the deposition of sediment on the delta's extensive floodplains (Syvitski and Kettner, 2011). The fluvial sediment flux carried from the Mekong Basin to the delta by the river builds the plains and helps counteract the natural process of sinking. Furthermore, sediment provides a host of services to delta communities (termed *sediment services* henceforth), including the provision of nutrients for agriculture and the stabilisation of river banks and coasts, upon which existing infrastructure depends. Despite a relatively poor level of understanding of the importance and requirements for provision of these sediment services, two key developments are being pursued which may fundamentally alter service provision.

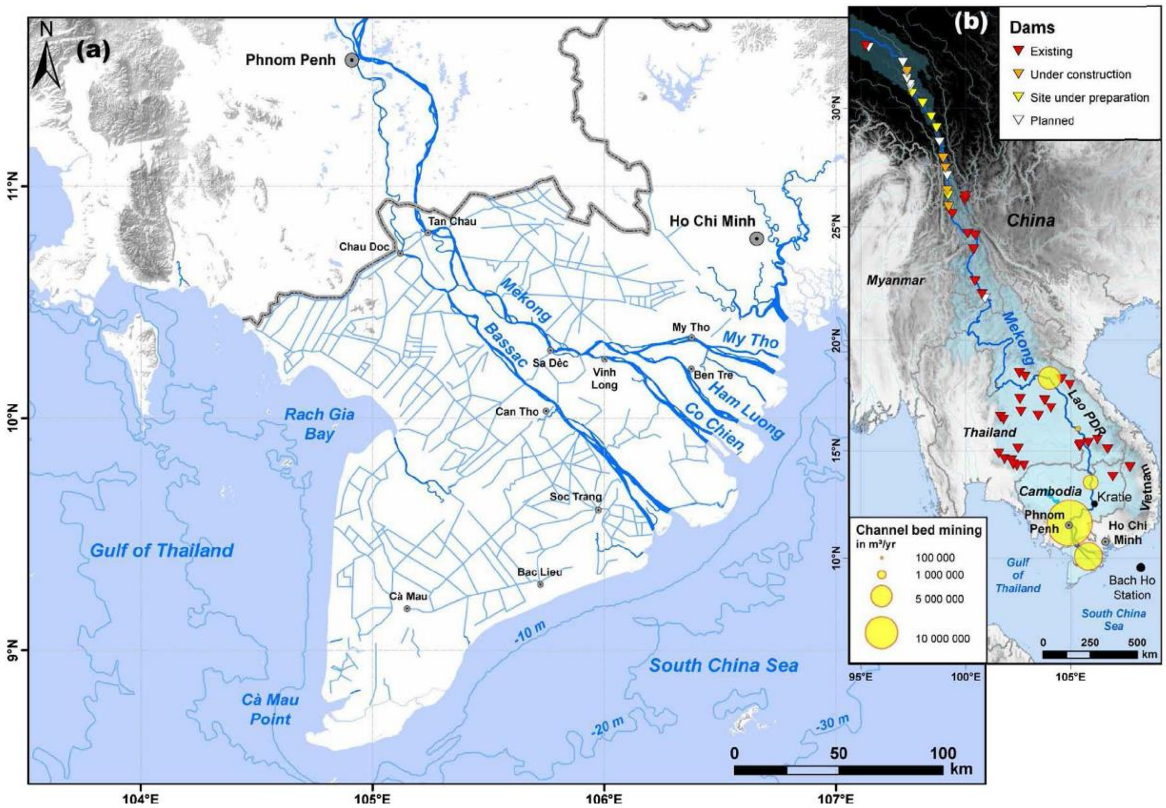


Figure 1.1 The Mekong Delta, highlighted (a), its extensive network of rivers (thick blue lines) and canals (thin blue lines), and (b) the Mekong Basin with the planned and constructed dams highlighted (Anthony et al., 2015).

Upstream, the construction of over 100 hydropower mega-dams (**Figure 1.1**) may be considered as both an adaptation and mitigation action. While primarily designed to produce low-carbon energy, there is evidence to suggest that dam construction on the Mekong may help communities adapt to climate change by reducing the impacts of increased runoff variability and extremes (Zhao et al., 2013). However, in doing so, dams regulate the flow, reducing the flood peaks (Poff et al., 2007) which deposit the majority of the sediment on the floodplains, and also potentially trapping 50-94% of the annual fluvial sediment flux upstream (Kondolf et al., 2014; Kummu et al., 2010). Within the delta a separate second adaptation has been taking place[1]; dykes, which traditionally ensured environmental stability for agriculture and livelihoods, are being heightened and expanded to provide protection from both fluvial and coastal flood and storm surges intensified by climate change. In the process, these dykes also reduce the frequency of floodplain inundation and sediment deposition (Birkmann et al., 2012). Again, this adaptation is driven by

[1] Whether the changes to the dyke network should be regarded as an adaptation might be disputed and thus the policy's nature is a matter considered in detail in **Chapter 4**.

mixed objectives, as the higher dykes facilitate the growing of a third annual rice-crop, which is known to be of importance to the Vietnamese government and their development goals (MPI, 2006).

The complex mix of physical changes and different policy objectives described above, that are converging in the VMD, create a sub-system which has potential for Oppenheimer et al.'s (2014) emergent risks. From our existing knowledge, which has seen recent development through the work of Hung et al. (2014a; 2014b) and Manh et al. (2015; 2014), we can establish that sediment is likely to play a central role in any emergent risks. However, great uncertainty currently clouds our understanding of the VMD system, and prohibits fully informed decision making, as highlighted by the knowledge gaps identified in the wide-reaching national strategy document, *The Mekong Delta Plan* (MDP, 2013) published by the Vietnamese government in association with the Kingdom of the Netherlands. The upstream trapping of sediment and the provision of the aforementioned sediment services in deltas are extremely difficult to link due to the processes which take place in the intervening distances (Liu et al., 2013; Petts and Gurnell, 2005) and the complex interaction of sediment dynamics and local management practices. There are also uncertain impacts of climate change on the sediment yield within the river basin (Shreshtha et al., 2013), though at present the available research is limited and even the direction of change is unknown. Perhaps of greatest significance for this thesis is that while our understanding of the physical dynamics of sediment is improving in the Mekong Delta, the interaction of sediment with social and economic systems, such as through its contribution to agricultural fertilisation, has been given very little attention in academic research and is an area identified as requiring attention by the MDP (2013).

In the limited academic literature looking at how dam and dyke development and the poorly understood impacts of climate change may have serious unintended consequences for the Mekong delta's communities is one study which put an economic value on the fertilisation service imparted by deposited sediment. The ICEM (2010) report attributed a loose estimated value of USD $24 million to the fertilisation that would be lost by a 75% reduction in sediment deposition in the VMD, at 2010 fertiliser prices. No study has yet attempted to understand the dynamics of these pressures and their interaction with sediment in a systemic manner that considers local socioeconomic factors and management practices. Neither has any study yet attempted to quantify the impact of the loss of sediment services on the wellbeing of delta communities. This dearth in knowledge has begun to be recognised. Academic publications raise questions about the fertilisation value lost under higher dykes (e.g. Manh et al., 2014) and the relative benefits of flood exclusion in order to allow larger numbers of rice crops to be grown (Pham et al., 2004); and policy documents identify the absence of knowledge on the socioeconomic role of sediment-bound nutrients in adaptation analysis, evaluation, and decision making (MDP, 2013). This gap, which is not only pertinent in the Mekong but in densely populated and productive deltas around the globe, guided the development of the aim of this thesis.

1.3 Aim

The aim of this thesis is to formulate and demonstrate a method of evaluating the development and implementation of a regional-level adaptation strategy (the VMD dyke network) designed to protect deltaic agricultural communities from altered hydrological conditions; and further, to analyse the system dynamics of policies aiming to minimise the negative impacts of this adaptation on local agricultural communities.

1.4 Objectives

1. Understand the drivers and pressures, both physical and socioeconomic, which led to the regional adaptation policy which has been implemented
2. Investigate the impacts, physical and socioeconomic, of the regional adaptation on the local social-ecological system
3. Develop and substantiate a quantitative model capable of simulating the system dynamics under the adaptation, and unearthing the key parameters which determine the adaptation's success (or failure)
4. Analyse the internal dynamics of the simulated system under various post-adaptation policy options and establish the preferentiality of those options from different stakeholders' perspectives
5. Evaluate how different future scenarios of environmental change (external to the system) will affect the dynamics, performance and preferentiality of different policies into the future

1.5 The structure of this thesis

The thesis that follows is divided into seven key chapters: literature review, methodology and case study, four substantive chapters, and the conclusions. This section gives a brief description of the contents of each of these chapters.

1.5.1 Literature review

The literature review (**Chapter 2**) aims to provide the background information required to approach the objectives and research process of this project. Some key questions are asked of the academic literature which relate to the different objectives described above. Those can be summarised as: what are the key processes defining the physical characteristics of deltas? What are the key drivers and pressures of change deltaic regions are subject to? What are the key mechanisms through which hydropower and climate change cause impacts on deltas? What are the future climate change scenarios and impacts projected for delta regions? Where are the key sources of uncertainty in those scenarios? How are those scenarios being approached under current adaptation policy? What can be learned from comparable past responses to environmental change? What methods are currently used to evaluate the impacts of planned and implemented adaptations? What impacts of adaptations have previously been documented? Through what mechanisms do those impacts manifest themselves?

1.5.2 Methodology and case study introduction

The methodology section of this thesis (**Chapter 3**) provides a broad narrative introduction and background to the methodology implemented in this thesis. There are two key components. First, an introduction to the policy analysis, stakeholder consultation, survey, system dynamics modelling, and multi-criteria analysis methods which were integrated in order to evaluate the adaptation and future policy options. Second, a detailed introduction to the case study site (the Vietnamese Mekong Delta). Notably, **Chapter 3** only provides a methodological overview and does not provide the technical aspects of the various methods applied; these details are reserved for the substantive chapters themselves in order to provide a more logical flow.

1.5.3 Substantive chapters

There are four substantive chapters to this thesis. Each chapter is presented loosely in the format of an academic journal paper, the results are preceded by an introduction and review of the methods utilised.

The first, **Chapter 4**, forms a bridge between the literature review and technical chapters. Using policy analysis and stakeholder consultation it tracks the development of the VMD dyke network as an adaptation. In doing so **Chapter 4** provides context to the later analysis and background as to why certain impacts from the adaptation may have arisen (**Objective 1**).

Chapter 5 presents the results of a survey examining the impacts of the adaptation (introduced in **Chapter 4**) on rice-farmers in two provinces of the delta (**Objective 2**), and in the process provides validation data for the system dynamics model produced in **Chapter 6**.

Chapter 6 presents the development of a system dynamics model used to simulate the trends found in **Chapter 5**; and designed to identify the operational mechanisms producing the adaptation's impacts on the local agricultural community (**Objective 3**).

Chapter 7 describes the system behaviours revealed by the model. Subsequently it reports the testing, weighting, and ranking of land-management (second-order adaptation) policies, actual and implemented as well as theorised, aimed at alleviating the negative impacts (revealed in earlier chapters) of the adaptation action under different scenarios of environmental change (**Objectives 4** and **5**).

Throughout each of these four substantive chapters runs a discussion into the significant areas, implications, and limitations of the work being presented.

1.5.4 Conclusions

Finally, in **Chapter 8** the findings of this thesis are summarised, its limitions outlined, and its implications for future research and adaptation policy, in the study area and further afield, are discussed.

Chapter 2: Literature review

2.1 Chapter introduction

This chapter provides the background information necessary to formulate and meet the objectives laid out in **Chapter 1** with due regard to previously conducted research. Running throughout the chapter is a structured investigation into changes to fluvial hydrological and sediment flows through the world's mega-deltas, including the social ramifications of such changes, potential responses, and the challenges faced in formulating successful responses. The case study delta for this thesis, the Mekong Delta, is most frequently cited as an example, but examples from other major deltas are also utilised. **Figure 2.1** presents the general structure which fits loosely to the DPSIR (*Drivers – Pressures – States – Impacts – Responses*) framework. DPSIR is a simple framing tool, pioneered by the OECD (2003), for investigating and elucidating complex issues of environmental change and/or degradation. The framework encourages the presentation of a problem's cause and impacts in a format that is clear and easily translated into effective research and policy (Tscherning et al., 2012).

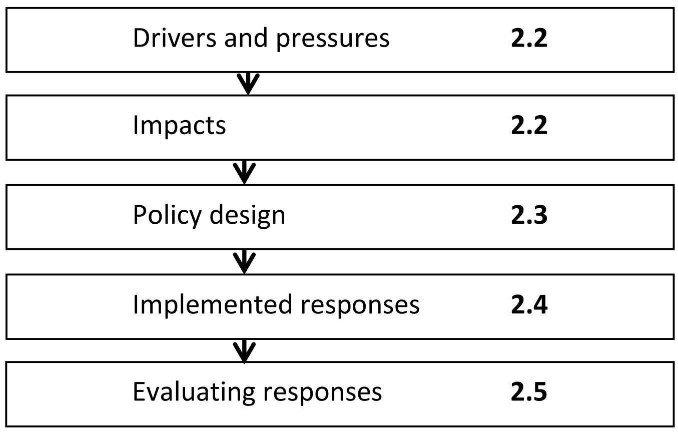


Figure 2.1 The content of Chapter 2 and the corresponding sections.

Section 2.2 begins with a wider discussion of the drivers of environmental change and the pressures they place on deltas, focusing in on the significance of sediment flux changes induced by climate change and dam construction, as well as the processes involved and the documented impacts. As part of the review process **Section 2.2** outlines the future scenarios of dam construction and climate change globally and regionally which are of high relevance to delta regions and also offers some forecasted impacts with regard to water and sediment flows. **Section 2.3** discusses the theory behind, and current state of, policy responses to climate and/or environmental change in deltas, and discusses the future directions of that policy, including some theoretical policy-targeting methodologies proposed in the academic literature. **Section 2.4** goes on to present some implemented and planned adaptations to environmental change in deltas, with mention of the typologies of adaptation which separate action along lines such as: autonomous or planned, scale and administrative levels, hard or soft. Included in **Section 2.4** is a look at how development and adaptation actions often overlap, with a particular focus on the two actions key to this thesis, the construction of river dykes (also termed levees) which control the overflow of rivers and channels, and dams, which store significant quantities of fresh water (also termed reservoirs). **Section 2.5** focuses initially on why and how previous adaptation actions have been evaluated but, due to a lack of evidence, focuses mainly on theoretical methods for adaptation evaluation proposed in the academic literature and particularly indicators of adaptation failure. The chapter ends with some key conclusions which hone the aim and research questions tackled in this thesis.

2.2 What environmental pressures are large delta systems subject to now, and over the coming decades?

This section examines the environmental pressures that threaten the world's mega-deltas, the livelihoods of the half a billion people living in their vicinity (Syvitski and Saito, 2007), and their extraordinary biological diversity (Ziv et al., 2012). The drivers of change are divided into two main categories: environmental pressures resulting from human development, both within deltas themselves and their wider river basins (endogenous and exogenous); and the environmental pressures resulting from climate change. This section particularly focuses on water and sediment flow changes due to their significant role in defining the physical characteristics and survival of a delta.

2.2.1 The impacts of human development on delta systems

In their 2007 paper Syvitski and Saito characterised 51 of the world's largest deltas. Their paper served to highlight the significant impact that human actions have had on the key processes which define the size and function of deltas. Their three main examples, the Yellow River Delta (fundamentally changed since 1855AD due to a dyke breach), the Colorado River Delta (fundamentally changed since 1929AD due to the opening of log jams), and the Po River Delta (fundamentally changed since 1600AD due to canal diversion) illustrate the impacts, planned and unintended, of human development choices on river deltas. Human influences on deltas have been particularly strong since the anthropocene epoch began, and those influences have resulted from actions both endogenous and exogenous to deltas (Syvitski and Kettner, 2011). The latter influences, are explored below and the former, subsequently in **Section 2.2.1.2**.

2.2.1.1 The impact of exogenous economic development on delta processes

Deltas are systemically linked with their river basin and a complex variety of different changes within the upstream feeder network can profoundly impact the delta downstream. The basin's hydrological regime, which brings water for ecosystem and human use, also transfers flora and fauna, sediments, nutrients, and pollutants which can be damaging in both wealth and dearth. A well known example is eutrophication; an excess of nutrients produced by human activities within river basins, can create algal blooms which threaten ecosystem functioning downstream in the delta (Zhao et al., 2012). Of the different exogenous factors influencing the physical characteristics of deltas, it might be argued that increases and decreases in the transfer of sediment can have the most profound impact on a delta's physical composition (Syvitski and Saito, 2007). Syvitski and Saito (2007) cite examples including the running-dry of the Huanghe river in 1997 and the ongoing, rapid, loss of the Mississippi Delta (see Blum and Roberts, 2009) as evidence. Syvitski and Saito's (2007) paper alerts policy makers to the potential impacts of planning large-scale development-oriented actions which may alter the sediment load of rivers, and also any changes that may result from anthropogenic climate change (Shrestha et al., 2013). The process of deltaic sediment deposition, and particularly the issues around its decline, take a central role in this thesis and hence it is discussed extensively both below and in later chapters. However, simultaneously, it must also be recognised that many delta environments have only emerged due to human alterations to water and sediment flows.

Most modern day deltas are built by the deposition of sediment brought by the river from upstream reaches of the basin, which accretes on the delta surface (Syvitski et al., 2009). Delta growth (*progradation*) prevails when the rate of deposition outstrips the rate of natural subsidence of the delta body. This sediment supply not only aids the building of deltas, but can also provide nutrients to sustain productive delta ecosystems (Olde Venterink et al., 2006). There is evidence that in the pre-industrial era humans contributed to the expansion of river deltas. Sediment loads increased due to activities such as: mining; deforestation; land conversion; poor farming practises; and road construction (Syvitski and Kettner, 2011). Of those contributors to delta progradation, the largest is suspected to have been deforestation. The 660% increase in suspended sediment discharge following deforestation of the Waipaoa River's drainage basin, and the major increase in sediment loads in the Yangtze basin, are good examples (Kettner et al., 2007; Liu et al., 2007).

Unfortunately, data attesting to just how significant a contribution humans made to delta formation is scarce. Along the better documented eastern coast of the United States there is evidence of an eight-fold increase in estuarine sedimentation rates taking place soon after human settlement began in the mid-1700s (Syvitski and Kettner, 2011). Better knowledge about the influence of humans on delta growth can instead be garnered from modern-day case studies. The Issaquah Creek Delta in the Northwest USA, is one example that has been studied in detail (see Nelson and Booth, 2002). In the space of only a decade (1985-95) the surface area of Issaquah Creek Delta almost doubled from 11,900 km^2 to 21,000 km^2 as a result of sediment-induced land building. Two of the key contributors to the increased sediment load which allowed this expansion relate to urbanisation, specifically land-surface erosion resulting from road-surface expansion, and channel-bank erosion induced by the increased runoff filtered into tributary rivers by urbanising landscapes (ibid). Another example is the modern Brazos Delta, which formed as an unplanned consequence of the engineered diversion of the sediment flow of the Brazos river, which was designed to strategically reduce flooding near to sensitive urban settlements (Rodriguez et al., 2000).

However, looking globally, since the industrial era the situation has rapidly changed for many major deltas (see **Figure 2.2**); river diversions and particularly dam construction have resulted in the re-direction and upstream trapping of sediment.

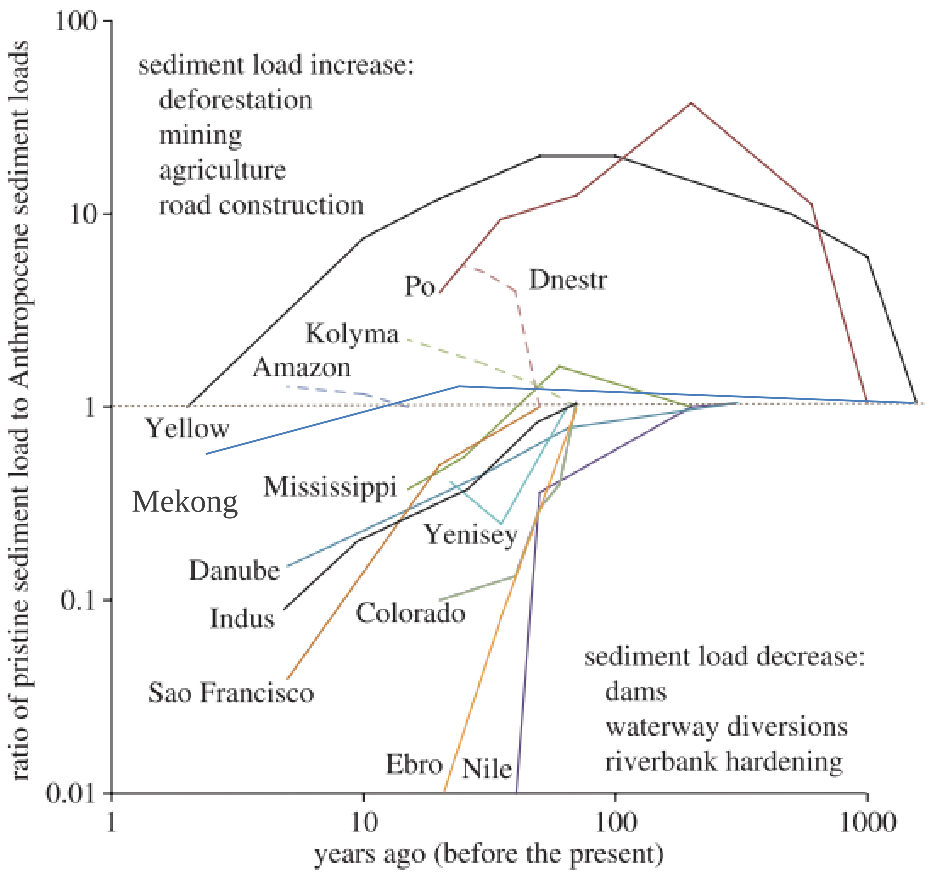


Figure 2.2 Changes in sediment loads carried by selected rivers adapted from Syvitski and Kettner (2011), Mekong estimate approximated from Lu and Siew (2006).

The Huanghe (Yellow River) Delta represents a microcosm of this phenomenon, experiencing a ten-fold increase in sediment flux over a millennium, reaching a maximum in the 1980s and, in the following two decades, reducing by 20% due to reservoir construction and other developments (Wang et al., 2007; Meybeck, 2003).

In the year 2000 the World Commission on Dams (WCD) report estimated that there were approximately 45,000 registered reservoirs on the planet. Vorosmarty et al. (2003) suggest those dams can be divided into 'large' (capacity >0.5 km^3) of which in 2003 there were 749, 'small', of which there were approximately 44,700, and 'smaller-unregistered' of which there may be >800,000. Attempts are underway to build dam databases which hold up to academic scrutiny (e.g. Mulligan et al., 2009), notably Lehner et al. (2011) report on the GRanD databse which, at the time of publication, held information on 6,862 dams but, as yet, none are complete. Vorosmarty et al. (2003) conservatively estimated that worldwide reservoirs are currently trapping 25-30% of the annual global fluvial sediment flux. However, despite the increase over the past 20 years in the quantity of academic research which highlights the ecological damage caused by dam-induced river regulation (see **Figure 2.3**), a resurgence of dam construction in developing countries is indicated by recent publications (see **Figure 2.4**).

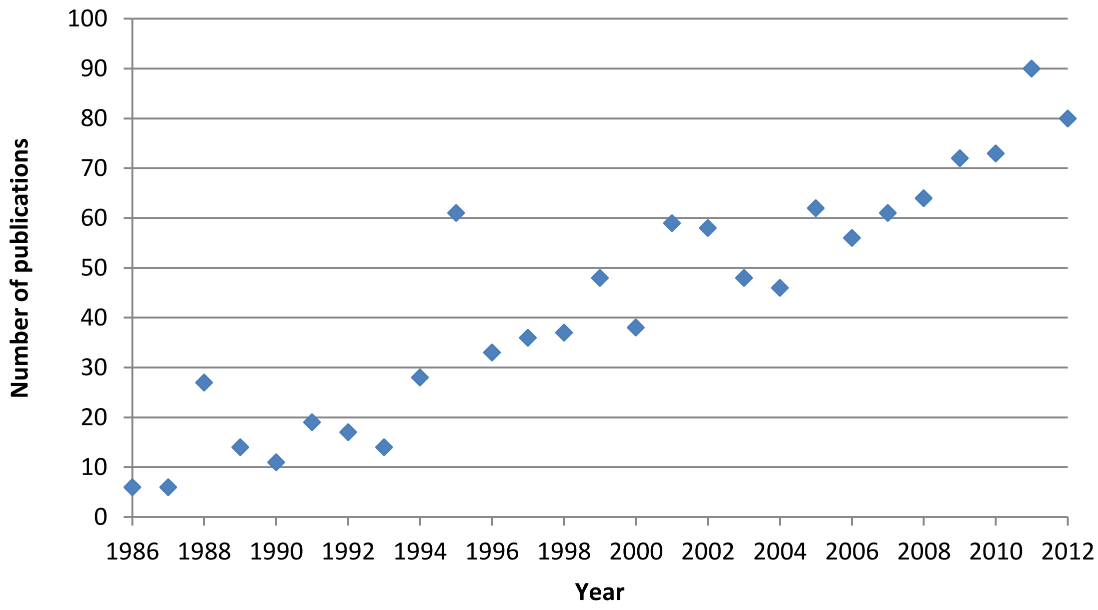


Figure 2.3 Number of publications in each year between 1986-2012 with "regulated river" or "river regulation" in the topic based on a Web Of Knowledge (WOK) search on 21/01/2013.

There is evidence to suggest that large reservoirs are currently being constructed at a rate of more than 1000 a year (Syvitski and Kettner, 2011). Of particular significance are the large dams under construction, for example: in the Lower Mekong Basin as many as 89 large dams could be under construction or completed by 2030 (Ziv et al., 2012); in the Andean Amazon region there are plans for 151 large dams (Finer and Jenkins, 2012); India is making progress on 33 projects (WWAP, 2012); and several dams are planned in east (McCartney and Girma, 2012) and west (Morand et al., 2012) Africa. The main motivation behind the construction of these dams has changed from the traditional drivers of agricultural intensification and flood control to hydropower generation and, in some cases, adaptation to climate change is also cited (e.g. Beckman, 2011; Barbier et al., 2009 cited in Morand et al., 2012). Whether the water storage and flood control properties of dams constitute adaptations, which is a controversial issue, is discussed further in **section 2.4.2.2**.

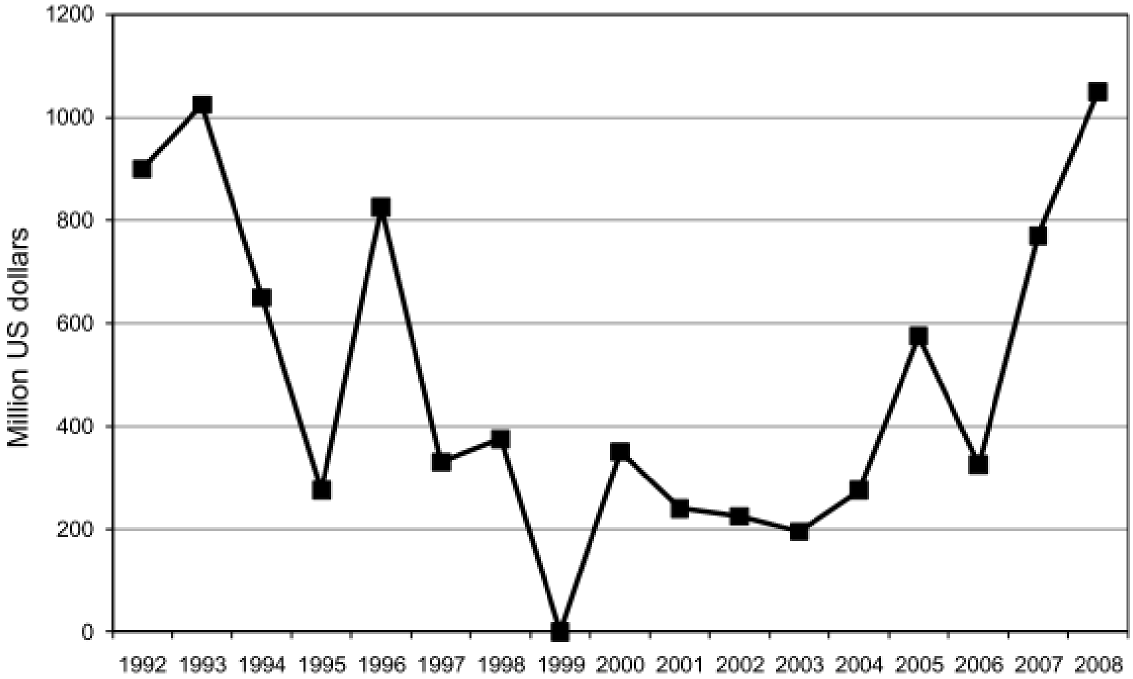


Figure 2.4 Global investment in dams between 1992-2008 in real terms, showing a ten year slump followed by a recent increase (Richter et al., 2010 adapted from World Bank Group, 2009).

The impacts of dam construction on downstream deltas are varied, many, and, due to the system size and complexity, often indirect and difficult to link. Kummu and Varis (2007) divide those impacts into three main categories (i) the trapping of sediment (as discussed above) (ii) the controlling of the water flow, in almost all cases dammed rivers exhibit a decline in average maximum flow and inter-annual daily maxima variability, and increased minimum flows (Poff et al., 2007); and (iii), blocking the river – dams place a physical barrier between biotopes (Ward and Stanford, 1995). **Table 2.1** explores specific impacts within these categories using the Mekong river as a case study to illustrate recent research into the various impacts of dams on downstream deltas. With such a myriad of positive and negative impacts represented in **Table 2.1** the motivation, and particularly financing, behind dam construction is an area which is hotly debated, but not discussed in detail here (see Merme et al., 2013; Richter et al., 2010; Shah and Kumar, 2008).

Table 2.1 The impacts of dams on the Mekong, adapted and expanded from Kummu and Varis (2007) predictive studies underlined.

Action	Positive impacts	Positive impact references	Negative impacts	Negative impact references
Controlling the flow	Increase flood control capacity	Lauri et al., 2012; Hoa et al., 2007	Change the natural flow pattern; possible increase of fluctuation	Lu and Siew, 2006
	More assured dry season flows	Lauri et al., 2012	Increased dry season flows; permanent flooding of ecosystems	Lauri et al., 2012
	Increase navigation options	Roberts, 2001	Decrease wet season flows	Lauri et al., 2012
	Reduced dry-season saline intrusion	MRCb, 2011	Shift of flood regime; shorter flood period	Räsänen et al., 2012
	Hydropower provision and its economic gains	Kubiszewski et al., 2013; Baran and Myschowoda, 2009		
Trapping of sediment	Ease navigation	Roberts, 2001	Decrease flux of sediment-bound nutrients to delta and coast	MRCb, 2011; Kummu et al., 2010
	Reduce sedimentation issues	Kummu and Varis, 2007	Increased geomorphological change (delta subsidence, river bank erosion etc.)	Xue et al., 2011; Syvitski et al., 2009; Kummu and Varis, 2007
Blocking the river	Water storage	Kummu and Varis, 2007	Blocking fish migration routes (and associated protein replacement costs)	Orr et al., 2012; Ziv et al., 2012; Dugan et al., 2010; Baran and Myschowoda, 2009
	Irrigation provision	Haddeland et al., 2006	Fragment and homogenise river ecosystems and biodiversity	Li et al., 2013; Zhao et al., 2012; Xiaoyan et al., 2010
			Encourage new undesirable/dangerous habitats	Ziegler et al., 2013; Lanza, 2011
			Economic/livelihood losses to local communities engaged in fishing	Kubiszewski et al., 2013 ; Wang et al., 2013

All of the negative impacts listed in **Table 2.1** are linked to changes in the hydrological and sediment delivery regime of the river, either directly or indirectly (e.g. via nutrient flow or flood pulse disruption). The dynamics of discharge which are required to prevent the listed impacts, or to sustain ecosystems dependent on the river, are often called *environmental flows* (Deitch and Kondolf, 2012; Richter et al., 2006). Some research has gone into evaluating the different methods of managing dams and other features of development in order to sustain the environmental flows required to retain a system close to its pristine state (ibid). The process is a complex one since the natural variability of nature is hard to simulate (Arthington et al., 2006).

Many hypothesise that, rather than functioning as a simple linear relationship, ecosystem integrity's response to external pressure is subject to thresholds but, the evidence is inconclusive (Poff and Zimmerman., 2010). Furthermore, as is often the case for dam impact assessments and management plans in the academic sphere, the focus of research has thus far tended to be on purely ecological systems (i.e. conservation objectives) rather than complex social-ecological systems such as deltas (e.g. Bradford et al., 2011; Renofalt et al., 2010; Montagna et al., 2009). The challenge of sustaining sediment and hydrological environmental flows through dams is now being further complicated by climate changes. The baseline environmental flows which existing dam management protocols were designed to sustain will be outdated by climate change. The interaction of dams with new water stressors, such as precipitation variability change, will need to be studied, with attention on the potential for new threats to social-ecological systems (Grumbine et al., 2012; Moran-Tejeda et al., 2012; Palmer et al., 2008).

Of the two key environmental flows, water and sediment, sediment is perhaps the least understood. Traditionally the research on deltaic sediment processes has been restricted to certain deltas, mostly in more developed countries, such as the Ebro (e.g. Ibáñez et al., 1997) and Mississippi (e.g. Meade and Moody, 2010). Only recently has there been a surge in research in the Mekong Delta (e.g. Manh et al., 2015; 2014; Hung et al., 2014a;b). But there remains a particular dearth of research into the contribution of sediment to social-ecological systems, as Manh et al. (2014) recognise. A very small number of papers have looked at the importance of flows of sediment to the agricultural sector of deltas (e.g. Nixon, 2003). Often highly productive, delta agricultural systems are freely supplemented by the deposition of sediment-bound nutrients onto the floodplain (Hung et al., 2014b). In the case of the Aswan Dam in Egypt inadequate environmental flows were allocated, resulting in a 95% reduction in natural Phosphorus and Nitrogen flows to the Nile delta. This oversight came at a high cost as the lost nutrients had to be replaced with additional artificial fertiliser application (Nixon, 2003).

Nutrient supply is one of a number of services provided to society by sediment; in **Table 2.1** the others (all abiotic) are grouped into "increased geomorphological change". Changes to the concentration of suspended sediment can lead to changes in the rates and locations of the erosion and deposition processes which shape fluvial systems. Brandt (2000) identifies: slope changes; cross-sectional changes; bedform changes; and potential tributary responses such as base level lowering, which have been recorded in rivers downstream of dams around the world (e.g. Sun et al., 2012). The general trend is towards an increase in erosion to compensate for the net sediment deficit, particularly in the first 100 km after the dam (Petts and Gurnell, 2005). All of these issues can also impact on downstream deltas but, with often long intervening distances the interaction is poorly understood. The issue is nevertheless important, particularly as, positioned along banks and dykes in developing world deltas, are large numbers of human homesteads, to which erosion represents a significant threat (Birkmann et al., 2012). Another poorly understood issue of geomorphological change related to sediment trapping is coastal erosion in deltas, which may be exacerbated by reduced fluvial sediment flux reaching the river mouth (Walling, 2008). Coastal erosion is another issue complicated by large distances from dam to coast, as well as the complex movements of tides and currents (e.g. Xue et al., 2012). Recent research in the Mekong Delta has estimated that sediment starvation has resulted in over 50% of the delta's shoreline changing from a state of net growth to net erosion (Anthony et al., 2015). A similar phenomenon was documented by Xue et al. (2009), who attribute coastal erosion rates of 3.7 m/yr to dam sediment-trapping in a host of Eastern Chinese rivers.

While increased river-bank erosion between dam and delta can sometimes, at least temporarily, compensate for upstream trapping (Liu et al., 2013; Phillips et al., 2004) once trapping takes place on a large scale some delta impacts are unavoidable. Of late, considerable attention has been paid to the accelerating rate of relative sea-level rise within river deltas. Upstream sediment trapping can reduce the sediment concentration in the river, and thus reduce floodplain deposition in the delta when the river overtops its banks, a process which would otherwise counteract the natural subsidence of the delta body (Syvitski et al., 2009). This situation is being exacerbated by other anthropogenic pressures which induce accelerated subsidence, particularly ground water extraction (Erban et al., 2013) and sand mining/dredging. Furthermore, climate change is itself causing the sea-level to rise (Church et al., 2013), as discussed in **Section 2.2.2**. Syvitski et al. (2009) identify 28 deltas at risk, but the two they draw out as *"particularly at risk"* (p. 685) are the Pearl Delta, China, and the Vietnamese Mekong Delta, which they estimate are threatened by 7.5 and 6 mm/yr of RSLR respectively.

2.2.1.2 The impact of endogenous economic development on delta processes

When compared with the geological processes which shape most of the Earth's terrestrial surface, deltas evolve and change over extremely short time scales. Many have established their current configuration only within the last 3,000 years (Goodbred Jr and Kuehl, 2000), with some of the largest changes occurring within the last 200 years. However, deltas are also highly changeable environments on intra-annual time-scales. Deltas are usually subject to seasonal flooding, particularly in the Asia-Pacific monsoonal regions, as well as pronounced dry seasons (Varis et al., 2012). The changeable nature of deltas and their associated rivers, both in terms of their geomorphology and short-term flow variability, have long presented challenges to humans wishing to utilise delta plains to sustain their livelihoods (Zhang et al., 2005; Fox and Ledgerwood, 1999). Fox and Ledgerwood (1999) claim that humans have made use of crude dykes and dams to control the water flow in deltas on a small scale for over 2000 years. In their example this control allowed inhabitants of the Mekong Delta to successfully cultivate one of flood-recession, wet season, or dry season rice, in order to reliably produce an annual crop (ibid). Since approximately the 1500s humans have been developing levee construction techniques to artificially build and fix the location of channels in, and upstream of major deltas (Blum and Roberts, 2009; Syvitski and Kettner, 2011) allowing even greater control and environmental consistency.

More recent refinement of these control systems has increased the number of annual cropping cycles possible (Sakamoto et al., 2006) and facilitated diversification of land uses into new crop varieties and aquaculture systems (Ottinger et al., 2013). Such developments define the landscape of deltas and remove many of their traditional ecological characteristics while also making them some of the most agriculturally productive regions on the planet. In order to maximise agricultural yields in the Nile Delta the density of its irrigation canals has increased to 0.5 km/km^2 (Nixon, 2003), while the Mekong Delta is even denser, with canals at a density of around 1.4 km/km^2 (Hung et al., 2014b). Such developments have helped the Nile delta feed the country's rapid population growth (Yates and Strzepek, 1998) and allowed the Mekong Delta to become the second largest rice exporting region on Earth (Kakonen, 2008).

Table 2.2 summarises the breadth of environmental impacts resulting from endogenous development however, the past two to three decades have been characterised by two key land-use changes in deltas. The first is urbanisation. Deltas, particularly those located in developing countries, such as the Yangtze, Pearl, and Yellow have been experiencing industrialisation (e.g. Du et al., 2015) and rapid urban expansion rates of 15-40% per year (Ottinger et al., 2013; Long et al., 2007; Seto et al., 2002) primarily as a result of migration to coastal urban centres, which is a global phenomenon (McGranahan et al., 2007). This urban expansion has brought new dangers and environmental pressures not unique to deltas. Air and soil pollution due to industrial activity have become serious issues in deltas such as the Yangtze, Pearl, and Mekong (Hang et al., 2009; Fu et al., 2008; Minh et al., 2007). Additionally, while most human settlement tends to take place along river banks and in elevated areas there are also cases of settlement directly on floodplains that have theoretically been entirely isolated from the flood by levees, notoriously for example, in the Mississippi delta (Black, 2008).

Table 2.2 Examples of documented endogenous environmental pressures on deltas caused by economic development.

Sector	Sub-sector	Impact	Example reference
Primary	Agriculture	Air and water pollution, ecosystem degradation/loss	Fu et al., 2003
	Aquaculture	Water pollution, ecosystem degradation, land subsidence	Higgins et al., 2013 ; Cao et al., 2007
	Mining/dredging	Pollution and ecosystem damage	Ohimain et al., 2005
	Groundwater extraction	Land subsidence and fissures	Shamsudduha et al., 2009; Zhang et al., 2008d
Secondary	Urban expansion	Air and water pollution, local climate changes, ecosystem damage	Tewari et al., 2009; Ouyang et al., 2006
Tertiary	Tourism	Noise and waste pollution, ecosystem damage	Mbaiwa, 2003
	Transport	Air and water pollution	Chau, 2006

The second key land-use change is the shift from agriculture to aquaculture in the near-coastal regions of developing world deltas. Globally, aquaculture is expanding and intensifying rapidly with the production of fish and shrimp increasing by up to 6 million tonnes each year (FAO, 2012). Increases in deltas such as the Mahanadi (Pattanaik and Prasad, 2011), the Godavari (Rajitha et al., 2010), the Mekong (Sakamoto et al., 2009a), the Yangtze (Long et al., 2007) and the Yellow (Zhang et al., 2011) have made a large contribution to this upwards trajectory. Such developments took place in part due to legislation changes and developments which have improved aquaculture’s profitability (Sakamoto et al., 2009) and in part in response to saline intrusion (Tuong et al., 2003). Increasing saline intrusion in deltas is resulting in the failure of some traditional crop types and forcing livelihood changes (Renaud et al., 2014), often to aquaculture, which may itself exacerbate the salinization of delta soils in a positive feedback loop (Zhang et al., 2011). These land use changes, along with agricultural intensification, bring with them further environmental stressors.

2.2.2 The impacts of climate change on deltaic systems

The fifth report of the Intergovernmental Panel on Climate Change (IPCC) strengthened the evidence base to suggest human-driven climate change will increasingly alter earth's environment over coming decades. Some key findings included projections that by the late 21st century it is (in the terminology of the report): *virtually certain* that Earth will experience more frequent hot days and nights over most land areas; *very likely* that Earth will experience an increase in the frequency and intensity of heavy precipitation events; *very likely* that Earth will experience an increased incidence of extreme high sea levels; and *likely* that Earth will experience an increase in the intensity of droughts (Kirtman et al., 2013). Many of these changes will impact on deltas. This section briefly examines measured and predicted climate changes and their impacts on deltaic environments.

2.2.2.1 Global predictions

As discussed in **Section 2.2.1**, changes which relate to hydrological flows and their associated sediment load, are of unique importance to the structural integrity of deltas. However, due to the particularly low elevation of most deltas, forecasts of rising sea-levels are also very likely to present challenges (Nicholls and Cazenave, 2010). Indeed, through secondary impacts, such as saline intrusion increasing its inland reach, challenges are already being faced. Most models of future sea-level change agree on the direction and approximate rate of change, suggesting deltas around the world are likely to be threatened by the predicted mean sea-level rise, which is in the range of a 0.4-0.7m increase on 2005 levels by the end of the century (Church et al., 2013). There is some regional variation, but the extremes of change variability are found in the uninhabited polar regions (ibid). Changes to precipitation regimes are considerably more unpredictable in terms of the extent and spatial homogeneity of change. The global models of precipitation change suggest some regions will see significant increases in mean seasonal precipitation while others will see declines (**Figure 2.5**). Given this spatial variability the physical impacts of climate change are better explored on the regional scale. However, greater certainty can be found in the global predictions of the changing *intensity* of extreme precipitation events. Collins et al. (2013) suggest that each degree of temperature increase is associated with a 4-5.3% increase in the annual maximum daily precipitation. The implication is that, even in regions where the annual average precipitation declines, preparations will have to be made for greater extremes.

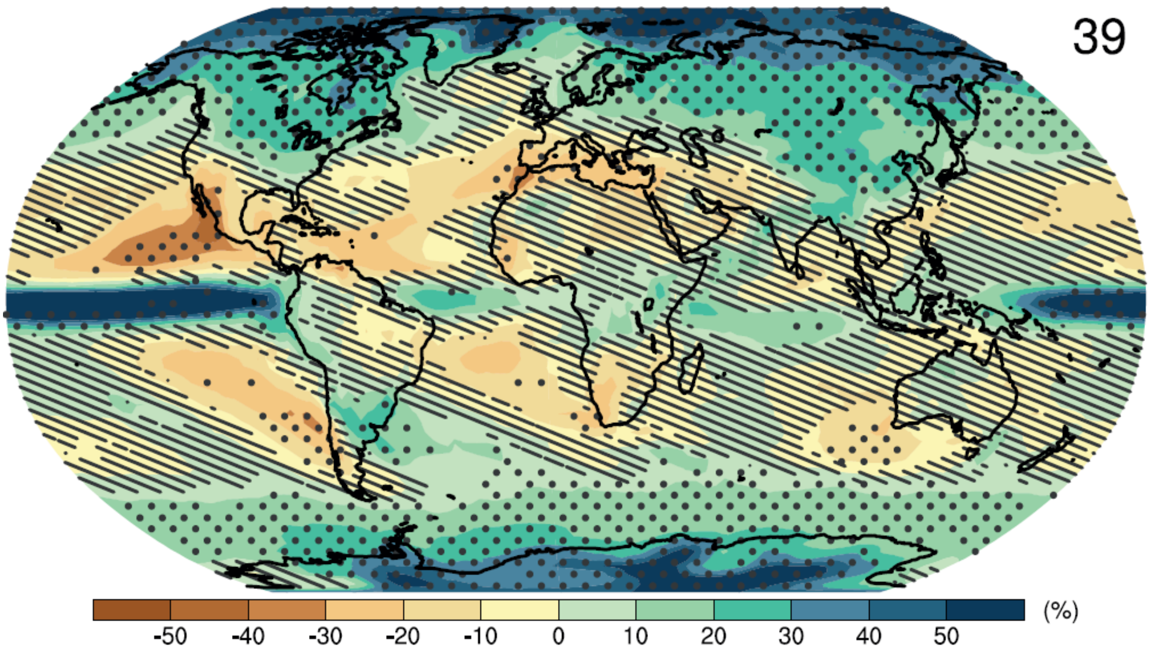


Figure 2.5 One example of an IPCC precipitation change model, forecasting the change between the 2005 baseline and the period 2081-2100 from (Collins et al., 2013). Hatching indicates regions where the multi-model mean change is less than one standard deviation of internal variability. Stippling indicates regions where the multi-model mean change is greater than two standard deviations of internal variability and where at least 90% of models agree on the sign of change. Colours represent the magnitude of change as shown in the legend below the figure.

2.2.2.2 Regional predictions

Many climate change forecasting studies covering delta areas contain high levels of uncertainty. It is innately hard to forecast for deltas, which are exposed to environmental pressures from highly diffuse sources. However, certain regions are also subject to relatively greater uncertainty in climate change projections than others. There is greater agreement on the magnitude and direction of change of hydrological variables, such as precipitation and runoff, in the north of the northern hemisphere, where increases are expected, and the south of the southern hemisphere, where decreases are expected (Collins et al., 2013). The Southeast Asian deltas, such as the Mekong, are situated within a highly uncertain region. Models disagree on the direction of change in the Mekong Basin for several variables, including precipitation (Mainuddin et al., 2010), river flow discharge (Thompson et al., 2013a; Kingston et al., 2011), and associated sediment discharge (Shrestha et al., 2013). **Table 2.3** illustrates the uncertainty of the discharges of the Nam Ou Basin, Lao PDR, which feeds the Mekong River and ultimately the Delta. For the 2041-2070 period two of five models are showing negative trends in water and sediment discharge and three showing positive trends, demonstrating Minville et al.'s (2008) conclusion that a researcher's choice of which global climate model to utilise currently drives uncertainty in river hydrological regime forecasts (also Thompson et al., 2013a;b).

2.2.3 Section conclusion

Some authors contend that the uncertainty discussed above is prohibitive to systemic adaptation action (Heikkila et al., 2013; Kubiszewski et al., 2013). Indeed, the magnitude of possible changes (e.g. from -26% to 158%) presented in **Table 2.3** may be intimidating to those in charge of future decision making on deltas. This section has further emphasised the huge number and variety of environmental pressures that deltas are likely to be subjected to over coming decades, with many additional to climate change. Particularly, it has highlighted poorly understood impacts from changes in sediment flows, influenced both by dam construction and climate change. When this uncertainty is combined with this level of complexity a purely *predict-then-act* (Lempert et al., 2004, p. 2) approach to policy making will be challenging. The drivers of change are too many, too great, and ultimately too complex to forecast the precise conditions of future deltas. Decision making processes will be needed which consider not just the pressures on the system but the susceptibility of the system to harm resulting from that pressure. **Section 2.3** goes on to discuss the theory behind the policy frameworks which aim to provide adapation actions which consider the location of vulnerabilities in complex deltaic social-ecological systems.

Table 2.3 Changes in average annual mean temperature, precipitation, discharges and sediment yield for all climate projections comparing the periods 2011-2040 and 2041-2070 to the baseline period (1971-2000) for the Nam Ou basin, Lao PDR (Shrestha et al., 2013).

Climate models	Green house gas emissions scenario (IPCC)	T_{mean} (°C)	Precipitation (%)	Discharge (%)	Sediment (%)
2011-2040					
CGCM3.1	A2	1.54	28.84	49.00	114.83
	A1b	1.56	35.94	62.28	158.49
	B1	1.47	31.16	54.32	143.05
CNRM-CM3	A2	0.91	-6.10	-9.27	-17.05
	A1b	1.11	-5.35	-8.29	-15.05
	B1	1.10	-4.47	-6.64	-11.25
MPI ECHAM5	A2	0.36	5.56	11.58	25.99
	A1b	0.41	11.35	21.23	47.95
	B1	0.57	4.63	10.04	21.29
NCAR CCSM3	A2	1.12	4.57	8.06	18.49
	A1b	1.12	7.42	12.85	28.58
	B1	1.04	5.39	8.83	19.29
PRECIS RCM	A2	0.76	8.34	13.22	24.57
	B2	0.84	3.55	7.35	14.69
2041-2070					
CGCM3.1	A2	2.46	32.90	55.17	147.15
	A1b	2.36	29.99	51.58	142.03
	B1	1.95	25.09	44.41	123.65
CNRM-CM3	A2	1.90	-5.68	-8.87	-12.21
	A1b	2.06	-10.97	-17.13	-26.92
	B1	1.52	-9.13	-14.12	-21.68
MPI ECHAM5	A2	1.41	1.62	4.04	13.92
	A1b	1.94	1.39	4.91	20.83
	B1	1.56	-1.62	-0.42	5.81
NCAR CCSM3	A2	2.23	-1.07	-1.74	-0.08
	A1b	2.10	11.46	19.84	58.32
	B1	1.50	-4.65	-7.91	-9.01
PRECIS RCM	A2	1.97	7.62	13.55	36.56
	B2	1.62	5.67	10.04	21.76

2.3 What is the theory behind adaptation policy making in deltas, and what are the challenges faced?

This section looks at methodologies and frameworks which national and regional policy makers can make use of to form environmental change adaptation policy. The approach here is to put these more general frameworks into the context of responding to the changes in hydrology and sediment flows caused by climate change and human development that were highlighted in **Section 2.2**. The last decade has seen a high number of reports strengthening the evidence base that suggests environmental change drivers are intensifying (e.g. IPCC, 2007; MA, 2005). In the academic literature there has been an explosion of research and publications discussing methods of deciding where and how policy responses to these changes should be targeted for best effect (Berrang-Ford et al., 2011). Contributions to this discussion have come from almost every discipline in modern science. Many of these contributions have coined new terms with highly nuanced definitions, and frameworks with highly discipline specific priorities; this has created a field which is difficult to navigate and distil information from (O'Brien et al., 2007). Purportedly different approaches often have overlapping aspects and ultimately the meanings and applications of the different terminologies in research are often themselves adapted to suit the context of the research (Adger, 2006).

The challenge facing policy makers responding to changes in hydrology and sediment flows is that the severity of the harm caused by environmental changes is not uniformly distributed. The extent to which drivers of environmental change might cause harm is a function of both the magnitude of that change and the susceptibility to harm in the impact location (Adger, 1999). There are, therefore, two challenges for policy makers:

(i) *Selecting and implementing a methodology for measuring and prioritising which regions and sectors are most susceptible to harm and therefore require action.*
(ii) *Implementing a policy design which is tailored to address the vulnerabilities identified.*

This section looks at the policy frameworks which can help unpick these challenges.

This section is guided by the emerging consensus coming out of climate change policy research which is outlined by Eakin et al. (2009). Eakin et al. (2009) divide environmental change policy into three categories (see **Table 2.4**): the risk-based approach; the vulnerability approach; and the resilience approach. Each of these approaches purports to tackle different aspects of the environmental change problem and operates on a different time scale, as **Table 2.4** outlines. These policy approaches also tend to encourage different adaptation actions, as identified by McGray et al. (2007) and added to **Table 2.4**. However, it is worth noting that successful action can also tackle social justice issues distinct from the climate change problem (e.g. Van Aalst et al., 2008) and as such there is increasing academic interest in the strategic design of adaptations to meet societal objectives on multiple fronts (Hallegatte, 2009). This section discusses the current and future directions of adaptation policy in deltas in the context of the three above approaches.

Table 2.4 Three policy approaches adapted from Eakin et al. (2009) and McGray et al. (2007).

Process criteria	Risk-based adaptation approach	Vulnerability approach	Resilience approach
Spatial scale	Sector focus	Places, communities, groups	Large scale coupled social-ecological systems
Temporal scale	Short and medium term future risks	Past and present vulnerabilities	Long term future
Actors	Public-private partnerships	Public sector, vulnerable groups	Civil society, public sector
Adaptation action encouraged (policy goal)	Building response capacity and managing evolving climate risks	Addressing drivers of vulnerability in populations most likely to experience harm	Confronting climate change by enhancing systems' capacity for recovery and renewal
Desired outcome	Maximum loss reduction at lowest cost	Minimise social inequity and maximise capacities of disadvantaged	Minimise probability of rapid, undesirable and irreversible change

2.3.1 Current environmental change policy in deltas – the risk based approach

The risk-based approach is perhaps the most tangible and easily quantifiable of the three examined here. The core components are: identification of a hazard/s, gauging the probability of exposure, and use of cost-benefit analysis (CBA) or an equivalent technique to evaluate and select a measure which can mitigate the risk down to a level deemed acceptable by society (Eakin et al., 2009). For example, floods might be identified as a hazard; the probability of a particular magnitude of flood can be described as a 1 in N year event and policy might be designed to prevent negative impacts resulting from a flood up to a certain (unlikely) level of probability, e.g. through regional infrastructure alterations and disaster-response institutions.

Deltas such as the Mekong Delta in Vietnam have well established risk-based policy in place (MRC, 2009). Most commonly, hydraulic infrastructure takes on the dual role of irrigation and mitigating water-related disasters down to an acceptable level (Garschagen et al., 2009). Commonly nations also have local disaster response institutions in place which, to some extent, provide support and education for and during extreme events, especially with regard to health issues (Few and Pham, 2010). Such strategies have evolved due to the sustained presence of disaster risk in deltas.

Present disaster risk is driven by the regular flooding and drought periods experienced by the world's deltas (e.g. Zhang et al., 2008a; Sakamoto et al., 2007; Gumbricht et al., 2004 see **Figure 2.6**) which are often particularly extreme when they coincide with exacerbating weather conditions such as typhoons (Sakamoto et al., 2007).

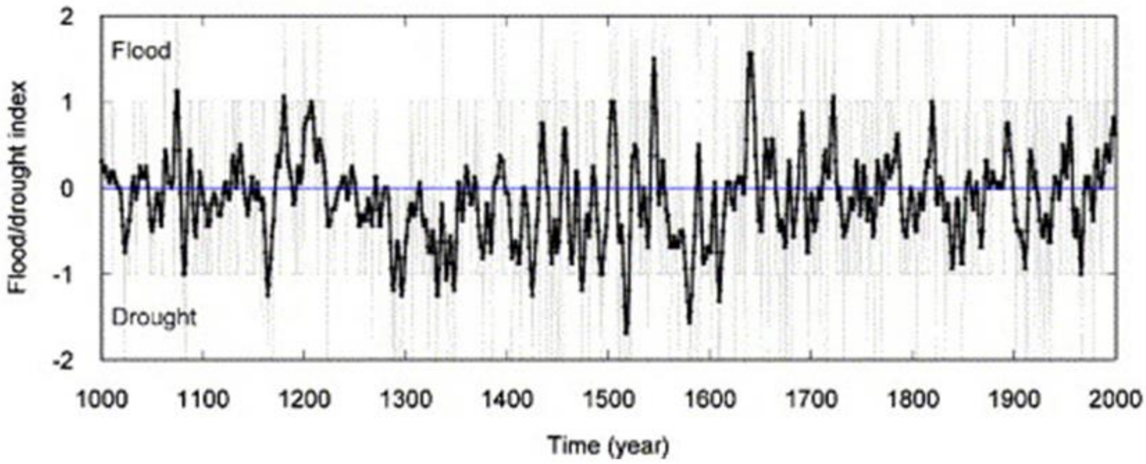


Figure 2.6 Flood and drought variability reconstructed by Zhang et al. (2008a) for the last millennium on an index from 2 (heavy flood) to -2 (heavy drought) in the Yangtze Delta.

2.3.1.1 Critique of the risk-based approach

The criticisms of the risk-based approach can roughly be divided into practical and methodological issues. A practical issue is that most risk based policies set an acceptable level of risk on which to make decisions on larger scale investments. Acceptability is often a balance of what can be afforded and what is desired. In disaster prone areas this approach risks catastrophes, such as Hurricane Katrina in the Mississippi delta, when the threshold-level disaster is breached (Burby, 2006). In the case of Vietnam, disaster risk policy was designed to withstand up to a 1 in 20 year flood (5%) probability, on a probability curve derived from past observations (**Figure 2.7**). Following the Mekong Delta's severe flood of 2000, which breached the 1 in 20 year threshold and resulted in severe loss of life (Dinh et al., 2012), the government's risk-policy was realigned to tolerate up to a 1 in 50 year event (MRC, 2011).

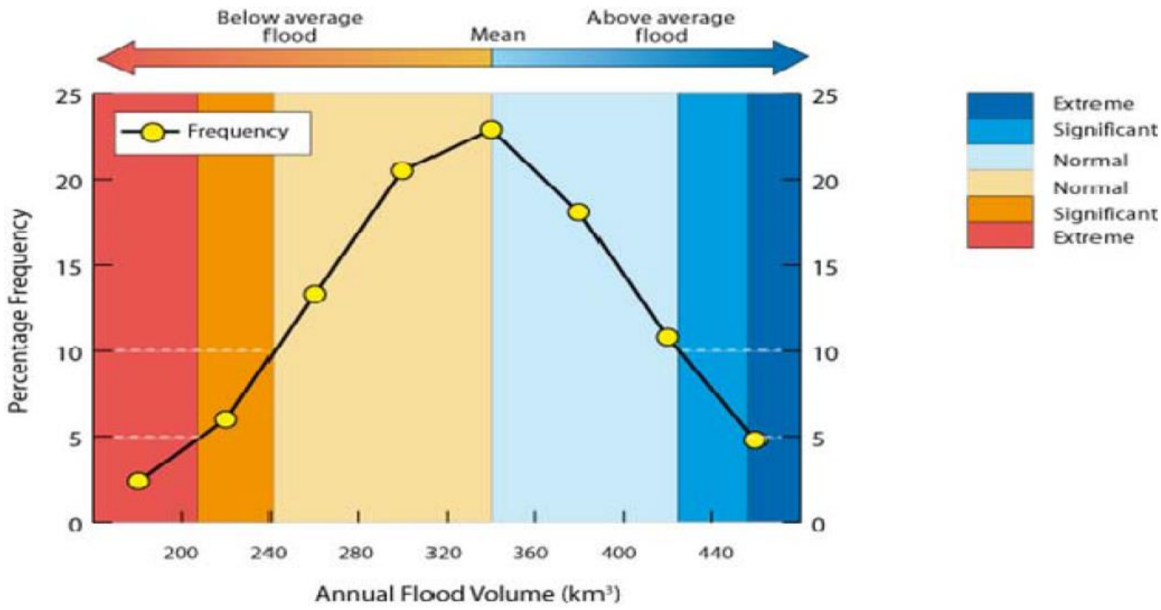


Figure 2.7 Annual flood volume and frequencies based on historical data, coloured by severity classifications (MRC, 2011).

Events which breach the threshold built into the risk-based approach become more common when disaster infrastructure does not keep up with environmental changes. As a result climate change, which shifts the baseline for disasters, has begun to dominate the discussion in the academic literature; however, commentators suggest some other key drivers of risk are being ignored and that the lack of a systemic approach threatens communities in developing countries (Mercer, 2010). One example is that many deltas, such as the Pearl (Zhang et al., 2008b) and Yangtze (Li et al., 2013), are experiencing rapid urban encroachment into flood prone areas. This was seen in the Mississippi delta prior to Hurricane Katrina (Burby, 2006). Such encroachment can alter both flooding probabilities and the population (and economic assets) exposed to flooding.

Another example is rivers experiencing large dam induced changes to their fluvial sediment flux; a human action which has implication for the containment of large floods. The effect of sediment transport and associated river morphology on flood risk is a fairly poorly understood area (Neuhold et al., 2009). Sediment flux can have a degree of control over the river bed elevation, which in turn may affect the height and extent to which the river floods. But such considerations are rarely factored into flood forecasting studies. Van et al. (2012), in a traditional disaster-risk approach, forecast the extent of a future major flood in the Mekong Delta, but considered only the impacts of climate change, and not upstream dam construction.

On the methodological side, criticisms of the risk-based approach are its restricted sectoral approach and specific focus on individual disasters/hazards. Both lead to disregard of the systemic issues driving vulnerability which are usually linked to poverty, and which, if addressed, can protect against even entirely unforeseen events (Thomalla et al., 2006). This is, for example, an accusation that has been made of the Vietnamese government's national adaptation strategies (which cover the Mekong Delta) which are risk-based (MRC, 2009). Issues of poverty and inequality were also ignored prior to Hurricane Katrina in the United States. When the threshold disaster level was breached in the Mississippi Delta, vulnerable areas of society that had previously been overlooked experienced catastrophic harm (Elliot and Pais, 2006). Commentators argue that such issues can also link to another practical issue with the disaster risk approach, its tendency to encourage policy makers to focus on politically expedient disasters (Eakin et al., 2009). This can lead to action driven by public perceptions of risk rather than scientific calculations, which is an issue because the public commonly misperceive risk magnitudes (see Ge et al., 2011)..

Nevertheless, for regions such as deltas which experience regular and severe disasters the risk-based approach is at the heart of current policy and protocol. Some suggest this is resulting in policies potentially detrimental to the underlying vulnerability of delta communities (Birkmann, 2012). Disaster risk is always present to some degree in delta systems and the findings in **Section 2.2.3** suggest it will increase in coming decades. Whether the disaster risk policy approach is the best mechanism for alleviating the harmful effects of those disasters remains very much open to debate.

2.3.2 New directions in delta policy - the vulnerability based approach

Vulnerability assessments of river basins (and their associated deltas) are currently being published at a high rate, primarily by governments and NGOs, at inter-basin scale (e.g. Varis et al., 2012; Bucx et al., 2010; IPCC, 2007) and intra-basin scale (e.g. Mainuddin et al., 2010; WWF, 2008). Many of these reports use vulnerability terminology but provide little or no explicit definition or guidance on its application (Hinkel, 2011). Assessments rarely have a common structure, and often draw from a particular disciplinary perspective (Polsky et al., 2007). In fact many of these vulnerability assessments deal with what O'Brien et al. (2007) term *outcome vulnerability* (sensitivity to hazards) which differs from the vulnerability addressed by the vulnerability approach of Eakin et al. (2009) which is guiding this review – referred to as *contextual vulnerability* and links more to chronic poverty and inequality. Outcome vulnerability is determined by the strength of drivers of environmental change in different regions. Outcome vulnerability has effectively been discussed in **Section 2.2** and might simply be considered the input information in the risk-based approach to policy of **Section 2.3.1**. However, the contextual vulnerability approach might be considered a newer direction in environmental change adaptation policy. Contextual vulnerability is, as Eakin and Luers (2006) put it, *"inherently about ethics and equity"* (p. 388) and considers environmental changes as only one component of a number, such as social, economic, and political structures which determine unequal severities of impact (O'Brien et al., 2007).

Table 2.5 Three classifications of vulnerability (GOS, 2012).

Type of Vulnerability	Method of data collection	Data collected	Example of measure	Implications for modelling vulnerability
'Vulnerability as deprivation'	Community-based or participatory vulnerability mapping	Village or community-level maps	Cuban approach to risk reduction Participatory disaster risk reduction	Good quality (small scale) data Difficult to scale up to national level
'Vulnerability as exposure'	National social statistics, census data Remote sensed data	EM-DAT type data e.g. percentage affected; number of fatalities per area or population group	US vulnerability to sea level rise Brooks et al. (2005) IPCC assessments	Good cross-national assessment Lack of understanding of deprivation of specific groups
'Vulnerability as capacity gap'	National income statistics Level of corruption Organisational crisis contingency planning Adaptive risk management assessment	Governance and corruption indices Poverty measures Organisational form and scope for learning	Afghanistan national risk and vulnerability assessment 2007/8 IADB Americas indexing programme	Includes scope for modelling adaptive capacity Some scope for cross-national assessment of capacity Lack of understanding of deprivation of specific groups

A consensus seems to be emerging around the work of Adger (2006) in dividing vulnerability into three more specific terms: sensitivity, exposure, and adaptive capacity. The British Government Office for Science (GOS, 2012) shares and further explains this divide (see **Table 2.5**) but with a slight realignment of the definitions (deprivation replacing sensitivity). By measuring and aggregating across all three categories of vulnerability, policy makers may target policy at the most vulnerable regions and communities.

2.3.2.1 Critique of the vulnerability approach to environmental change policy

Chapter 2.2 highlighted why it is unsurprising that deltas frequently rank highly on exposure indicators of vulnerability. Often, discussion revolves around the potentially huge impacts of sea-level rise on the large and densely populated deltas (see **Figure 2.8**). For example, the Nile delta has been subject of a number of papers discussing the effects of exposure to sea-level rise on sensitive and dense populations (Hassaan and Abdrabo, 2013; Hereher, 2010; El-Raey, 1997), and there has been a similar focus in the Mekong, but with the added dimension of the local dependence on rice agriculture (Hoang et al., 2013; Van et al., 2012; Wassman et al., 2004).

However, these studies focus heavily on exposure vulnerability and are selective about which indicators they consider. Sea-level rise, the most common indicator of pressure, is only the coastal element of an extremely complex system. Using only population density, a commonly used social exposure indicator (e.g. Vermaat and Eleveld, 2013), is also short-sighted in that it says nothing about the adaptive capacity of the population. Selection of indicators is one of the biggest challenges to the vulnerability approach, and it is common that in reality, the chosen indicators are little different to the risks which were used to target the risk-based approach to policy (e.g. Hall and Bouapao, 2010; Brooks et al., 2005).

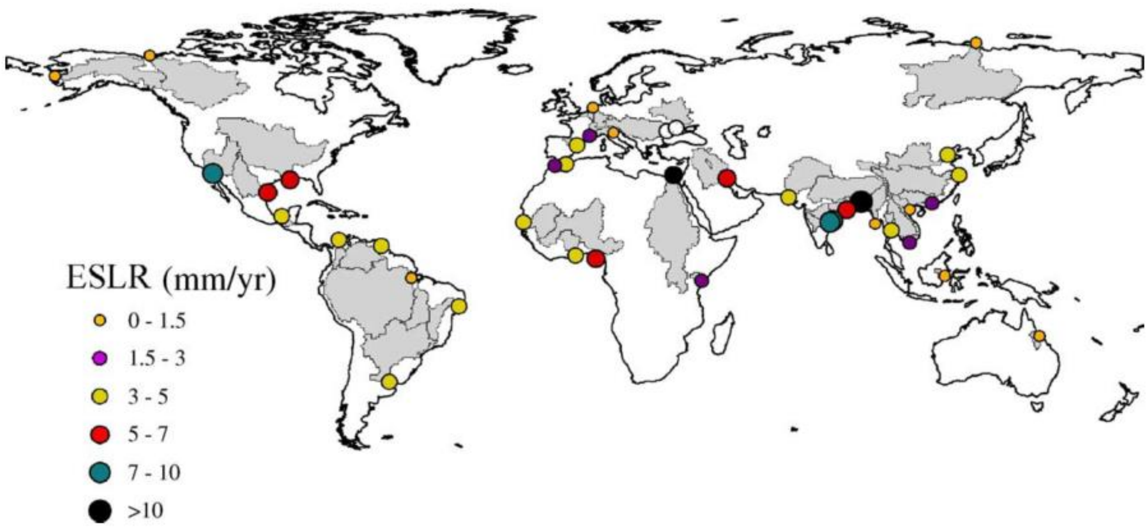


Figure 2.8 Effective Sea Level Rise (ESLR) rates as calculated for 40 deltas worldwide with their basins (in grey) (Ericson et al., 2006).

More recently the discussion has begun to consider that exposure vulnerability in deltas might not only be a factor of climate change impacts such as sea-level rise but also sediment flux reductions associated with dam construction inland (e.g. Syvitski et al., 2009; Day et al., 2007; Ericson et al., 2006). Indeed, Nicholls and Cazenave (2010) note that non-climate related drivers may be of greatest concern for exacerbating exposure vulnerability with relation to sea-level rise. Again taking the Mekong as an example, **Table 2.1** highlighted the fairly strong evidence base for exposure vulnerability caused by inland dam-linked sediment and hydrological changes. However, what appears to be lacking is any assessment of the interplay between sensitivity vulnerability and hydrological and sediment flow changes related to dam construction in the context of climate change. While some recent vulnerability studies have included the services sediment deposition provides which may be damaged by dam construction (e.g. Vermaat and Eleveld, 2013), they remain focused on coastal flooding. Most ignore further exploration of exposure or sensitivity vulnerability to the complex river flow dynamics likely to result from combined climate change and dam construction.

McElwee (2010) is an example of a study which used Adger's (2006) three categories of vulnerability in an assessment of Vietnam which had an outlook restricted to climate change. Of the eight regions of Vietnam she examines, the Mekong Delta is ranked as the 2nd most vulnerable zone, based on indicators of exposure (storms, floods, salinity, sea-level rise, flash floods, droughts) and sensitivity (poverty, diversification, minorities, women and children, migrants, urban population, education, health and sanitation). A lack of a clear definition and data meant no adaptive capacity ranking was made. McElwee's (2010) study is an extremely useful document in that it presents a comprehensive picture of where susceptibility to climate change might come from in the Mekong Delta but it does not present evidence for how some of the key susceptibilities identified (e.g. the presence of under-represented minorities) might interact with non-climate related drivers of change. **Table 2.6** expands on the work of McElwee (2010), including other studies that discuss the evidence for different sensitivity vulnerability indicators in the Mekong Delta. The formation of **Table 2.6** was difficult as relevant studies were hard to find, and as a result the table relies heavily on three key studies: Hall and Bouapao (2010); Few and Pham (2010); McElwee (2010); furthermore, no studies exploring the interaction of the local vulnerabilities with other drivers of change were found.

Building an interaction between a known vulnerability and an impact influenced by human actions, such as sediment flow change, is no easy process. But, what **Table 2.6** clearly shows is that avoiding such challenges by defaulting to indicators such as gross domestic product per capita (GDP) as the only indicator of vulnerability is not adequate, as was suggested by Brooks et al. (2005). Taylor (2004) gives two Mekong Delta examples where there is an inverse correlation between GDP and education levels, and Few and Pham (2010) find that health and education indicators were not solely determined by income poverty. Community vulnerability in deltas is clearly highly nuanced and there is a clear need for studies with a more systemic outlook, both in terms of the drivers of exposure and the indicators of vulnerability explored.

Table 2.6 Recent studies providing information about the status of sensitivity vulnerability indicators in the Mekong Delta.

Indicator	Reporting sources	Example measure
Income poverty	Few and Pham, 2010; Hall and Bouapao, 2010 (MRC); McElwee, 2010	Average cash income $1.56 per person per day, 1/3 very poor or poor
Income diversification	Hall and Bouapao, 2010 (MRC); Bosma et al., 2005	Very high dependence on irrigation and natural resources
Status of ethnic minorities	Hall and Bouapao, 2010 (MRC); Taylor, 2004; Glewwe et al., 2002	Serious poverty issues, nationally, minorities make up 13.5% of population but 44.4% of the poor
Status of women and children	McElwee, 2010	Considerably increased vulnerability of women due to an education gap and lack of access to disaster warning system
Status of migrants	Hall and Bouapao, 2010 (MRC)	Very high levels of internal migration, 28% of rural households have changed occupation in the last 5 years
Urban population	Hall and Bouapao, 2010 (MRC)	1.8 million living in urban areas in the Delta
Education status	Few and Pham, 2010; Berg, 2002	Clear evidence that better educated farmers (average of 1.3 years longer in education) are more capable of employing advanced sustainable farming techniques
Health and sanitation conditions	Few and Pham, 2010; McElwee, 2010	Lack of healthcare protection for poorer communities

2.3.3 Future directions in delta adaptation policy – the resilience-based approach

Another method of targeting adaptation policy and action on environmental change that has emerged is the resilience approach (see Eakin and Luers, 2006, for an in depth discussion). The roots of the concept of resilience lie in Holling's (1973) *ecological resilience* which addresses a whole ecosystem's ability to buffer external change. Considerable work has, and is, going into the operationalization of resilience terminology for social-ecological systems, and a host of challenges are being met as disciplinary boundaries are crossed (Folke, 2006). The resilience approach attempts to remove issues arising from too heavy a focus on selected indicators, discussed in **Section 2.3.2**, by assessing a system as a whole and its ability to buffer shocks and stresses. When dealing with a complex, changeable, social-ecological system such as a river delta, use of the resilience methodology may be advantageous for its comprehensive and integrated approach which may avoid issues caused by focusing too heavily on high profile pressures, such as sea-level rise. Some of the primary challenges are found in the complexity of feedbacks from social-ecological systems and the inability of stakeholders to create either mental or physical models of such feedbacks in order to appreciate where action should be targeted (ibid).

In ecology low resilience systems are a priority for policy intervention because research has shown that once a disturbance exceeds a threshold and the resilience of the ecosystem is broken, it may result in a transition to a new stable state with permanent loss of the old system and associated biodiversity (Scheffer et al., 2001). Converting this concept to a social-ecological system context is difficult but Walker and Meyers (2004) explore it, suggesting that there may be five classes of threshold involving different interactions between the social and ecological components of the system (see **Table 2.7** overleaf).

Walker and Meyers (2004) conclude with a set of questions including:

> *"A key question in the dynamics of any system is whether or not that system has, or is likely to have, thresholds. Can a threshold be identified before it has been crossed [?...] which research avenues will allow us to best approach this question?"* (Walker and Meyers, 2004, p. 13)

If social-ecological systems do indeed have thresholds, with intensifying climate change drivers, there is an urgency to identify these before they are crossed. The passing of a threshold and transition to a new stable state, which has long been of concern in ecosystem research on conservation grounds, is also of concern in social-ecological systems because of the level of dependency societies develop on their current states. This dependency was briefly outlined in **Section 2.2.1.2**, where endogenous development was shown to have evolved to strategically manage the particular environmental variability of the delta environment. The ability of a social-ecological system to transition to a new state was defined by Walker et al. (2004) as *transformability*. Transformability constitutes a selection of desirable traits associated with a system's ability to develop a new state when the existing state became untenable, such as human capital and communication between human systems. In a world of perfect transformability, low resilience might not be seen as such a negative trait as systems would switch seamlessly between structures to suit their environment. This does not tend to be seen as desirable due particularly to the *existence value* placed on systems by humans (human preference for the existence of certain ecosystems irrespective of whether they make any practical use of the system; Rosenthal and Nelson, 1992).

However, few systems have perfect transformability; the examples in **Table 2.7** highlight that most transitions do involve what we might define as harm (ranging from biodiversity loss to human deaths) and that many social systems might be considered to lack transformability. The goal of adaptation under this methodology, therefore, might either be in (i) preventing a transition to a new system state, or (ii) lessening the harm of such a shift (increasing transformability). Whether the former or latter is preferable requires a value judgement which some argue can only be determined on a case by case basis through discussion with stakeholders (Owens, 2000). In either case (i or ii) a new duty exists for the researcher no longer just to forecast changes in external drivers to a system, but also to locate the most unstable internal pillars of a system's resilience and implement action to prevent or soften their collapse and/or the shift to a new system state.

Nguyen and James (2013) is an example of a small-scale study examining resilience to extreme floods in the Mekong Delta. The authors found that the factors affecting the resilience of Mekong Delta households could be grouped into three categories: (i) the capacity to secure food, income, health and evacuation during the flood season, (ii) the capacity to secure their homes during floods, (iii) the level of interest in learning and carrying out new flood-based livelihoods during the flood season (ibid). Points (i) and (ii) are common factors in delta community resilience and are often linked to access to financial (e.g. Garschagen et al., 2011), natural (e.g. Motsholapheko et al., 2011), and social capital (e.g. Mmom and Aifeshi, 2013). It could be argued that Nguyen and James (2013)'s work takes more of a vulnerability than resilience approach, as it primarily considers the response of a small number of indicators of sensitivity to a limited number of drivers of change rather than the operational mechanisms generating system resilience.

Table 2.7 Five classes of threshold in social-ecological systems adapted from Walker and Meyers (2004).

Class		Type of linkage	Relationships and drivers	Example
1	**a**	No linkage, externally driven change in ecological or social systems	Shift in the ecological system, driven by an environmental event from outside, with no impact from society	Upper basin rainfall variability causing a shift in the delta salinity gradient
2	**a**	No linkage, internally driven change in the ecological or social systems	Internally driven shift in the ecological system with no external pressure from society or from environmental drivers outside the ecosystem	Thresholds and feedbacks in the response of vegetation to natural precipitation variability
3	**a**	Linked social-ecological systems, with a threshold change in only one system	Shift in the ecological system, driven by the social system	Dam impacts on downstream vegetation
	b		Shift in the ecological system, causing a change in the social system	The effects of climate oscillation regime shifts in the Pacific Ocean on agricultural preferences
4	**a**	Linked social-ecological systems with reciprocal influences, but a shift in only one system	There is a shift in the ecological system; society works to reinstate the ecological system, which has a feedback effect on social behaviour	Biodiversity declines and in response changes are made in agricultural practices e.g. nutrient management
	b		There is a shift in the social system which increases exploitation of an ecosystem. The ecosystem changes which (often with an environmental shock) causes a regime shift in society	Society intensifies agriculture. Ecosystem degradation then makes intensive agricultural unviable and a new agricultural system emerges
5	**a**	Linked social-ecological systems with reciprocal influences, shifts both the ecological and social systems	Collapse of an ecosystem caused by a social system, followed by collapse of social system (or vice-versa)	Damming of the Mississippi river results in loss of Mississippi Delta system and the dependent human system.

However, their final factor affecting resilience, the level of interest in learning new livelihood techniques, highlights the fact that social resilience has a moving baseline/identity and furthermore is a factor that would not necessarily be identified by traditional vulnerability measures. In order to be resilient in other aspects of their current system (i.e. wellbeing) communities must be transformative in others, particularly in social learning. Commentators are increasingly highlighting the importance of social learning in maintaining resilience in desirable areas of a system (Lebel et al., 2010).

2.3.3.1 Critique of the resilience approach

Eakin and Wehbe's (2009) explanation of the nature of resilience emphasises that system resilience is not just the sum of its component's capacities and vulnerabilities, rather it is the non-linear interaction between a potentially huge number of system parameters that regulate the system, and human behaviours and institutions. As such, the measurement of social-ecological resilience has posed many challenges to researchers. The first and most important challenge is that measurement of system resilience has only previously been possible through experimental breaking of system resilience, which for large scale social-ecological systems is undesirable or impossible (Allen et al., 2005). Recognising that measuring system resilience itself is near impossible or unethical, Bennett et al. (2005) propose that the search should in fact be for surrogates of resilience, identified through an academically rigorous process.

Cumming et al. (2005) propose such a framework for empirical measurement of system resilience. The authors attempt to simplify the problem by providing a clear goal. The initial and crucial step involved in their proposal is the selection of a *system identity*. Identity is a sub-set of system characteristics that must be maintained for a system to be considered resilient. Once the goal of preserving an identity is set, Cumming et al. identify five key steps towards examining the future of that identity: define current system, define possible future systems, clarify change trajectories, assess likelihood of alternative futures, and identify mechanisms and levers of change.

The issue with Cumming et al.'s framework is that the selection of the identity is subjective (Walker et al., 2006) and that it reduces the resilience approach to the selection of critical indicators. The example Cumming et al. (2005) provide, a community wishing to maintain its water supply, is one for which there may be a degree of unity and shared interest. In the case of a delta system which experiences pressures from highly disparate sources, such unity may be less common. As a result the identity of a social ecological system is now more commonly seen as a moving baseline, which develops with social change and varies between social groups (Cote and Nightingale, 2012). As the term 'identity' implies a static picture of a system other commentators have preferred to focus on the preservation of system functions which are identified as key (Allen et al., 2005).

Looking at the published resilience studies, a tendency to maintain the traditional ecological roots in which a static identity/baseline is applied can be seen (e.g. Bellwood et al., 2006). Others focus on smaller scale household or community-level systems (e.g. Nguyen and James, 2013) and examine only the social component of resilience (e.g. Maguire and Hagan, 2007) thereby maintaining a distinction between social and ecological resilience which was established in the earlier days of resilience research (e.g. Adger, 2000).

The lack of large scale resilience measurement projects is perhaps explained by Lebel et al.'s (2006) point that the surrogates mentioned above, identity or function, can only practically be maintained for particular, and not all, stakeholders. In larger systems, where stakeholders often have varied and conflicting interests, decisions must be made on the "resilience of what, to what? […] for whom?" (ibid, p. 15). As a result, the prevalence of social-ecological resilience remains elusive in many systems. However, studies of social and ecological resilience as separate entities are available for deltas and, it might be argued, offer more hope of achieving some form of sustainability in deltas.

2.3.4 Section conclusion

The disaster risk, vulnerability and resilience approaches to policy design can be seen as differing strategies for prioritising and guiding policy aimed at reducing harm from environmental changes. Choosing between the approaches themselves involve implicit trade-offs, e.g. efficiency vs equity (Eakin et al., 2009). In deltas the literature suggests a progression through the different approaches is taking place, driven by their relative merits. Delta stakeholders are historically, and largely at present, planning and prioritising action using a disaster risk approach. As a result of the consequent focus on specific disasters and impacts and oversight of the underlying drivers of vulnerability, commentators in the academic literature have been attempting to encourage a shift in the methods being used to design policy towards the vulnerability approach (e.g. Birkmann et al., 2012). Vulnerability assessments of deltas are becoming increasingly common but are still plagued by inconsistent use of indicators and terminology. Commentators acknowledge they may have also mistakenly placed too much emphasis on climate change drivers which are actually of lesser importance when compared to the other threats to delta system integrity in the present day (e.g. Nicholls and Cazenave, 2010). The review conducted herein would suggest this is the case not only for the drivers of relative sea-level rise but as a general point about deltas facing other developmental drivers of change.

The resilience approach to prioritising action is still in its infancy with no assessments of overall social-ecological system resilience found for deltas. However, due to its systemic nature, the resilience approach shows better potential for appreciating the disparate drivers of change putting pressure on deltas both currently and into the future.

2.4 What evidence is there of delta systems adapting to hydrological and sediment supply changes?

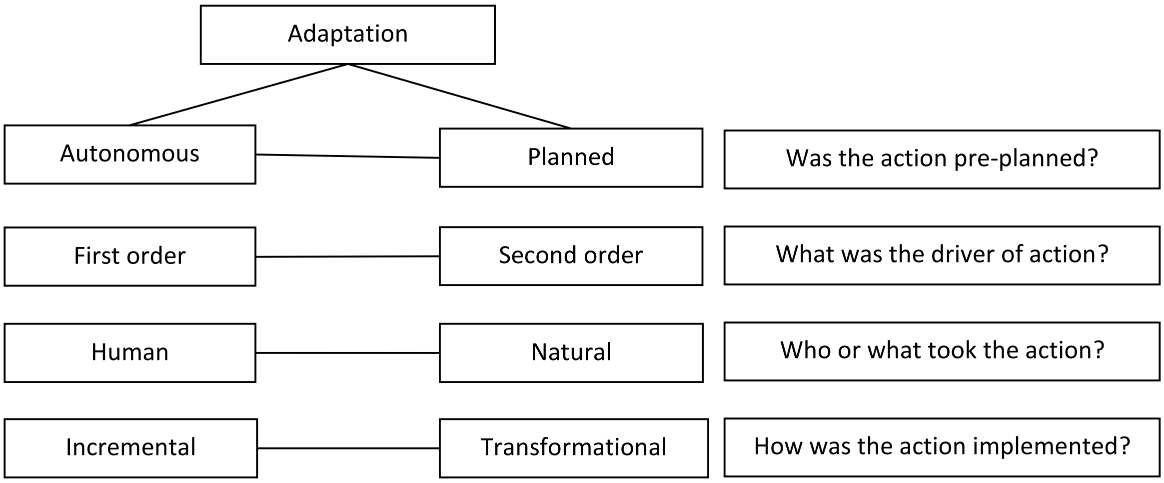


Figure 2.9 Some divisions of adaptation and the question addressed by each division.

From the last two decades of adaptation research have come a series of typologies of adaptation. The divisions help to answer three key questions relating to an adaptation: (i) adaptation to what? (ii) who or what adapts? (iii) how does adaptation occur? (Smit et al., 1999).

Figure 2.9 shows the divisions of adaptation based on the work of Smit et al. (1999), which later informed the IPCC's 2007 report, merged with the work of Birkmann (2011) who added the division which split adaptation into first-and second-order actions. Birkmann (2011) differentiates the two as follows:

First-order: *"those strategies and measures that households, communities, or societies develop to adapt to actual or expected climate change consequences and natural hazard phenomena [i.e…] adaptation to changes and thresholds in physical and ecological systems"*

Second-order: *"processes, strategies and measures that can and most likely need to be executed by households, communities, and societies to adjust to the direct and indirect consequences of the measures and structures implemented within the scope of first-order measures"* (p. 818)

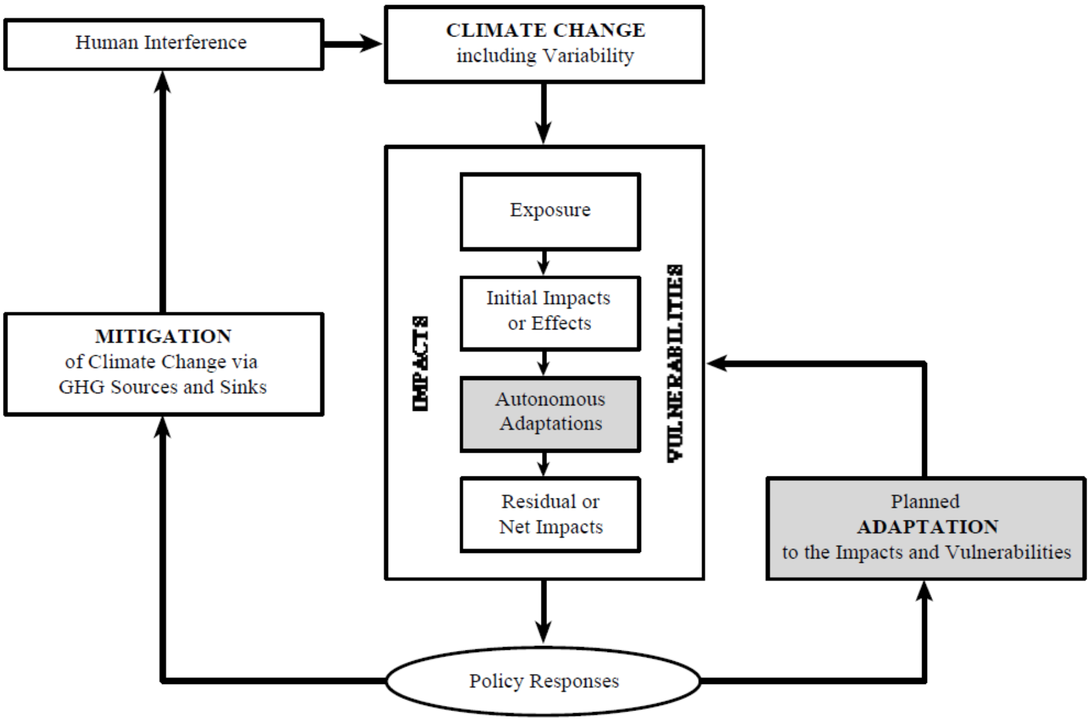


Figure 2.10 Adaptation in relation to climate change (Smit et al., 1999).

Smit et al. (1999) advocate putting a clear framework around the use of the term 'adaptation'. This section examines the evidence for first-order adaptation in river deltas while **Section 2.5** looks at second-order action and post-adaptation challenges. Different implementation approaches and both planned and autonomous adaptation are discussed, but the focus remains only on human adaptations to climate and development driven environmental changes (as opposed to adaptations by nature, e.g. species migration). The adaptation field has evolved out of the climate change threat, locating itself in the system as shown in **Figure 2.10**. But, the unique connectivity of a delta system with non-climatic drivers of change upstream in its river basin means adaptation strategies must often be designed with consideration of multiple diverse environmental pressures. Indeed, most commentators agree that human management is having a heavier impact on deltas than climate change (Fatoric and Chelleri, 2012).

2.4.1 Autonomous human adaptation to environmental change in deltas

Cliggett et al. (2007) illustrated how communities living under "chronic [environmental] uncertainty" (p. 29) for long periods of time can develop strong autonomous adaptive traits and techniques. **Chapter 2.2** has highlighted that deltas are particularly sensitive and changeable systems, even when recent anthropogenic climate change is not considered. Delta communities may be considered to live under "chronic uncertainty". As a result delta ecosystems and communities surviving in deltas have been forced to exhibit autonomous adaptation for generations (Morand et al., 2012). In the Mekong Delta, for example, the changes made to rice planting dates by local farmers in response to inter and intra-annual variability in flooding and runoff are considered to be autonomous adaptations (e.g. Kakonen, 2008).

Two common examples of human adaptations to environmental conditions in deltas are through livelihood diversification, and routine migration (e.g. Bosma et al., 2005; Morand et al., 2012). A lack of livelihood diversification is frequently cited as an indicator of vulnerability to climate change as highlighted in **Table 2.6**, but in deltas livelihood diversification is often already widely practised. The existing bountiful natural resources of deltas, combined with extreme climate variations between seasons, make diversification perhaps both more straightforward and necessary than in some other regions. Conversely, specialisation and intensification are high-risk high-reward strategies reserved for the cash rich (Nhan et al., 2007). The above actions are only adaptations *to* an environment and not to a *changing* environmental baseline, as is the climate change context. However, the same actions have been shown to be useful in the climate change context. For instance, the ability to diversify has proved a useful trait for communities experiencing dam induced environmental change. For example, Thomas and Adams (1999) document the success of communities adapting to a new hydrological regime downstream of the Tiga dam in Nigeria through diversification of livelihood sources. Also common in deltas are some autonomous disaster preparedness adaptations. Few and Pham (2010) find 45 out of 48 households interviewed in the Mekong Delta use some or all of the strategies of: securing house structure, clearing waterways, reserving food and water supplies, and preparing an evacuation boat.

The ability to autonomously adapt is an asset. However, the drivers of change highlighted in **Section 2.2** are sufficiently strong to suspect that the impacts may exceed the extent to which communities can autonomously adapt and some form of intervention will be required. As a result, planned adaptation will be required in deltas.

2.4.2 Planned human adaptation to environmental change in deltas

There are many further divisions of planned adaptation than just those shown in **Figure 2.9**. Adaptation can take place across scales, through action by individuals, groups, societies, and governments (Adger et al., 2005), and can involve either social (soft) or physical (hard) action. Decisions on what type of planned adaptation to pursue will depend on the scale of change faced (i.e. the level of benefit required from the adaptation, as in **Figure 2.11**) and wider political objectives for the system (Rickards and Howden, 2012) but Berrang-Ford et al. (2011) have already identified that reporting on planned adaptation action is particularly low. As a result, categorising delta adaptations with a highly specific typology adds an unnecessary level of rhetoric to a sparsely populated body of evidence. This section collates what evidence there is of first-order planned adaptation *for deltas*, with a particular focus on adaptation to the water and sediment flow changes which have already been identified as key vulnerabilities in delta environments. Emphasis is placed on the term *for deltas* because adaptation action need not necessarily take place *in* deltas for it to influence the livelihoods of populations living in deltas.

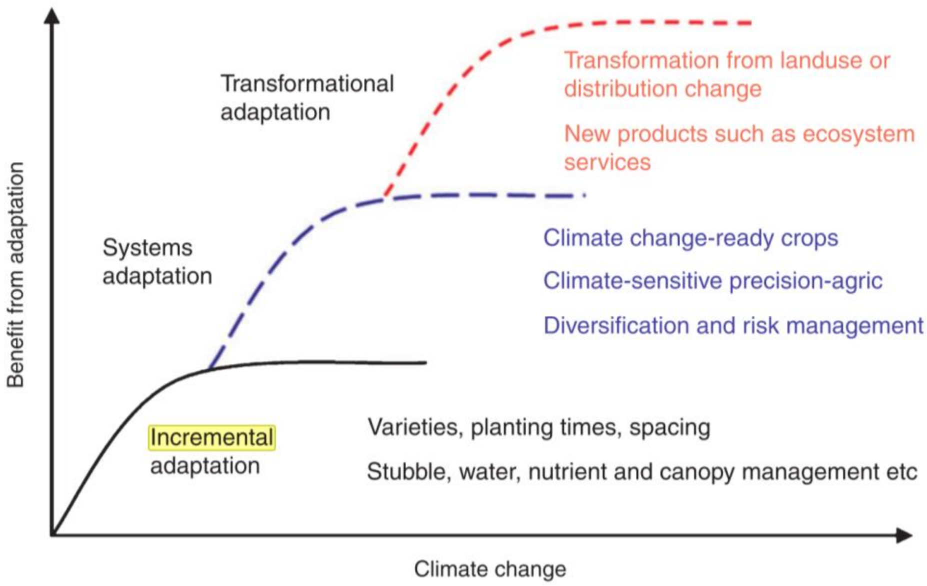


Figure 2.11 An illustration of the different levels of adaptation with examples in agriculture (Howden et al., 2010 cited in Rickards and Howden, 2012).

2.4.2.1 First order adaptations for deltas

The issue identified by Berrang-Ford et al. (2011) with the academic adaptation literature, that there is far more reporting of intentions to act than actual actions, extends to the grey literature and policy spheres (e.g. MRC, 2009), making identification of first order adaptations difficult. Schipper et al.'s (2010) review of adaptation in the Mekong Basin finds that of 39 adaptation project reports from the region, only 9 actually implement adaptation actions, the other 30 are entirely theoretical intentions to act.

There are four actions that occur most commonly in the adaptation literature on deltas, those include: the hard adaptations of dyke and barrier flood-defence construction and strengthening (Fatoric and Chelleri, 2012; Schipper et al., 2010; MRC, 2009); alteration and construction of houses to be more flood resistant (Schipper et al., 2010; Costanza et al., 2006); the planting/replanting of mangrove systems for flood defence (Inman, 2010; Nguyen et al., 1998); and the soft adaptation of optimising crop choices and planting and harvesting dates to suit new weather patterns (Mainuddin et al., 2010 and see **Figure 2.11**). But, as highlighted in **Section 2.4.1** these are not especially new or original ideas in communities which have already developed resilience to more extreme environmental conditions. In the agricultural sector Mainuddin et al. (2010) report that a number of adaptations which have been found to be useful in other geographical areas, such as improving water-use efficiency, have proven ineffectual in delta areas due to the high level of productivity and the level of specialisation that delta agriculture already operates at.

Of the adaptations which have been proposed (but with limited literature documenting implementation) in deltas there are some which are particularly commonly cited, such as: development of heat resistant crop varieties; investment in advanced rapid data acquisition and dissemination systems reporting environmental conditions; improving water efficiency use; and changes to the design of public infrastructure, especially roads, to handle a more variable climate (Douven and Buurman, 2013; CIEM, 2012). There are also some more extreme proposed adaptation options which are currently being discussed in the literature. Two adaptations are commonly mentioned. Firstly, sediment nourishment (large-scale artificial deposition of sediment) is gaining popularity, to counteract relative sea-level rise and provide flood protection (Fatoric and Chelleri, 2012). Dutch researchers experimentally tested *mega-nourishment* techniques for rapidly creating land which provides storm protection (Slobbe et al., 2012). Secondly, permanent evacuation/withdrawal has been discussed (Fatoric and Chelleri, 2012). In the case of the Mississippi Delta, commentators are already beginning to recognise the inevitability of the loss of much of the Delta and its consequent evacuation (Blum and Roberts, 2012; Costanza et al., 2006). Should climate projections prove accurate, such action may become necessary in other deltas and indeed is already appearing in adaptation plans in the grey literature (e.g. ISPONRE, 2009). However displacement of peoples is fraught with difficulties, particularly research suggests health and social integration problems can arise (Cao et al., 2012).

Some actions reported but not described as adaptations may in fact be considered as such. In developed countries, where deltas have spent a greater period of time under dam regulation and experienced the impacts outlined in **Section 2.2.1.2**, considerable effort has recently gone into studies looking at managing existing sediment budgets to most effectively build the height of deltas. Rovira and Ibáñez (2007) describe what they see as the objectives necessary for restoration of the Ebro Delta. Kenney et al. (2013) describe similar plans for the Mississippi delta. Sediment management of this sort might be seen as an adaptation action in response to changing sediment flux into deltas due to dam construction. Over time, it may also be seen as a climate change adaptation due to the likely influence of climate change on sea-levels. As such the research field, known as *restoration sedimentology*, which has been identified as so important for stabilising coasts (Edmonds, 2012), is being recognised as a high priority first-order adaptation (Ibáñez et al., 2013).

The Mississippi delta, perhaps the most anthropogenically altered delta in the world, is in most urgent need of restoration sedimentology, with up to 100 km^2 of land being lost every year (Blum and Roberts, 2009). Two key methods have been proposed for land building: piping of sediment from inland and offshore deposits; and diversion of the Mississippi river. The latter has received strong recent attention as a possible solution (e.g. Kenney et al., 2013), but there are still a number of critical issues which need to addressed before the diversions can be constructed, particularly advancing the complex modelling techniques which guide management decisions (see Allison and Meselhe, 2010). Such action has only become necessary due to the construction of dams which trap upstream sediments. The construction of those dams themselves might also be considered an adaptation action, but they are less commonly described as such, as the following section discusses.

2.4.2.2 Is river regulation an adaptation to climate change?

Section 2.2.2 discussed the fact that developing nations are proceeding with dam construction despite many years of research demonstrating the damage river regulation causes to ecosystems and ecosystem services (Dugan et al., 2010). The motivation behind dam construction has shifted mainly to hydropower, but occasionally theoretical climate change adaptation benefits (Grumbine et al., 2012; Barbier et al., 2009 cited in Morand et al., 2012). The controversial nature of dam construction has perhaps affected attitudes towards research into these new directions.

Over the coming century there will be unpredictable and potentially drastic changes in mean runoff and runoff variability from the earth's continents due to climate change (Nohara et al., 2006; Milly et al., 2005). This variability is often described in the literature as a loss of stationarity and has already been identified as a serious challenge for water managers (Milly et al., 2008). There is a pressing need to understand risks and identify adaptation options for vulnerable communities and ecosystems, such as the 48 million or so people directly dependent on the Lower Mekong River (Orr et al., 2012).

A theoretical premise exists for suggesting that increasing river regulation and human control over river flows by constructing dams can be considered a first-order climate change adaptation. Changes in river basin water balances in large river systems around the globe could result in the increasing duration, frequency and magnitude of floods and droughts. This in turn could cause damage to many elements of riverine social-ecological systems, including floodplain vegetation, crops, and infrastructure (Vastila et al., 2010). A greater degree of control over the basin water balance may therefore appeal to some policy makers, especially for economic stability (Barbier et al., 2009 cited in Morand et al., 2012). Ahead of such decisions, dam construction should be given careful consideration in un-biased interdisciplinary research. This is especially the case as dam construction is an adaptation which is frequently implicitly recommended in reports by international bodies (e.g. CIEM, 2012 (Central Institute for Economic Management); UNEP, 2011 (Technologies for Adaptation); Bates et al., 2008 (IPCC Technical paper VI); Olsson et al., 2008 (NATO Science for Peace and Security); Kirshen, 2007 (report to UNFCC)). Crucially, a recent study by Zhao et al. (2013) was the first to put this premise to the test in academic research and they concluded that the Manwan Dam in Yunnan province, China, has indeed reduced the impact of climate variability on the hydrologic regime of the Mekong River. But, in most high impact academic studies, mention of dam construction is usually avoided as an adaptation action and dissociated from the climate change issue (e.g. Palmer et al., 2008). Dam construction is a divisive issue, and bodies such as the International Commission on Large Dams (Grennier, 2012) and some academic opinion pieces (e.g. Koutsoyiannis, 2011) have claimed that it is not given fair consideration as a climate change adaptation action. If correct, this assertion would be of particular significance as dam construction is cited as a planned adaptation action being pursued in the majority of the National Adaptation Plans of Action (NAPAs) submitted to the UNFCCC by developing countries (UNFCCC, 2013).

2.5 What challenges are faced post-adaptation?

"Adaptation is a continuous process which influences the location of a system in relation to thresholds. In order to evaluate the influence of adaptation activities there must be sensitivity to changes, or feedbacks, in the system. Sensitivity to feedbacks relates both to the timing as well as where these feedbacks occur." (Adger et al., 2011, p. 762)

While the adaptation process is a continuous one, as Adger et al. (2011) describe, the framing of post adaptation challenges will vary between contexts of *incremental* and *transformational* adaptation (defined below). Where *incremental adaptation* is preferred, first-order adaptation is an ongoing process. Success relies on anticipating approaching thresholds/tipping points in the system and predicting the impacts of different incremental adjustments aimed at avoiding them (Rickards and Howden 2012) - a complex process which requires a firm grasp of system dynamics. Dealing with this complexity requires adaptation designs which are flexible. Room must be left for uncertainty and real-time adjustments to the policy design based on the ongoing evaluation process (Haasnoot et al., 2013). Such an approach is time sensitive, policies must be phased in during the *window of opportunity* prior to the system reaching a tipping point which would drive it irreversibly into an undesirable state (Abunnasr et al., 2015).

While dynamic management of adaptation policies may be effective in contexts where minor adjustments are sufficient to meet societal objectives, in some more extreme contexts more systemic action will be required. Kates et al. (2012) contend that such actions (which may be referred to as *transformational adaptations*) differ from incremental changes in that they may be: *"adopted at a much larger scale or intensity"*, or *"truly new to a particular region or resource system"*, or may *"transform places and shift locations"* (p. 7156). In such situations the post-adaptation challenge shifts to evaluating the ability of second-order adaptations to alleviate any undesirable impacts of the first-order adaptation. Following implementation of an irreversible adaptation a suite of second-order adaptation pathways/trajectories opens up. Designing a pathway which is effective at achieving the desired goals, again, requires understanding of highly complex system dynamics (Adger et al., 2011).

2.5.1 Defining and evaluating adaptation success and failure

A principle challenge when developing both pre and post-adaptation strategies is defining what success and failure would look like. Of late the concern in the academic literature that undesirable consequences might result from ill-planned actions has been growing (Barnett and O'Neill, 2010) and ideas about what constitutes adaptation success and failure have been forming. A key challenge of defining adaptation success and failure is elucidated by McDowell et al. (2014):

> *"adaptation is normative, and what is adaptive for some may be undesirable or maladaptive for others"* (p. 86)

As a result, some seminal works have presented adaptation success as entirely context-specific (e.g. Adger et al., 2009; Adger et al., 2005). However, other publications have attempted to homogenise the process of adaptation evaluation, usually by applying criteria to definitions of either adaptation success or failure. Two more recent definitions of adaptation success are highlighted in **Table 2.8**. Both of the definitions in **Table 2.8** shift the normative decision away from defining success and towards defining indicators of the author's chosen parameters of success (e.g. environmental sustainability or institutional change). The papers in **Table 2.8** are therefore only frameworks for adaptation evaluation in the very loosest sense, leaving considerable room for interpretation, particularly with regard to what trade-offs are acceptable. The reality is, most adaptation policy-making processes are littered with trade-offs between different objectives, such as between development and climate change mitigation (Suckall et al., 2014b), and between time scales (Tompkins et al., 2008).

Table 2.8 Two definitions of successful adaptation.

Source	Definition
Doria et al., 2009	*"any adjustment that reduces the risks associated with climate change, or vulnerability to climate change impact, to a pre-determined level, without compromising economic, social, and environmental sustainability"*
Osbahr et al., 2010	*"those actions which promote system resilience, promote legitimate institutional change, and hence generate and sustain collective action"*

Adaptation failure (*maladaptation*) is defined in Barnett and O'Neill's (2010) influential editorial as actions which, in the process of reducing vulnerability to climate change in one sector of a system, increase vulnerability in another. Literature exists which theorises different routes to maladaptation (**Table 2.9**) and hence the maladaptation framework might be regarded as more clearly defined than the approaches to defining adaptation success discussed above. However, there are few examples of how maladaptive actions arise in practice (Atteridge and Remling, 2013).

Table 2.9 Five routes to maladaptation (Barnett and O'Neill, 2010).

	Characteristics of maladaptation
i.	*Increased emissions of greenhouse gas*
ii.	*Disproportionate burdening of the most vulnerable*
iii.	*A high opportunity cost*
iv.	*Reducing incentives to adapt*
v.	*High path dependency*

Despite the thin literature exploring and defining the concept of maladaptation (ibid), uses of Barnett and O'Neill's (2010) definition of maladaptation in academic publications are increasing. The majority of studies utilising their definition are theoretical and refer to maladaptation in passing, as something to be avoided, but provide either no definition of their use (e.g. McDowell et al., 2014) or the broader definition of Barnett and O'Neill (2010) *"that adaptation actions do positively increase the vulnerability of other groups and sectors in the future"* (p. 211). This broad definition often occurs in discussions framing adaptation (e.g. Wise et al., 2014; Butler et al., 2013; Serrao-Neumann et al., 2013) or hypothetical adaptations (e.g. Pittock, 2013) rather than in adaptation case studies. The high prevalence of theoretical studies over practical examples is a known issue within the adaptation literature (Berrang-Ford et al. 2011). Those case studies which do make a more detailed attempt to evaluate maladaptation tend to do so based only on the presence of one of Barnett and O'Neill's (2010) five pathways to maladaptation (**Table 2.9**). Their lack of any quantification means they tend to ignore any potential trade-offs implicit in the maladaptation criteria. Furthermore, such studies primarily study soft, i.e. behavioural, adaptations (e.g. Suckall et al., 2014b; Barnett and O'Neill, 2011; Fazey et al., 2011) rather than hard, i.e. infrastructural (e.g. Gersonius et al., 2012).

Despite the difficulties in defining success and failure the most recent Intergovernmental Panel on Climate Change report created a additional framing to account for risks evolving out of adaptation (Oppenheimer et al., 2014). In addition to *key risks* and *key vulnerabilities* as established in Assessment Report Four (Schneider et al., 2007) the newly coined term *emergent risk* represents those previously underrepresented sources of exposure and vulnerability which emerge when climate change impacts and human attempts to adapt, mitigate, and develop under climate change collide. Notions of emergent risk have existed under different guises for some time, such as in O'Brien and Leichenko's (2000) *double exposure* to development and climate change. But the complexity of the social-ecological interactions involved in the production of emergent risk and the relatively recent evolution of the adaptation literature mean that evidence of the processes involved in emergent risk is currently lacking in quantity and depth. Again, key to that complexity is the manifestation of emergent risk as a system feedback, which can be unpredictable in magnitude and scale, subject to temporal delays, and has long been known to be conceptually challenging (Forrester, 1971). In consequence, Oppenheimer et al. (2014) provide very little practical guidance for the identification and study of emergent risk.

2.5.2 Examples of adaptation failure in deltas

Although only a small number of planned adaptations have been implemented in deltas, evidence is already emerging of some negative impacts of those adaptations. As a result, adaptation in deltas is receiving growing attention and debate in the academic literature. Authors such as Smajgl et al. (2015), Temmerman and Kirwan (2015), and Tessler et al. (2015) all emphasise the risks of what they argue are short term hard-engineering solutions currently being pursued for many of the world's coastal deltas. Two examples include the dam and the dyke, although the policy associated with both is not purely focused on adaptation. The use of river dykes to protect floodplain agriculture from inundation has become common place. Dyke networks stretch across deltas such as the Pearl (Seto et al., 2002), Rhône (Hensel, 1998), Nile (Nixon, 2003), Ebro (Ibáñez et al., 1997), Skagit (Hood, 2004) and Mekong (Hung et al., 2014b) at densities up to 1.3 km/km^2 (ibid). These networks provide environmental stability but, through their concurrent exclusion of fluvial sediment deposition (Manh et al., 2014), they threaten the long-term sustainability of the delta-body (Syvitski et al., 2009).

Jones et al. (2012) suggest such transformational adaptations, which are the most commonly implemented type of adaptation in coastal regions, are displaying maladaptive traits as a result of their inflexibility and reliance on disaster-risk forecasts made at the time of inception. They highlight the case of the Mississippi delta where dykes, built to protect against a forecasted maximum level of storm surge were actually detrimental to the situation when that level had been surpassed, by trapping floodwaters in with the afflicted population.

Birkmann et al. (2012) uses the example of the failings of dyke construction in the Mekong Delta to highlight why second-order adaptation will become crucial for communities in vulnerable regions. Dyke construction is designed to protect communities from increasing water-levels, increasing frequency and intensity of extreme flood events, and saline intrusion; but there is evidence to suggest that it may in fact reduce the resilience of delta communities (ibid; Hung et al., 2014b; Hoa et al., 2007). Two as yet poorly understood regrets have been identified, both linked to the way dykes block sediment deposition on floodplains during the seasonal flooding. First the blocking may starve the floodplains of the nutrients which support the productive agriculture of the delta, thereby undermining the livelihoods of the local communities (Hung et al., 2014a; b). Secondly, starving floodplains of sediment reduces the sediment building effect which has previously helped to counteract natural subsidence, human-induced subsidence (e.g. through groundwater extraction in aquaculture (Higgins et al., 2013)) and eustatic sea-level rise. On differing time scales both of these impacts will affect local communities who will be required to adjust their way of life to maintain their wellbeing.

River damming is another example. **Section 2.4.2.2** highlights that upstream damming might be considered a climate change adaptation (though it is not always called such) and **Section 2.2.1.2** has highlighted the multiple serious regrets linked to dam construction, which displays maladaptive characteristics. These maladaptive characteristics may well require second-order responses from delta communities, but, research is lacking in this area.

As an additional note, maladaptation in deltas is not reserved to hard actions, but can also be found in soft responses. Christian-Smith et al. (2014) document how maladaptive traits arose from soft action taken to cope with extended periods of low-flow reaching the Sacramento-San Joaquin Delta. For example, they highlight how insurance policies which compensate farmers too well for crop losses associated with climate change, can reduce farmers' incentives to adapt by encouraging them to persist with an unsuitable livelihood. Christian-Smith et al. also outline how the high utilisation of groundwater as an adaptation to drought in regions with very low rates of groundwater replenishment represents a high opportunity cost to society.

2.6 Chapter conclusion

There are multiple increasing and intensifying pressures on deltas. Those pressures, highlighted in **Section 2.2**, are caused particularly by alterations to hydrology and sediment flows induced by climate change and dams; as a result **Section 2.4** highlighted a need to take a more systemic approach to adaptation policy than the prevailing disaster risk reduction frameworks presently do. Such policy will require support from academic research in achieving three key goals, as outlined by Smajgl et al. (2011):

"(a) identification and articulation of desired outcomes at the relevant levels of decision making, (b) improved understanding of complex interactions that link potentially transforming decisions, and (c) contrasting desired outcomes with likely, potentially mal-adaptive outcomes." (p. 1).

In order to achieve these goals a methodology will be developed which is capable of evaluating adaptations, such as the dam and the dyke, and supporting policy makers in Smajgl et al.'s three areas.

The impacts brought by changes to sediment and hydrological flows will be multi-faceted, particularly with regard to the geomorphology of the delta and the socioeconomic success of local societies, therefore, any adaptation evaluation methodology must be systemic in its approach. With such little existing understanding contrasted against such large and transformational solutions as dams the stakes are high and no prior assumptions about functions within the system can be made. The resilience approach (laid out in **Section 2.2**) which has yet to be operationalised, but is designed to aid development of systemic policy, may help inform such a methodology. However, operationalising such an approach presents many challenges that will need to be overcome in the development stages of the methodology. The progression through environmental change policies in deltas highlighted in **Section 2.3** suggests there is potential for a significant contribution to the field in conducting systemic research to identify weaknesses in key pillars to a system's resilience, and propose policies capable of effectively addressing any such weaknesses. Ultimately an approach is required which can help avoid regrets in planned adaptation actions. **Chapter 3** goes on to discuss the formulation of such a methodology. In doing so, a case study can be contributed to what has been highlighted as a sparse literature body documenting applied adaptation evaluations.

Chapter 3: Methodology

3.1 Chapter introduction

Chapter 2's literature review established some key points with regard to the threat of environmental change in delta regions. Particularly: around the world deltas are facing intensifying climate change and development pressures; some key pressures relate to changes in hydrological flows, and reductions in the associated sediment flux; few adaptation responses to those pressures have yet been implemented, and the formation of successful responses depends on a body of theory which is contentious and rapidly changing. Also noted, was the fact that once implemented, adaptations may bring negative impacts of their own; and that the theory behind how adaptations are evaluated post-implementation, and especially how and when to implement second-order actions, is presently under-developed and lacking case studies. This thesis aims to contribute to the sparse literature documenting how negative impacts of deltaic adaptations develop, and test a methodology for how both first and second-order adaptation actions might be evaluated. This aim is met through the lens of an important and topical case study: adaptation in the Vietnamese Mekong Delta.

A further finding of **Chapter 2** was that previous adaptation policies which have been implemented in delta regions have often lacked a systemic appreciation of the system in which they operate and negative impacts have results. A key objective of this thesis is to approach the evaluation of adaptation to environmental change in deltas in a systemic manner, considering human-environment linkages that span disciplines and control a social-ecological system. Particularly it focuses on the vital services provided to social systems by fluvial sediment deposition which are presently underrepresented in the academic literature. To achieve the above goals this thesis spans and utilises a variety of social and physical-science research methods that are brought together under the umbrella of a system dynamics methodology. Rather than presenting the intricacies of all of the methods utilised in one extensive methods chapter, each of the different technical methods are presented alongside their corresponding results and discussion sections in the substantive **Chapters 4**, **5**, **6** and **7**. This chapter aims to present the overarching strategy which guided the choices of methods, and also introduces the case study to which the methodology is applied.

3.2 Strategy and theoretical framework

The literature review conducted in **Chapter 2** of this thesis has highlighted the complex and poorly understood relationship between large-scale hydropower developments, climate change, local development, and environmental services to local communities within deltas. **Chapter 2** presented evidence to suggest that alterations to the current dynamics of this relationship are likely to pose problems for delta communities globally over coming decades, particularly through adverse impacts on the provision of services provided to local delta communities by hydrological and sediment flows. In order to respond to these challenges effectively policy makers will need to be supported in the development of adaptation policy, and in some rapidly sinking deltas the need for well planned action is urgent. Such policy is facilitated by a systemic understanding of the system and its responses to pressure, without which interventions in the system may result in maladaptation and/or emergent risk. Previous research and policy into adaptations to hydrological alterations has tended to use a disaster-risk reduction approach and focus on only a select few physical changes (hazards/indicators) associated with climate change, and their potential to cause disasters. This approach made little attempt to integrate development related pressures, such as the regulating effects of dams on environmental flows, with climate changes, see for example Van et al. (2012). This chapter develops an interdisciplinary methodological framework that will provide a better understanding of a case study delta-community's relationship with hydrological and sediment flows and hence the impact of an adaptation. Additionally to advancing our knowledge of system dynamics, this methodology aims to inform second-order adaptation policies which can help to mitigate any negative impacts of the first-order action effectively, across a selection of physical (sediment flux reduction) scenarios.

On the basis of recent research into (i) the resilience of social-ecological systems (outlined in **Section 2.2.3**) and (ii) environmental flows (outlined in **Section 2.1.1.2**) it is hypothesised that the system in question is subject to thresholds, feedbacks and patterns which are hard to appreciate with mental models and cannot be assumed to be analogous with past events. These dynamics may exist in either, or between, the physical and social sectors of the system. Furthermore, these dynamics may mean that the strength of the environmental change pressure applied may not be analogous with the severity of the impact it delivers on social-ecological systems, something which the disaster-risk reduction approach tends to assume; and, in addition, complex dynamics may mean the severity of an impact may not be appreciable through measurement of isolated (often financial) outcome oriented indicators of change. The methodology applied here will therefore need to be suitable for building understanding across both social and physical systems and examining disparate drivers of change.

3.2.1 Mixed methods research

If the dynamics which are of concern in an adapting or adapted system can potentially operate across physical and social sectors of a system then ultimately interdisciplinary quantitative research will be required if a functional model (physical or mental) of the system in question is to be constructed. In addition, the concept of evaluating first and second-order adaptation actions to environmental change has an implicit subjective (i.e. social) component. Measuring the importance of a particular dynamic within a system may be a subjective judgement, based on what impacts the judger deems most undesirable, and what indicators are used. As McDowell et al. (2014) highlight:

"…adaptation is normative, and what is adaptive for some may be undesirable or maladaptive for others" (p. 86)

Therefore, in order to identify what is an important dynamic in a system, and ultimately determine optimal strategies, the quantitative modelling side of the adaptation evaluation process will need to be informed by qualitative research into the social context and the different priorities stakeholders hold for the system. Merging qualitative and quantitative research methods is often referred to as *mixed methods research* (Johnson and Onwuegbuzie, 2004). Creswell and Clark (2007) suggest that, historically, qualitative and quantitative methods have been treated as incompatible, arguing that they were based in fundamentally different paradigms (objectivism/positivism vs phenomenology). More recently, however, researchers have begun to accept that paradigms and worldviews on research are not as immovable as once thought, indeed some suggest multiple worldviews can be integrated into single studies (ibid). As a result, mixed methods research is rapidly gaining popularity across disciplines (ibid). Johnson and Onwuegbuzie (2004) contend that there are two distinct approaches to mixed methods research. In the first, the *mixed-model* approach, methods are mixed throughout the project, and in the second *mixed-method*, a project contains separate qualitative and quantitative phases.

3.2.2 Overarching methodology

Considerate of four key factors: the need for systemic understanding, the need to cross disciplinary boundaries, the need to integrate the qualitative findings of stakeholder consultation into the analysis, and the need to produce outputs translatable into policy due, especially, to the urgency and severity of the encroaching threats; this thesis is brought together under a system dynamics methodology. Such a methodology is outlined extensively by Ford (2010). The key steps include: *problem familiarisation, problem definition, model formulation, model evaluation, simulation*, and finally *policy analysis* (*model iteration* might be regarded as an additional component). The specific techniques of *system dynamics modelling* (SDM) itself are discussed in detail in the methods section of **Chapter 6**. What brings thesis together, however, is the philosophy of the system dynamics methodology, i.e. an acceptance that social-ecological systems are of extreme complexity and capable of unintuitive non-linear dynamics and, as such, that the implementation of effective policy is as dependent on our understanding of *process*, as it is our ability to predict future states of the system. The substantive chapters of this thesis track loosely onto the six steps presented above from Ford (2010), and are outlined below. The system dynamics methodology and all of the sub-methods utilised (including the modelling) in this thesis have track records in mixed model research and have facets which make them particularly suitable for such work, as outlined in their respective sections in the substantive chapters (**Chapters 4** - **7**). With the additional objective of ensuring that the outputs of this process are suitable for informing policy in the case study system (which is selected for the intensity of pressure it faces and hence the urgency of policy implementation) the different methods which are brought together in this thesis are all key components of the *decision support system* (DSS) presented by Turner et al. (2015). In summary the DSS identifies the key components required in a study of coastal social-ecological systems to ensure research best supports policy design. The key components are shown in **Table 3.1**, all of which track closely onto the different components of Ford's (2010) system dynamics methodology.

Table 3.1 Components of the decisions support system as laid out by Turner et al. (2015)

Decision support components
An interdisciplinary scoping exercise to establish or model baseline ecosystem and co-evolving socio-economic system conditions and trends, together with a focused attempt to identify 'key' policy contexts and issues (probem familiarisation and problem definition)
The selection and development of appropriate functionally related indicators of ecosystem state (the stock position) and changes in services (the flow position) supply over time (model formulation and model evaluation)
A futures assessment through the use of scenarios covering prevailing conditions and alternative future states (simulation)
The deployment of 'tools' (including models) to enable scientific, economic, and social appraisal of policy options, including distributional concerns and the use of deliberative methods and techniques to foster social dialogue across interest groups (policy analysis)
Appropriate formatting and presentation of appraisal data, assumptions and findings into an evidence base
Setting up adequate monitoring and review procedures (iteration)

3.2.3 Thesis methods

The context within which an adaptation develops holds great importance in determining its nature and performance (Biesbroek et al., 2013). In **Chapter 4**, qualitative research techniques of policy analysis and key informant consultation are utilised for problem familiarisation i.e. to put the action which has been implemented in the VMD in social, political, and historical context. In the process, information is gathered which later determines the policies of second-order adaptation which are tested. Importantly, the qualitative techniques mentioned above help establish the priorities of different stakeholders which will, in the later examination of scenarios of second-order adaptation (i) set the criteria/objectives against which success should be measured, and (ii) provide the relative criteria weights with which scenario performance can be measured.

In **Chapter 5** the basics of social science research and fieldwork in the environmental change field are introduced, and a household survey is reported (primarily quantitative) which forms the problem definition phase. The survey serves to highlight key trends associated with the adaptation in the case study region which are worthy of further examination. Through a comparative investigation of the pre and post-adaptation contexts, the quantitative social survey opens the process of evaluating the first-order adaptation. Additionally, the survey provides validation data for the model developed later in the thesis.

In **Chapter 6** model formulation takes place. System dynamics modelling is justified and introduced as the interdisciplinary modelling technique used to simulate the structure, function, and key dynamics of the delta's social-ecological system. The model constructed is then reported on and, in **Chapter 6**, the model evaluation phase is conducted, assessing its ability to accurately simulate the system under examination. The model is designed to explore the trends revealed in **Chapter 5** from an operational perspective, seeking the causation of the negative traits of the adaptation. Construction of the model is informed by the systemic understanding (problem familiarisation) developed in **Chapter 4**. Additionally, the model construction process serves to highlight our varied levels of understanding of the different sectors of the system.

Some of the parameters within systems models can theoretically be manipulated by human actions, effectively by first or second–order adaptation, dependent on the parameter. In system terms this means attempting to enhance the resilience of the system and move its components further from thresholds which lead to undesirable transformative change (Adger et al., 2011). In system dynamics this approach is described as policy analysis (Martinez-Moyano and Richardson, 2013). The method of policy analysis used to explore various second-order adaptation actions is introduced and executed in **Chapter 7**.

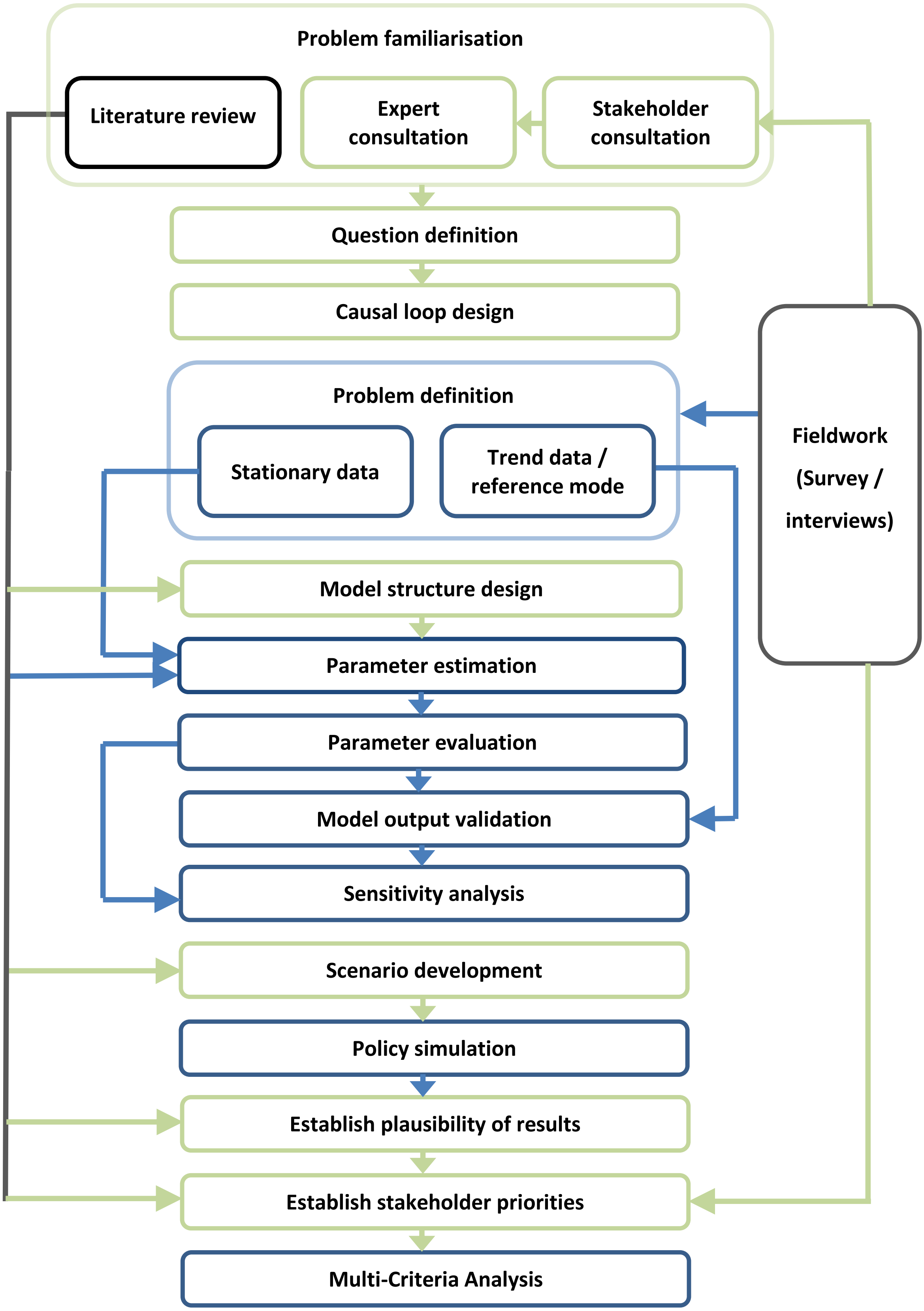


Figure 3.1 A flow diagram of the methods implemented in this project with quantitative (blue), qualitative (green), and mixed qualitative/quantitative (black) stages highlighted.

Finally, in **Chapter 7**, the model simulation phase is reported on. In order to meet the objective of producing outputs useful to policy development in the VMD region the simulation results are accompanied by a basic *multi-criteria decision analysis* (MCDA - a technique specialising in revealing preferential policy choices from a selection of scenarios based on stakeholder preferences) which is utilised to extract meaningful implications from the model simulation outputs. **Figure 3.1** presents the logical flow of how these various methods were implemented in practice, and how the qualitative and quantitative aspects interact.

3.2.4 Positioning and originality of methods

3.2.4.1 System dynamics modelling and multi-criteria decision analysis for adaptation evaluation

While not part of a traditional system dynamics methodology (as described by Ford, 2010), the concept of integrating system dynamics modelling techniques with multi-criteria decision analysis is not a new one. The approach was originally pioneered by Brans et al. (1998), though with a purely socioeconomic rather than social-ecological outlook. Indeed, **Figure 3.1**, bears close similarities with the methodology Brans et al. (1998) set out (discussed further in **Chapter 6**). Since their work, there have been early signs of the approach being utilised to analyse management options for social-ecological systems. But, thus far, it has only been applied in a qualitative manner for the purpose of vulnerability assessment (e.g. Costa et al., 2011).

Within the adaptation field, system dynamics modelling appears most commonly only as a tool for visualising social-ecological feedback loops (e.g. Fazey et al., 2011). Applying system dynamics modelling to the task of quantitative adaptation evaluation is also very much in its infancy, but has shown strong potential through studies such as Gies et al. (2014). It would appear that the further step of combining SDM and MCDA quantitatively in the manner described by Brans et al. (1998) to the climate change adaptation evaluation process is yet to be tested. Such a hybrid methodology, it is hoped, holds potential for explicitly identifying dynamics key to the negative impacts of adaptations on social-ecological systems, but further, the methodology, designed around policy testing, is well suited to testing the performance of different second-order adaptation policies designed to alleviate negative impacts.

3.2.4.2 Data from stakeholders

Participation from stakeholder groups in SDM projects is common. For example, Ford (2010) describes 9 large SDM projects (primarily conservation focused) which all involved the participation of up to 60 different groups. All used a focus group approach (e.g. Beall and Zeoli,

2008) and all used participation for cooperative modelling (see Cockerill et al., 2006) also known as collaborative modelling (see Van Den Belt et al., 2013). The qualitative data in this thesis, collected from stakeholders, informs the conceptual model but fully cooperative/collaborative modelling was not seen as appropriate for a model with strong physical (i.e. involving sediment geomorphology and agricultural science) components and the model was constructed independently.

While not collaborative, information collected from stakeholders was utilised in this project. Key informant interviews were used to aid in the structuring of the model (familiarisation) as well as to weight and prioritise the policy scenarios explored. Also integrated into the hybrid methodology referred to above, is collected survey data. The survey conducted helps define the problem, identifies questions that need asking of the system, and provides validation data for the systems model. Integrating a survey with a model in such a manner is not an entirely novel approach, indeed it was recommended for the process of adaptation evaluation by Claessens et al. (2012), however, the authors recommended further development of the approach, and in their work it was applied not to SDM, but their own combination of a trade-off analysis model and a multi-dimensional impact assessment. The three way combination of a social survey, system dynamics model, and multi-criteria analysis, would appear to be entirely unique in the context of adaptation evaluation.

The most significant novel contribution of the survey executed and the model constructed for this project lies in the task to which they were applied. The use of a household survey (and particularly the decision to utilise farmer estimates of the physical process of sediment deposition) to measure and value the socioeconomic services provided by floodplain sediment deposition is entirely novel. Subsequently, the use of a system dynamics model to operationally link sediment deposition to socioeconomic aspects of the system, and give policy significance to deltaic sediment deposition, is also novel. Given the global importance of deltas to the livelihoods of millions of people and the food security of billions, and the vital role of sediment to sustaining both delta integrity and agricultural productivity these might be seen as the most valuable contributions of this project.

3.3 Case study: the Vietnamese Mekong Delta

Fundamental questions that must be considered when studying adaptation and resilience are: resilience and adaptation to what? And for whom? (Lebel et al., 2006; Smit et al., 1999). This thesis explores adaptation options designed to protect human livelihoods from the present and future threat of disparate pressures, but particularly hydrological and sediment flow changes in delta systems. In order to put the strategy outlined in **Section 3.1** into practice a case study site was required. This section aims to locate, introduce, and justify the selection of, the Vietnamese Mekong Delta, the chosen study site.

3.3.1 Introducing the Vietnamese Mekong Delta

Among the world's mega-deltas the Mekong stands out as a suitable case study. Unlike other deltas such as the Nile, Mississippi, and Ganges-Brahmaputra the basin upstream of the Mekong remained largely undammed at the turn of the 21st century and has been described as relatively pristine in ecological terms (Dudgeon, 2011). However, the Mekong Delta is now experiencing an extremely rapid rate of change, concurrently feeling impacts from the construction of over 100 upstream dams and its status as one of only three deltas identified as having extreme vulnerability to climate change in the IPCC's 4th assessment (Nicholls et al., 2007). Furthermore, the Vietnamese portion of the Delta has seen extraordinarily rapid development following the *Doi Moi* opening up of the Vietnamese economy in 1986 (Beresford, 2008). This particularly unique set of circumstances in the VMD will likely result in previously undocumented system dynamics which are especially difficult to forecast and therefore worthy of study. There is also an urgent need to assess the potential impacts of these dynamics due to the Mekong Delta's status as a significant contributor to global food security through its expanse of productive rice paddies, and in the interests of its ca. 18 million inhabitants, of whom approximately 10% live under the poverty line, and many are ethnic minorities, landless, or migrants (McElwee, 2010).

The Mekong Delta is considered to be the last of eight stages of the Mekong River (Gupta and Liew, 2007 **Figure 3.2**). At 4900 km long, and draining a basin of 795,000 km^2 (ibid) the Mekong Delta is fed by the 12th longest river in the world (Darby et al., 2010). Passing through the Upper Mekong Basin (UMB) in Tibet and China (where it is known as the Lancang river), and the Lower Mekong Basin (LMB) consisting of Lao PDR, Myanmar, Thailand, Cambodia, and Vietnam the Mekong river transports an annual sediment load of approximately 1.45×10^8 t (Liu et al., 2013) and, via the Delta, discharges approximately 475km^3 of water to the South China Sea every year (Lu and Siew, 2006).

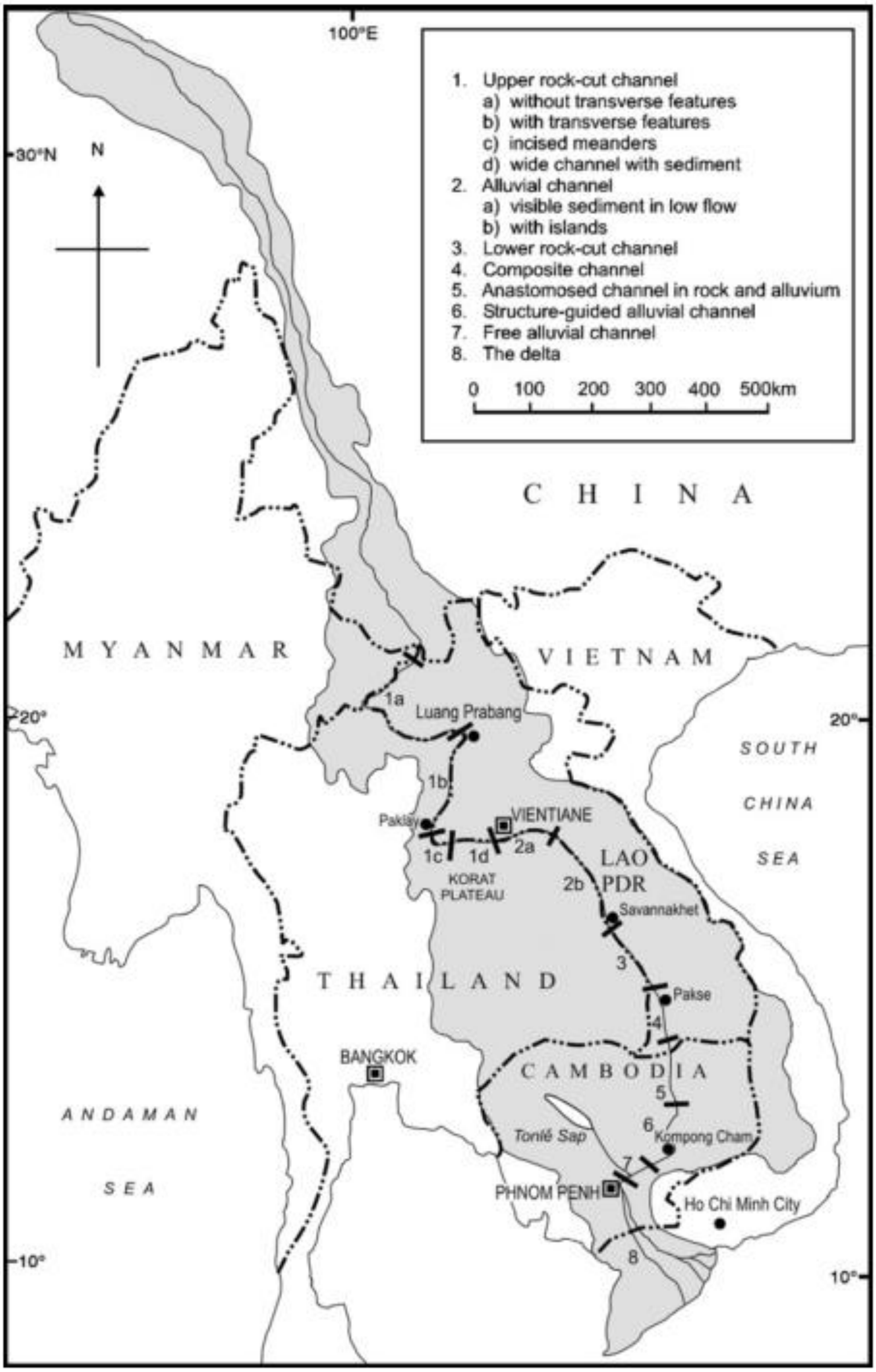


Figure 3.2 The Mekong Delta as the eighth functional component of the Mekong River (Gupta and Liew, 2007).

In Syvitski and Saito's (2007) influential paper characterising global deltas the Mekong Delta is considered a low gradient, fine grained, muddy delta, with no strong tendency towards tidal, river, or wave domination. Some 31% of its total area (ca. 40,000 km^2) lies at less than 1m above sea-level (Carew-Reid, 2007) and around 52% at less than 2 m (Syvitski et al., 2009). Despite slightly higher reaches in the Cambodian section the average elevation of the Delta is less than 5 m (Van et al., 2012). The low elevations of the delta mean it is exposed to flooding; since 2000, some 92% of its total area has experienced river flooding (Syvitski et al., 2009) but there is considerable inter-annual variation. In any given year flooding can cover 50-90% of the Delta with the most severe flooding typically occurring in the north and north-west regions. During the severe floods of 2000 these regions experienced inundation depths of over 50 cm for several months (Van et al., 2012).

The Mekong delta is considered to begin where the Mekong River passes Phnom Penh, Cambodia. At this point the river splits into two branches, the Mekong (east branch) and the Bassac (west branch). The Cambodian section of the Mekong Delta (ca. 16,000 km^2) has experienced considerably less anthropogenic alteration and maintains more of its natural and historic state (Hung et al., 2014a). However, within the Vietnamese portion (ca. 39,000 km^2) the two main river branches feed a complex network of channels which have been developed by local communities and various levels of government. National policy has fuelled rice paddy expansion as Vietnam has successfully developed a specialised rice exporting economy in the delta, covering 60% of the regions surface area and exporting upwards of 7 million tonnes a year (GSO, 2014; USDA, 2014). Some estimates suggest the supporting channel network stretches 87,500 km in total (Huy, 2010 cited in Hung et al., 2014a). Man-made ring dykes (protecting paddy fields) line about 14,600 km of that length and can generally be divided into two categories, high (average crest of 4-4.5 metres above sea-level lining 1,300 km) and low (average crest of 2-2.5 metres above sea-level lining 13,300 km) (ibid). These dykes, and an associated ca. 21,500 sluice gates, control the annual flood. The annual monsoon floods water the vast expanse of commercial and subsistence rice paddy cultivation which covers most of the Delta. The Delta does, however, contain multiple distinct agro-ecological zones (see **Figure 3.3**). In the coastal and south-west regions a variety of crops (e.g. coconut, pineapple, sugarcane) and shrimp farming can be found (see **Figure 3.4**), albeit sometimes rotated with rice to suit the environmental conditions. Crop choices near the coast are often forced due to the damaging effect of saline intrusion which extends up to 50 km inland during the dry season (Carew-Reid, 2007).

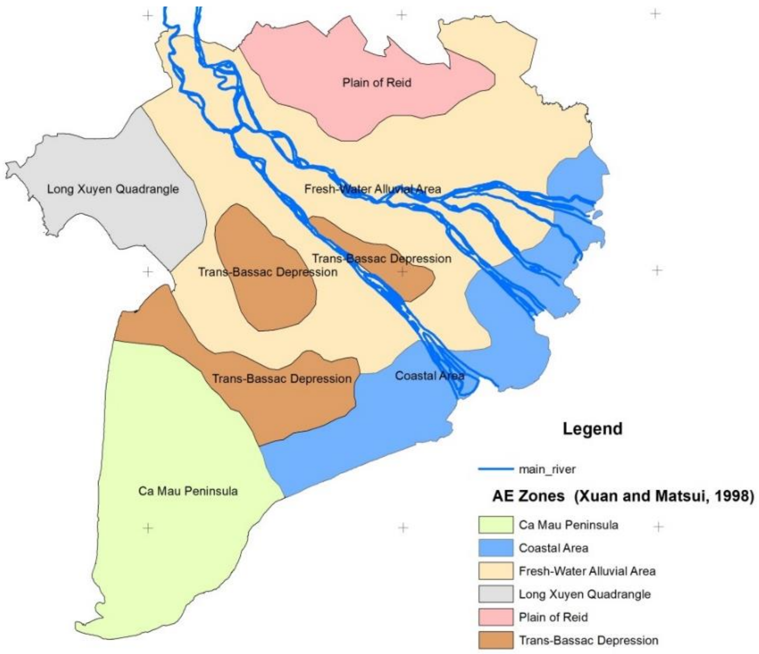


Figure 3.3 An overview of the agro-ecological zones of the Vietnamese Mekong Delta, provided by Can Tho University.

3.3.2 Intensifying pressures

The Vietnamese Mekong Delta (VMD) (**Figure 3.3** and **3.4**) now faces an array of environmental pressures and changes and represents an archetypal example of a system with potential for emergent risk. From the offshore direction sea-level rise (Van et al., 2012; Västilä et al., 2010; Hoa et al., 2007; Wassman et al., 2004) threatens the future of the Delta's 18 million inhabitants and inland, climate change will likely alter the volume and spatial distribution of runoff generated from the Mekong Basin (Thompson et al., 2013a; Kingston et al., 2011; Eastham et al., 2008). These changes will interact, through poorly understood mechanisms, with the large scale hydropower development which has recently begun. Plans for over 100 dams are at various stages of approval and the completed and planned projects are summarised in **Table 3.2**. Hydropower development will further alter the flow regime of the Mekong River and its tributaries (Lu et al., 2014; Lauri et al., 2012; Rasanen et al., 2012). However, since the directions of change of climate and hydropower impacts on hydrological regimes, especially peak flows, are opposed, hydropower development also has poorly understood potential to mitigate the climate induced change (Zhao et al., 2013).

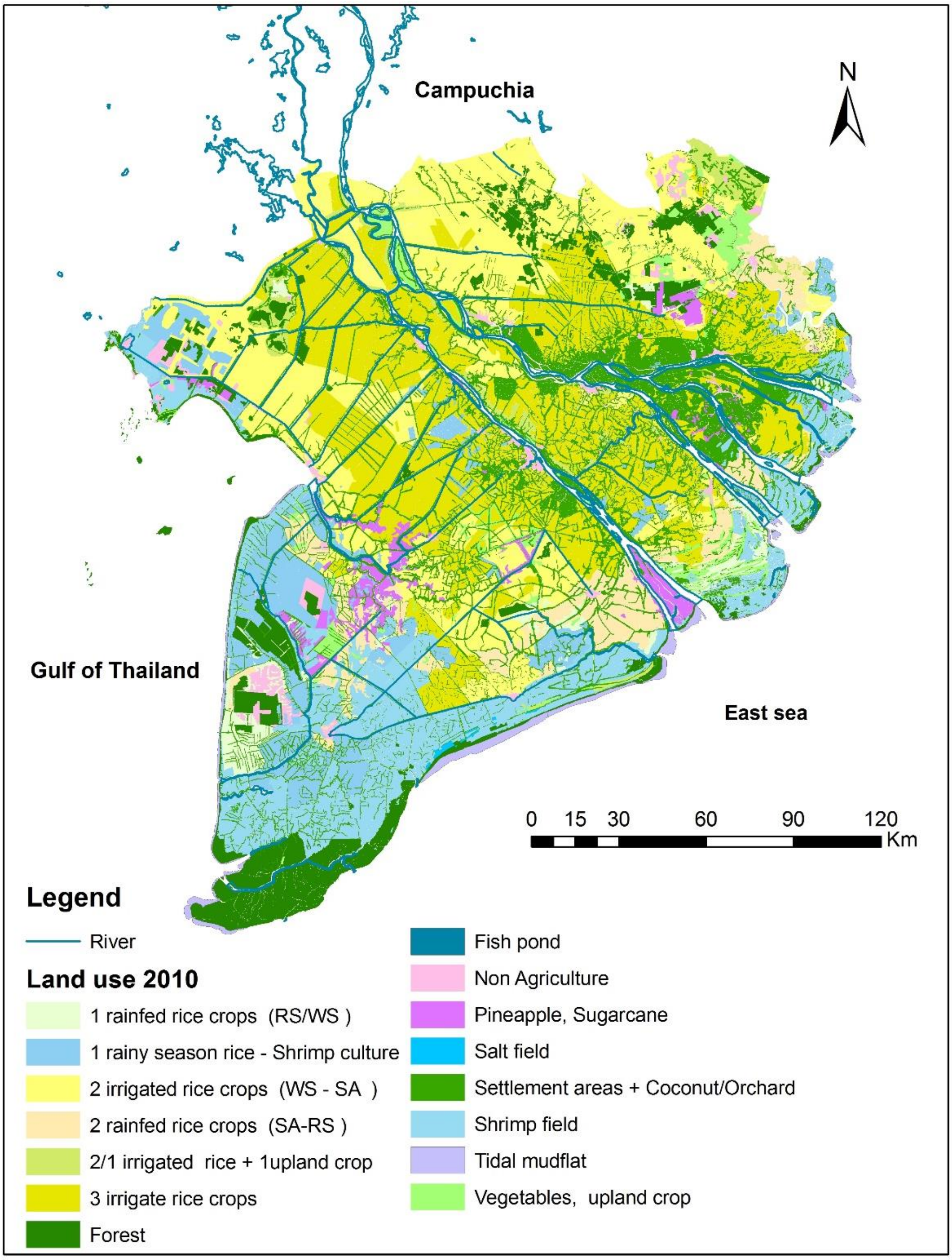


Figure 3.4 An overview of land-use in the Vietnamese Mekong Delta as established from a land cover classification from 2010 Landsat TM satellite imagery, provided by Can Tho University.

Table 3.2 Mekong basin hydropower development in numbers. Large reservoirs defined by having a capacity > 0.5 km^3 based on Vorosmarty (2003). Data from the Mekong River Commission's hydropower database (2013 version).

<table>
<tr><th>Total dams</th><th>Commission date</th><th>Size class</th></tr>
<tr><td rowspan="4">143</td><td rowspan="2">Past (pre-2013)
47</td><td>Large
8</td></tr>
<tr><td>Small
39</td></tr>
<tr><td rowspan="2">Future (post-2013)
96</td><td>Large
24</td></tr>
<tr><td>Small
72</td></tr>
</table>

Other adverse impacts may be felt through alterations to the flows of sediment in the basin, with climate change potentially altering the total load (Shrestha et al., 2013) and hydropower dams potentially trapping over 50% of that load (Kondolf et al., 2014; Kummu et al., 2010). Complicating the above changes is the poorly understood intervening relationship between the Mekong River and the Tonle Sap Lake, which currently diverts flow during the wet season and contributes discharge during the dry months (Kummu et al., 2014). There are also endogenous drivers of environmental change linked to local human development, such as ground-water extraction induced subsidence (Erban et al., 2014), and those issues relating to land-use change, particularly the shift towards aquaculture (Nhan et al., 2007). On the receiving end of this quantity and magnitude of physical changes are the local Vietnamese people and policy makers, faced with the challenging task of adapting their environment and behaviours to protect lives, livelihoods, and the success of their great rice producing machine.

3.3.3 Adaptation action

The policy makers of the VMD are well under-way with what, as stated in recent policy documents (Fortier and Trang, 2013; Vietnamese Government, 2011a; MARD, 2008, discussed further in **Chapter 4**), is a sizeable hard, planned, adaptation of the VMD's social-ecological system: the lengthening and heightening of the Delta's river and sea dyke network to the 'high' classification described above. While the initiative is financed as a major component of the national government's budget (which favours large infrastructure projects) context-specific decisions are taken by the provincial governments (Hoanh et al., 2014). The aim of the dyke infrastructure program (explored in detail in **Chapter 4**) is now to support adaptation to environmental change, but, as mentioned above, historically its objectives were to support intensified agriculture (2006; MPI, 2001; Vietnamese Government, 1996) and hence the adaptation might be regarded as one which is targeting *co-benefits* (meeting overlapping objectives) for adaptation and development (Suckall et al., 2014a). In the north the adaptation objective of the high dykes is to provide river-flood protection, and adapt to increases in the magnitude of extreme events. In the south they also protect against river flooding, but the discourse is primarily around sea-level rise and saline intrusion (Van et al., 2012).

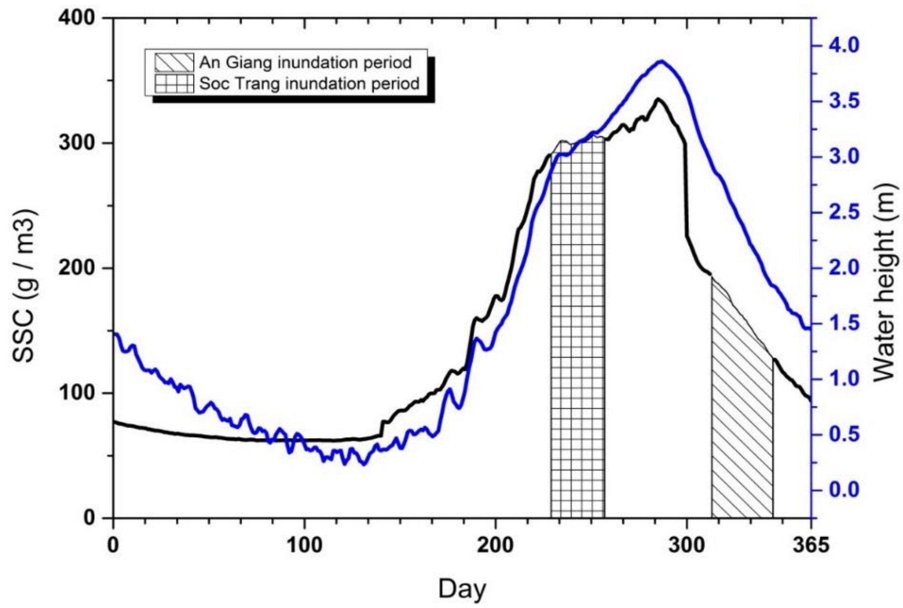


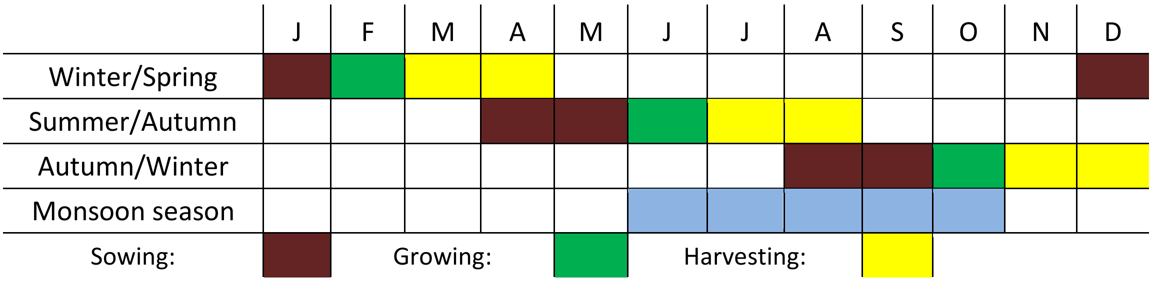
Figure 3.5 Mean daily suspended sediment concentration (SSC; black line) and the height of water (blue line) entering the VMD at Tan Chau (2005-2010) (data accessed through the MRC data portal and provided by SIWRR, Vietnam). Highlighted are the periods during which farmers growing three crops tended to open sluice gates and allow flooding of their paddies.

3.3.4 Impacts of the adaptation

In the years following the social and economic liberalisation and de-collectivisation of the Vietnamese markets during the late 1980's (known as the Doi Moi policy) a system of two yearly rice crops (Dec-Jul) became the norm, usually with a degree of flexibility and a break between crops. In this system, at the onset of the monsoon (usually between Jun-Aug), the floodplain would be left fallow and ultimately inundated by the floodwaters when the water height breached the low (0-2m from ground level) dykes or, when the sluice gates were opened. During the early-peak monsoon season (Aug-Sep) when suspended sediment concentrations (SSC) and water levels are highest (Hung et al., 2014b, and see **Figure 3.5**) fluvial sediment would be deposited, through known physical processes (Manh et al., 2014; Hung et al., 2014b), and left behind as the flood water subsided (Oct-Nov). This two-crop system, while partially controlled by low dykes and some pumping of water in and out of the delta plain, still bears some resemblance to the natural inundation regime (a semi-natural regime).

Since the closing of higher dyke rings across large areas of the delta (Sakamoto et al., 2009b) natural overflow and inundation have been either rare or have not occurred at all (Sakamoto et al., 2007). Controlled inundation of the plain is possible through sluice gate operation and pumping, but any such flood would have significantly different characteristics to a natural regime, including reduced sediment concentration (Hung et al., 2014b). Hence, minimal sediment deposition now takes place in the adapted areas (Manh et al., 2014). Perceiving an otherwise fallow compartment, the Delta's comparatively poor farmers (Biggs et al., 2009), subject to government pressure to produce, are incentivised to grow a third rice-crop. This crop, known as Autumn/Winter rice (see **Table 3.3**) is usually sown in August and September, the peak months of the monsoon flood, and is only possible with high dyke protection.

Table 3.3 An approximation of the Vietnamese rice cropping calendar (adapted from GIEWS, 2014).



The Autumn/Winter rice crop might therefore be considered an impact of the adaptation, or arguably an unplanned second-order adaptation to, what is stated by the government to be, a first-order adaptation. It is worth noting that as multiple farmers operate within one dyke compartment, once the majority, or the authority, have opted for a three-crop system, all the farmers are left with little choice but to conform. In most areas, and particularly in areas receiving little or no floodwater, water is pumped into the compartment for irrigation. However, the sediment deposition contribution of this process has also been shown to be negligible (Hoa et al., 2006).

The provincial government are aware of the increasing sediment exclusion taking place and therefore have recommended (but do not enforce) what is known as a three-three-two (3-3-2) crop cycle across An Giang province (discussed further in **Chapter 4**). This policy might be regarded as a planned second-order adaptation. Compartments are fully opened to allow flood inundation and sediment deposition once every three years however, Sakamoto et al. (2009) previously documented the poor uptake of this initiative.

There is a small body of literature suggesting that these systemic changes have negative impacts on the local community (Fortier and Trang, 2013; Birkmann et al., 2012; Cong, 2011; Kakonen, 2008; MRCS/WUP-FIN, 2007; Howie, 2005). A number of issues are mentioned, such as increasing the inequality between the landless and the land owners (Birkmann et al., 2012; Cong, 2011), increasing the prevalence of pests and disease (Cong, 2011; Sakamoto et al., 2009), and reducing soil fertility through the exclusion of fluvial sediment deposition (Biggs et al., 2009; Kakonen, 2008).

For the last of these issues there is some further supporting evidence. Hoa et al. (2006) used a VMD case study to illustrate the contribution of deposited fluvial sediment to the Potassium (K) needed to sustain intensive rice agriculture. Hoa et al. (2006) further highlight the greater contribution sediment makes to enhancing the (indigenous) soil K buffer than other K sources such as straw and fertiliser application. Pham et al. (2004) argue that the provision of indigenous K has allowed farmers to perform less K fertilisation than would be required in other environments. In total, Manh et al. (2014) estimated that under a normal inundation regime, the nutrient content (N, P, K) of deposited Mekong sediments could provide more than 50% of the fertilisation required for a wet-season rice crop.

Recently, work by Hung et al. (2014a; b) and Manh et al. (2014; 2013) has substantially improved our understanding of the physical processes involved in depositing sediment-bound nutrients on the VMD floodplain. The phenomenon of sediment and nutrient exclusion by high dykes has also already been reported in studies citing word of mouth evidence such as Howie (2005) and qualitative interviews in two communes in Can Tho province performed by Cong (2011) found 62% and 43% of farmers respectively were reporting a decline in land fertility since dyke construction. But, despite the well-known link between fluvial sediment deposition and the high productivity of deltaic environments (Olde Venterink et al., 2006) there has been little in-depth quantitative research into the socioeconomic impact of its exclusion in the VMD, nor indeed in any other of the world's major deltas.

3.4 Chapter conclusion

A methodology has been set out to evaluate the development of the Vietnamese Mekong Delta dyke network as an adaptation. The method aims to overcome some of the issues with the disaster risk reduction approach to policy design by employing a system dynamics approach, seeking out dynamics within the adapted system, and policies proposed for the system, which threaten and/or strengthen its resilience. The methods outlined above contain three key original contributions (listed below) which will advance the field, these contributions are developed further in the relevant substantive chapters:

(i) The demonstration of a combined survey and SDM approach to translating a geomorphological process into a socioeconomic service to society.

(ii) The demonstration of SDM as a tool for evaluating a climate change adaptation option and analysing second-order adaptation strategies.

(iii) The development and operationalising of the integrated and quantitative MCDA and SDM approach to policy evaluation and comparison in environmental change contexts.

Additionally, through the selection of an important, topical, case study, it is intended that the outputs of the methodology executed here will be tangible, practical, and helpful for informing systemic and effective adaptation policy design both within the study region and in comparable environments.

Chapter 4: The Changing Significance of the Vietnamese Mekong Delta Dyke Network, and its Emergence as an Adaptation

4.1 Chapter introduction

This chapter functions as a bridge between the literature review, case study introduction, and technical analysis. It forms the first step in the process of evaluating the adaptation of the Vietnamese Mekong delta dyke network. Furthermore, this chapter details the findings of the problem familiarisation phase of the system dynamics methodology (which later informs model construction) and sets the scene for a policy debate which runs throughout the subsequent quantitative research and discussion.

4.1.1 Chapter aim

Past research has highlighted that, when analysing adaptation policy in a complex social-ecological system such as the Vietnamese Mekong Delta, an adaptation's social and historical context is as, if not more, important to its nature and performance than the physical processes controlling the system it operates in (Biesbroek et al., 2013). The main aim of this chapter is to document a case study of the emergence of a regional-scale, hard, first-order adaptation. The example utilised is the expansion of the Mekong Delta dyke network, an adaptation action which was introduced towards the end of **Chapter 3**. Through analysis of various primary and secondary data sources, including government policy documents (**Table 4.1**), the body of this chapter tracks the transition of the network's objectives from agricultural intensification to climate change adaptation over the past 30 years. Interviews with key decision makers within the Vietnamese Mekong Delta itself are used to triangulate the analysis and evaluate current policy implementation strategies. This chapter begins a discussion on the implications of the manner in which the adaptation was adopted into policy. In other words, this chapter explores how facets of the process by which the adaptation was implemented might impact on its present day performance, and highlights the gaps in our existing knowledge in this area.

The principle research questions, which relate to the first objective of this thesis (**Section 1.4**), are:

i.) *What are the main objectives behind the policy to construct, expand, and heighten, the Vietnamese Mekong Delta dyke network?*

ii.) *Is the VMD dyke network delivering adaptation to climate change?*

iii.) *If so, what are the implications of the background to the network's development on its success as an adaptation?*

Table 4.1 The government policy documents informing this chapter.

Citation	Government department(s)	Document
Vietnamese Government, 1996	Prime Minister's Office	"Long-term orientation and the five-year plan of 1996-2000 for development of irrigation, transport and construction in rural areas of the Mekong river delta"
MPI, 2001	Ministry of Planning and Investment	"The 5 year plan for socio-economic development 2001-2005"
MPI, 2006	Ministry of Planning and Investment	"The five-year socio-economic development plan 2006-2010"
MARD, 2008	Ministry of Agriculture and Rural Development	"Issuance of the action plan framework for adaptation to climate change in the agriculture and rural development sector period 2008-2020"
Vietnamese Government, 2011a	Prime Minister's Office	"National strategy on climate change"
Vietnamese Government, 2011b	Prime Minister's Office	"Socio-economic development plan for the 2011-2015 period"
Vietnamese Government, 2012	Prime Minister's Office	"Viet Nam sustainable development strategy for 2011-2020"
MDP, 2013	Ministry of Natural Resources and the Environment; Ministry of Agriculture and Rural Development (in association with other non-governmental organisations and national governments)	"Mekong delta plan: Long term vision and strategy for a prosperous and sustainable delta"

4.2 Methods applied to analysing dyke policy evolution

Five key sources of information inform this analysis, each of them are outlined below. Where required, transcribing of interviews and translation of materials were provided by researchers from Can Tho University, Vietnam.

1.) The first source is the government policy documents themselves, freely available in the English language from government websites. These documents were systematically searched for the terms “dyke”, ”dike”, “irrigation system”, “irrigation structure” and “hydraulic infrastructure” where used in reference to the VMD. In each case the context of the terms use was noted, and particular attention was paid to the objectives which were linked to its management. **Table 4.1** lists all of the policy documents which were investigated.

2.) The second source is those peer-reviewed publications, cited throughout this chapter, which provided secondary data on government policy which is either not publicly stated or not readily accessible to English language researchers (e.g. Fortier and Trang, 2013).

3.) The third source is the testimony provided in semi-structured interviews conducted with senior officials of the departments responsible for hydraulic infrastructure in An Giang and Soc Trang provincial governments (see **Table 4.2**) in April and May 2014. Four senior officials were asked a set of five questions (see **Table 4.3**) about the objectives behind their dyke management, which were designed to stimulate wider discussion.

Table 4.2 Administrative units in Vietnam.

Administrative unit	~Population	~Area (km^2)
Commune	5-20,000	5-30
District	1-300,000	100-1,000
Province	1-3,000,000	1-10,000

4.) The fourth source is evidence collected in a series of six unstructured interviews with local experts at Can Tho University (CTU) that were conducted in May 2013. The experts chosen specialised in research which supports central and provincial government policy on environmental management, agricultural management, and hydrological systems management in the Delta.

Table 4.3 The five open questions asked of the policy makers interviewed (translated from Vietnamese).

What are the objectives which guide your management of land and water?
Can you rank the most important objectives?
Can you describe any threats to meeting those objective?
Can you describe any actions taken (adaptations) to mitigate those threats?
Can you describe any impacts that have resulted from those actions?

5.) The fifth source is the responses to the single qualitative question that was asked of farmers at the end of the interviews conducted for the survey which is outlined in detail in **Chapter 5**. For the survey 438 farmers were interviewed in An Giang and Soc Trang Provinces during April and May 2014. The final question asked by the enumerators was answered by 85% of respondents (although around 40% of those responding gave only a cursory two or three word answer). The question translated as:

"Please provide any comments you have on the role of sediment in your rice production" (Household Survey, 2014)

This chapter utilises a variety of different data sources. A number of additional supporting figures can be found in **Appendix 9.1**. Its overall structure is a chronological narrative which draws on these different evidences where appropriate to highlight the drivers that have influenced the development of the dyke network (**Image 4.1**). The chapter begins by setting the historical (pre-1996) scene, and ends discussing the Mekong Delta Plan which was published in 2013.


Image 4.1: A high river dyke in the final stages of construction

4.3 The evolution of VMD dyke network

4.3.1 Pre – 1996

Crude channels, dykes, and dams have been used to control the water flow in the Mekong Delta for an estimated 2000 years (Fox and Ledgerwood, 1999). However, the Doi Moi opening up of the markets throughout the 1980's changed the landscape of the VMD (Beresford, 2008). During the late 80's and early 90's, following the withdrawal of the old collectivised farming system, competition was driving production, farmers were gaining greater ownership over their land and being afforded more power to make decisions on their farming practises (Biggs et al, 2009; Pingali and Xuan, 1992). However, this new freedom was heavily curtailed by the need to meet strict production targets set by a central government that saw (and some argue still sees) economic growth as the route to prosperity, and economic growth as underpinned by the exploitation of the environment's plentiful resources (Orchard et al., 2015). Intensification resulted, with farmers utilising new higher yielding varieties of rice and more advanced technology. Yields, which as of 1986 were down at around 3 t/ha (ibid), began a steady rate of increase which would lead to present day levels of up to 8 t/ha (GSO, 2014).

Alongside the opening of the Vietnamese markets a process of decentralisation began which passed management responsibility for the hydraulic infrastructure to the provincial and district level governments (**Table 4.2**). Those local authorities further drove total production by pushing wider adoption of the double-cropping system, facilitated by the development of the canal, dyke, and sluice gate network (Biggs et al., 2009). Some argue (e.g. Evers and Benedikter, 2009) that a modern *hydraulic society* (Wittfogel, 1957) emerged in which the bureaucracy (and a growing number of private enterprises) who control hydraulic infrastructure hold disproportionate power over all corners of society. In summary, the post Doi Moi period to 1996 was a period during which market forces were aligning themselves, and newly created power vacuums were being filled. Economic growth was slower than in the period that was to come, as the nation was still recovering from the Vietnam War (World Bank, 2012), as a result the development of the delta's hydraulic infrastructure was also comparatively slow. However, the scene was being set for an explosion in growth and in the county's desire to harness the forces of nature.

4.3.2 1996 – 2000

In 1996, responding to three particularly damaging floods during the 1994, '95, and '96 monsoon seasons which resulted in around 856 deaths (Tvedt et al., 2006), (but before the threat of climate change had fully been recognised) the Vietnamese government made decision 99/TTg. The decision set out, as part of the government's five year (1996-2000) socioeconomic plan, the restructuring of the delta to provide more protection to transport networks, residential areas, and irrigation systems (Vietnamese Government, 1996):

"Article 1.- To set a long-term orientation and the five-year plan of 1996-2000 for the development of irrigation, transport and construction in the rural areas of the Mekong River delta with the aim of stabilizing the people's life, developing production comprehensively, and building the rural areas of the Mekong River delta along the line of industrialization and modernization, thus contributing to ensuring the national food security and accelerating the economic growth rate of agricultural economy and rural development" (Vietnamese Government, 1996, online)

In practice this meant canalisation and dyke expansion took hold on an industrial scale (Cong, 2011). The government used its newfound economic power to cut off almost the entire delta from the rivers with low dykes (average crest 2.5 m.a.s.l; Hung et al., 2014a) which in turn allowed the planted area of rice crop to increase by 4.4% a year during the lifetime of the plan (see **Figure 4.1**, GSO, 2014). Fortuitously the production boom this allowed coincided with the 1995-'99 boom in rice prices which, with the Vietnamese government operating a high (20%+) export tax, meant significant financial gains and a vindication of the government's strategy of natural resource exploitation for economic growth (Nielsen, 2003). Despite this success however, the above quotation taken directly from a key (Cong, 2011) policy document would suggest the objectives for the dyke network during the 1996-2000 period focused on control of the environment for the safety of lives and livelihoods.

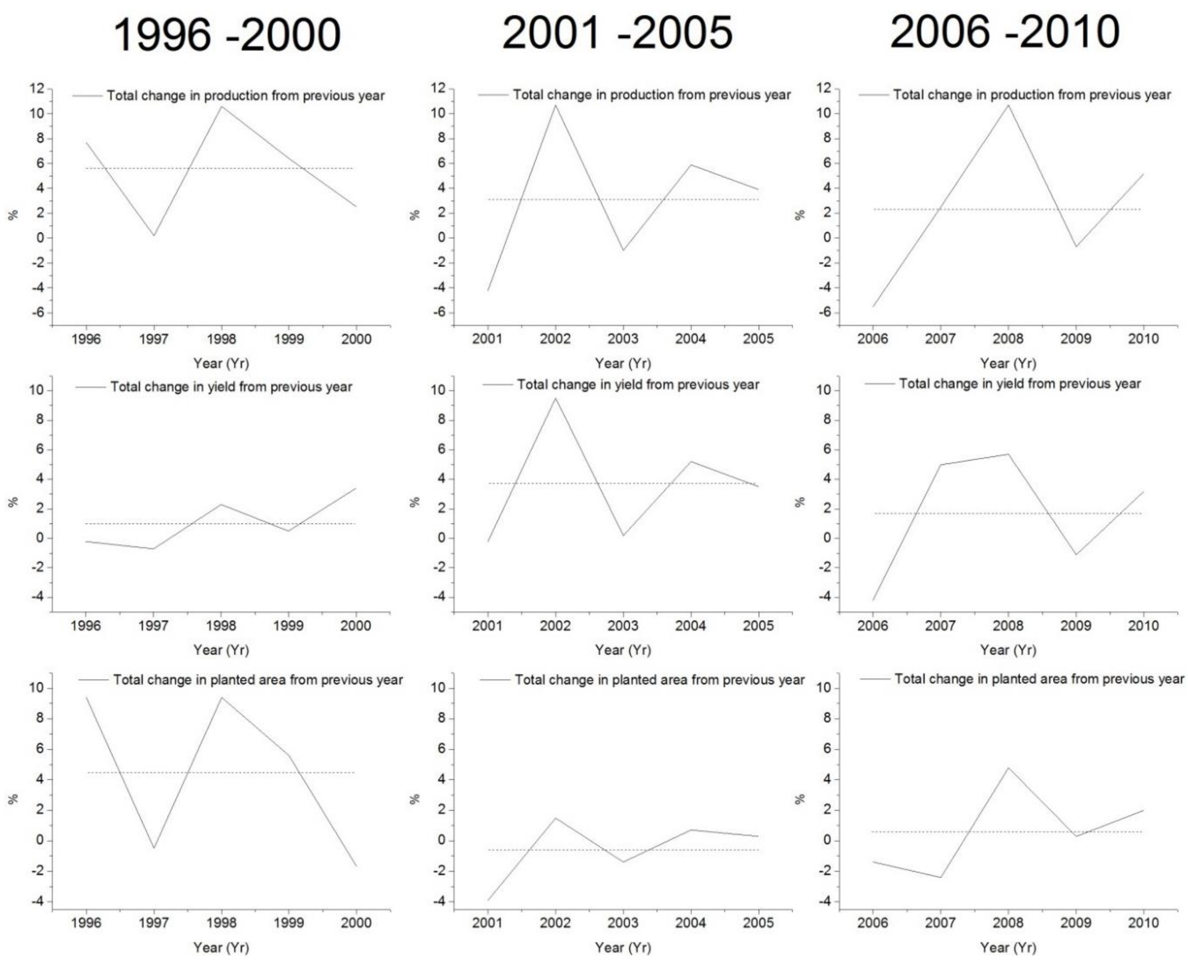


Figure 4.1 Mekong Delta agricultural performance (production, yield, and planted area) change year-on-year for three five-year socioeconomic plan periods of the central Vietnamese Government (data from GSO, 2014).

4.3.3 2001 – 2005

Despite the efforts of the government to control flows in the VMD the year 2000 flood was one of the worst on record, resulting in an estimated 482 deaths (Tvedt et al., 2006). This tragedy gave the government a mandate for further work on the dyke network (Van et al., 2012). This time the focus was on increasing the height of the dykes to entirely block the flood-water from entering the floodplain. In interview, a senior policy maker reported the success of this action in greatly reducing (unquantified) the casualties resulting from subsequent floods, such that deaths only occurred in the event of dyke failure (High ranking official, interviewed April 2014). This claim is substantiated by a Mekong River Commission report (MRC, 2012).

However, government documents highlight that flood protection may not have been the only motivation behind the dyke changes. The 2001-05 socioeconomic plan, published by the Ministry of Planning and Investment (MPI, 2001) focused more on the dyke network's ability to drive agricultural intensification:

"The system of irrigation will be developed, facilitating soil improvement, intensive cultivation, multiplication of crop and exploration of new lands" (MPI, 2001, p. 35)

The plan is explicit in its aim to develop the dyke network to allow a greater number of crops to be grown in a year (*multiplication*). Multiplication (i.e. moving to double or triple rice cropping) is only possible through heightening of the dykes. Triple-cropping requires heightening from low to high (average crest 4.5 m.a.s.l) to keep out the flood water even at its peak (Hung et al., 2014a). There was a financial incentive for such a change as rice prices had begun to fall, and despite production increases the value of Vietnamese rice exports had fallen considerably (Nguyen and Singh, 2006) as had the export tax rate (Nielsen, 2003).

Image 4.2: A high dyke rice paddy compartment

Some farmers were still transitioning from single to double cropping. But, by the end of the 2001-2005 period the triple rice-cropping pattern had gained traction (Kontgis et al., 2015). For example, in one district, Thoai Son, An Giang, covering 456 km^2, documented by Sakamoto et al. (2009a), 86% of the planted area was converted to triple rice cropping between 2002 and 2004. By 2005 over 1/3 of An Giang province's planted area was protected by high dykes (see **Figure 4.2** and **Image 4.2**). As a result of such changes, during the 2001-2005 period the planted area reduced on average by 0.6% annually, yet total production was able to increase by 3.6% a year (see **Figure 4.1**) (GSO, 2014). It would seem a key objective of the dyke network was now to intensify production within the existing cropped area and meet macro-economic growth objectives.

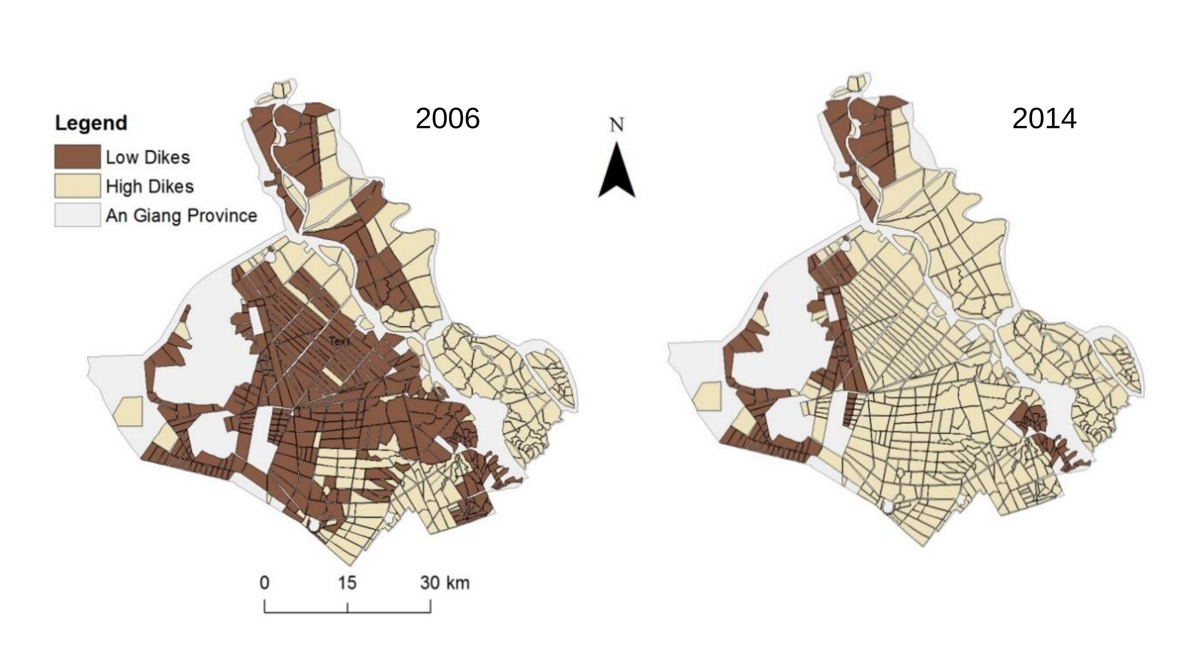


Figure 4.2 The (estimated) expansion of high dykes across An Giang province (data provided by the WISDOM project on 2006 dyke extent was updated using cropping data from AGSO, 2013).

4.3.4 2006 – 2010

The 2006 socio-economic plan (MPI, 2006) highlighted that, not only was increased agricultural production still being targeted, but it was seen as the catalyst of all other development goals and focus of the plan's $139 billion investment, a principle shared by the World Bank's 2006-2010 programme direction (World Bank, 2005). The government's aim for the Delta was to:

"mobilize the most possible resources to make full use of its strategic location and advantages, promote industrialization and modernization in agriculture and rural areas to establish a large-scale and specialized commodity-producing region" (MPI, 2006, p. 114)

In reality this meant, along with investment, strict and ambitious top down targets for the provinces to achieve in paddy rice production which required triple-cropping, and enforced designation of about 40% of the fertile land base for paddy rice agriculture (Giesecke et al., 2013). Kontgis et al. (2015) estimate that by the end of the 2006-2010 plan the extent of triple-cropping in the VMD had grown to around two thirds of the paddy area. Driving production through triple-cropping systems meant further development of the dyke network, on which the 2006 plan stated it would aim for:

"complete flood control and irrigation works, better satisfying the requirements of production" (MPI, 2006, p. 115)

Since the plan's completion the enforcement of such targets has continued, in 2011 MARD demanded a one million tonne increase in production, primarily to be obtained by increased winter (third) rice-cropping in the Mekong Delta (e.g. MARD, 2011).

This heavy focus on specialisation is directly at odds with the recommendations of high profile adaptation research coming out at the time of the plan's inception, which emphasises the importance of diversification of income streams (e.g. Howden et al., 2007; Thomas and Twyman, 2005). The call for diversification in the region has only strengthened since (Renaud et al., 2014). Hence, commentators (e.g. Giesecke et al., 2013) and the World Bank (2011) have latterly criticised the restrictive approach high level government has imposed on land use and livelihood choices in the Delta, claiming the specialisation strategy it employs is high risk and open to catastrophic failure. Others also claim that specialisation marginalises the poor who perhaps: cannot afford the necessary technological advances, do not own land or, lose access to alternative income sources brought by the now excluded flood (Birkmann et al., 2012; Kakonen, 2008), facets which might be identified with Barnett and O'Neill's (2010) characteristics of maladaptation. Particularly, dykes reduce access to wet-season fisheries which are primarily utilised by poorer groups within society (MRCS/WUP-FIN, 2007); although such fisheries are already threatened by the damaging effects of upstream dam construction (Ziv et al., 2012). The academic experts interviewed at Can Tho University described how Mekong delta farmers are fighting a losing battle against increasing and fluctuating agricultural input prices in a context of stagnant rice prices and, as a result, sinking into debt. This issue is reflected in the high rates of outmigration from An Giang province (see additional figures presented in **Appendix 9.1**). While the farmers themselves were not asked about the sensitive issue of governmental control over land management in the household survey, one farmer did raise the issue of control in the final question of the interview:

"If we don't have sediment the soil will not have sediment and the [fruit] *tree is not healthy. But, we are not allowed to open the sluice gate"* (Household Survey no. 31, 2014)

Despite documented drawbacks to this scheme, and others (such as large scale damming, see Ziv et al., 2012), the national government are known to favour large scale hydraulic infrastructure projects as a combined strategy for driving development, rice production, and protecting the population from environmental catastrophes (Hoanh et al., 2014). However, research by Evers and Benedikter (2009) suggests the motivation behind this preference may lie outside of purely humanitarian objectives. Evers and Benedikter contend that in the hydraulic society that emerged during decentralisation complex networks of nepotism between (formerly state run) private hydraulic infrastructure companies and the state bodies allocating funding have formed. Some suggest such networks may be driving hydraulic infrastructure works in an effort to sustain and expand the political and financial power of some individuals (Biggs et al., 2009).

To summarise the 2006-2010 period, the dyke network and the social systems around it were cementing their specialisation, and it might be argued their path dependency, in order to maintain the delta as an agricultural and economic powerhouse in a context of falling prices and rising costs. The extent of the high dyke network continued to grow.

4.3.5 The 2008 reorientation towards climate change adaptation

The above discussion of the five year plans highlights how the development of the dyke network has helped the delta community adapt to their environment and maximise agricultural productivity. What is not present is any discussion of adapting to a changing environment. Indeed, at the time of initiation of the 2006-2010 plan adapting to climate change was very rarely mentioned in any government communications (Francisco, 2008). However, a swift change took place and Fortier and Trang (2013) claim dyke enhancement is now a core element of the central government's strategy for adapting to climate change and, as a result, it is also leading the adaptation discussion at the local policy level (Birkmann et al., 2010).

Examination of the Ministry of Agriculture and Rural Development's *"Action Plan for Adaptation and Mitigation of Climate Change […] 2008-2020*" (MARD, 2008) provides evidence of this new adoption of environmental change objectives into the management of the dyke network. The section of the plan titled *"detail activities"* (p. 10) suggests the dyke network is central to all three of its primary objectives: (I) stability and safety of residents; (II) stable agricultural production and food security; and (III) ensuring maintenance of the dyke and infrastructure systems, under climate change.

Vietnam's subsequent "National Strategy on Climate Change" published in 2011 by the Prime Minister's office (Vietnamese Government, 2011a) further highlights the large role planned for river dykes in adapting to climate change:

"To improve, upgrade, repair and build […] systems of river dyke and breakwaters which can effectively cope with floods, droughts, sea level rising, and salt contamination in the context of climate change" (Vietnamese Government, 2011a, online)

The new direction is affirmed in the most recent five-year plan (Vietnamese Government, 2011b). Unlike the two previous plans this iteration contained no mention of utilising irrigation infrastructure for agricultural intensification. Instead the focus was on:

"…consolidating the system of sea dykes, river dykes […] to mitigate natural disaster consequences" (Vietnamese Government, 2011, online)

Therefore, while the VMD dyke network's expansion was initiated with the aim of environmental stability and to protect livelihoods, its stated objectives changed over time, initially towards agricultural intensification (which contributed to its heightening), then latterly to climate change adaptation.

4.3.6 Adapting to the environment vs adapting to climate change

The difference between an initiative that is designed to optimise and protect agricultural systems in an environment, and one which is designed to adapt to climate change is subtle and at first might seem trivial. Commentators suggest the difference, and hence the challenge, lies in coping with an unpredictable baseline condition, which is changing with *"speed, severity, and complexity"* (Adger et al., 2011, p. 758) versus adapting to a static baseline. The fact that the dyke network was not purpose-built to deal with these challenges may be significant but is largely un-studied. The development of the network was not evaluated against any criteria of successful adaptation and its impacts, in terms of its ability to support climate change adaptation, have not been assessed. The choice to pursue and develop the dyke network as a climate change adaptation was largely pre-determined due to path dependency (a key feature of Barnett and O'Neill, 2010's maladaptation) caused by past decisions.

Vietnamese policy makers already had a dyke network stretching an estimated 14,600 km across the VMD (Hung et al., 2014a) in place. The network has become particularly important for sustaining agriculture in the more frequently flooded northern provinces of An Giang, Dong Thap, Kien Giang, and Long An where crops are commonly grown during the peak monsoon season and hence require protection (Sakamoto et al., 2009b). These four provinces are the greatest rice producing provinces in Vietnam, in 2012 producing almost 14 million tonnes of rice (GSO, 2014) enough, on their own, to rank as the 9th largest paddy rice producing country in the world (FAOSTAT, 2013).

In interview one policy maker illustrated their path dependency when they explained their concern that any steps which prevented growing of the third rice crop (i.e. backtracking on high dykes) would jeopardise the livelihoods of their citizens (High ranking official, interviewed April

2014). Recent research recommends adaptation policies be fixed only in the short-term, and dynamic over the long term, in order to account for uncertainties in climate change trajectories (Haasnoot et al., 2013), of which there are many in the Mekong Basin (Thompson et al., 2013b).

The end result of this multi-faceted evolution process is that the local policy makers tasked with its implementation are managing an extremely complex suite of objectives and in reality they have few courses of action available to them. **Table 4.4** shows the objectives which were reported and ranked for importance by the four policy makers consulted in An Giang and Soc Trang province. It can be seen that in both provinces climate change objectives were ranked as most important. It can also be seen that the policy makers are trying to simultaneously meet a wide variety of needs.

Taking one of those climate change objectives as an example: sea-level rise linked inundation, which both MARD and the Prime Minister's Office often highlight as their priority:

"Special attention will be given to the issues of temperature increases and sea level rises" (MARD, 2008, p. 7)

"To reduce harmful effects of natural disasters, actively and effectively respond to climate change, especially sea level rise" (Vietnamese Government, 2012, p. 1)

Had the policy makers not been path-dependent, the adaptation action, dyke heightening, which was pursued, would not have been the only option available. Ibáñez et al. (2014) outline the alternative, which was to take steps to maximise sediment deposition on the delta floodplains, a strategy known as *rising grounds* which is currently being tested in the Mississippi delta (Kenney et al., 2013). Rising grounds aims to counter sea-level rise by elevating the land level through strategic control of the natural processes of fluvial sediment deposition (Ibáñez et al., 2014). The policy makers' chosen path, referred to as *rising dykes* takes a more hard engineering approach in banishing water (and sediment) from the floodplains. It might be argued that upstream dam developments and the associated sediment trapping weakens the potential of the rising grounds strategy, but no systemic analysis has been performed.

In fact, no objectives relating to fluvial sediment deposition are present in **Table 4.4**, despite its key role in the formation and sustainability of river deltas (Syvitski and Saito, 2007), and clear interaction with delta dyke networks (Hung et al., 2014b). When asked, two of the policy makers (who have direct responsibility over hydraulic infrastructure in their province) stated that sediment management did not fall under their remit (High ranking official, interviewed April 2014). As there are no other departments at the provincial level that would take responsibility for fluvial sediment management this would suggest that sediment-linked objectives do not have any representation at this level of management. This, again, provides an explanation for the absence of sediment-related objectives in those listed by the policy makers and would also make the current management practice of triple-cropping, which totally excludes sediment, a more viable option.

Table 4.4 The success criteria against which the provincial officials managing the dyke network are managing their work, with the top 5 ranked by importance.

		Climate change adaptation objectives			**Other environmental change objectives**	**Other objectives**			
Province	**Zone**	Protect people and livelihoods from increasingly intense river flooding	Protect people and livelihoods from increasingly intense tidal flooding	Protect livelihoods from increasing saline intrusion	Manage water supplies under upstream dyke and dam development	Ensure profitability of agriculture (including during the dry season)	Manage the competing water needs of different crops	Provide water for domestic use	Flush pests and disease out of compartments
An Giang	Fresh water alluvial	1		3	5	2		4	
Soc Trang	Fresh water alluvial / Coastal area	4	2	1		3	5		

4.3.7 Adapting during decentralisation

Vietnam is going through a process of decentralisation, and as a result, local government authorities have been taking over more responsibility for forming development plans, including adaptation plans (Garschagen and Kraas, 2011). The devolution of power over decision making is often cited as a key step towards implementation of effective adaptations (Adger et al., 2011) as it facilitates the development of context-specific, tailored, adaptations and hence this might be seen as a positive step. Furthermore, decentralisation is a step which has explicitly been recommended for successful adaptation in Vietnam (McElwee, 2010). However, decentralisation is not without its dangers, Adger et al. (2011) suggest a mismatch of scales between the long-term and strategic problems of climate change against short-term and local decision making from local governments on elected terms can lead to adaptations which undermine resilience. Some of the academic authors who have assessed the situation in Vietnam have been critical of the performance and operations of local authorities tasked with designing policy in these areas identified by Adger et al. (2011). Garschagen and Kraas (2011) suggest that the segregation of responsibilities to individual sectors is resulting in adaptation policy which is ineffective because it is not systemic in its outlook. Orchard et al. (2015) also contend that the authorities holding devolved powers still maintain too great a focus on the short term goals of meeting economic and production targets set centrally, and attaining financial independence.

The objectives laid out by the local policy makers in **Table 4.4** provides evidence of these issues. All of the listed objectives tackle issues which operate on short, day-to-day or season-to-season timescales, and are local to the province. Absent from the objectives are any that deal with the long-term, wider, future of the VMD. Decentralisation might therefore provide a second explanation for the absence of sediment related objectives reported by the provincial policy makers, as such issues are often long-term and not localised. Below are two examples of such issues that are absent from the reported objectives.

A long-term objective affected by the dyke policy is the prevention of permanent inundation resulting from eustatic sea-level rise. The sediment deposition process, banished by the presence of high dykes (Hung et al., 2014b), builds the height of the delta floodplain, and counteracts the natural subsidence of the delta-body (Syvitski et al., 2009). With the VMD already rapidly sinking (Erban et al., 2014), the objective of sustaining the integrity of the delta body operates only over a time scale of 50-100 years (Syvitski et al., 2009), but this is, perhaps, too long for it to factor into the concerns of the local-level policy makers.

A non-local objective of dyke management is in the mitigation of flooding between delta provinces. Reducing the flood buffering capacity of the upper delta by closing off the floodplain with dykes may increase the flow velocities and height of water reaching downstream areas not protected by high dykes (Van et al., 2012). This increase could result in increased severity of flooding in the southern delta and remaining non-dyked areas (Birkmann et al., 2012; Van et al., 2012; Kakonen, 2008; MRCS/WUP-FIN, 2007). Sakamoto et al. (2007) have already documented an increase in the long term flooded area in the downstream provinces of Bac Lieu and Ca Mau during the expansion of the triple-cropped areas in the north between 2000-2004 however, it is uncertain whether this is related to the expansion of aquaculture in the region or the aforementioned phenomenon.

A number of factors affect the policy formulation process. Another for consideration, which offers an alternative hypothesis for why the above example objectives did not factor into the policy-makers considerations lies in the technical capacity of the departments to which responsibility was devolved. In the case of Vietnam, where devolution is only a very recent (mid 2000's) event, Garschagen and Kraas (2011) contend that local level governments have not yet evolved the technical capacity to develop effective adaptation action plans. To support this Orchard et al. (2015) provide qualitative evidence of local governments failing to understand more advanced and recent ideas in ecosystem management (in their case in the management of mangrove forests).

In interview the policy makers were asked to identify any negative impacts of their adaptation actions. In response, the interviewees were open about the inadequacies of their own knowledge, citing a lack of scientific evidence on the issue of delta subsidence driven by sediment exclusion from the floodplain, and a lack of understanding on the issue of nutrient exclusion from the floodpling. One official stated:

"Because my major is not agriculture I am not sure about the impacts of sediment on yields" (High ranking official, April 2014)

A lack of technical capacity for effective adaptation planning at the local government level is something that has been documented in other regions (e.g. Macintosh, 2012), and is a factor which might help explain why and how adaptation actions with potentially maladaptive traits arise.

4.3.8 The Mekong Delta Plan

In 2010 the two key departments of the Vietnamese Government, MARD, and MNRE responsible for the socio-economic and environmental management of the delta joined forces with the Kingdom of the Netherlands to perform another reappraisal of the Delta's governance strategy, the Mekong Delta Plan (MDP), published in 2013. This assessment, influenced by the interests of the international community, took a longer-term look at the management of the Delta, with scenarios reaching as far as 2100. Recognising some of the issues mentioned above a key feature of the plan was a focus on systemic assessment of the impacts of actions across the whole deltaic system:

"… careful weighting of costs and benefits against multiple interests, and coordination and integration of measures and policies… [to] avoid sunken costs that may emerge when measures and investments made at one province or locality become sub-optimal or obsolete by unforeseen measures taken elsewhere" (MDP, 2013, p. 72)

The MDP recognised that past efforts lacked a systemic outlook due to some of the factors mentioned above, but particularly a lack of capacity. The MDP pointed out that less than 1% of staff at the Provincial and District levels of government were educated to Masters level or above (MDP, 2013). It also highlighted that the bachelors qualifications held by the majority of staff employed at the lower levels of governance (provincial and district) were achieved at universities teaching only a very narrowly focused field of study and in an environment where critical analysis of issues was not encouraged.

This time, among the key findings of the assessment was that sediment would play an important role in successful adaptation in the region up to 2100. Particularly:

"it is therefore important to optimise and maximise the natural sedimentation as an adaptation to sea level rise" (MDP, 2013 p. 79)

The objective of maximising sediment deposition on the Delta's floodplain would fall, at least in part, under the responsibility of the managers responsible for the Delta's dyke network. As such, it is notable that the provincial policy makers did not regard sediment management as a key objective in interview in 2014. With regard to allowing flooding and sediment deposition during the monsoon season an interviewed policy maker stated:

"we cannot tell the farmers to reduce their production because the farmers need the production to sustain their livelihoods" (High ranking official, interviewed April 2014)

The policy maker's comment refers to a supposed economic dependence of farmers on growing a third monsoon-season rice crop. This statement goes some way to explaining why the provincial government do not enforce their recommended 3-3-2 cropping rotation (see **Section 3.3.4**). The case that cultivating a third crop improves the livelihoods of the farmers has not been firmly made, a fact that was also conceded by the interviewed policy maker. Indeed, of the 384 farmers interviewed in Soc Trang and An Giang province that were asked about the role of sediment in their paddy, 68% of farmers pointed to either a positive relationship between sediment and yield or a negative relationship between sediment and the requirement on them to apply fertiliser. This suggests potential economic benefits to sediment deposition that have not been weighed against the value of the third rice-crop. The policy maker expressed the need for further study into the matter (High ranking official, interviewed April 2014). Furthermore, the absence of research quantitatively assessing the relative social value of encouraging sediment deposition versus growing further rice crops was identified in the MDP as a key gap in existing knowledge:

"The extra income of a third rice crop needs to be weighed to decreased yield of the first two crops, loss of fertile sedimentation, costs of fertiliser, increased costs of flood protection and other economic prospects for the wet season" (MDP, 2013, p. 24)

For the policy makers who currently implement dyke-based adaptation strategies within the VMD, and who will be implementing any policies taken up from the MDP (2013) this knowledge gap is an important weakness. Particularly, as evidence has already been presented to suggest their understanding of the role of sediment in their system is low and that they are reluctant to take responsibility for it.

4.3.9 Evaluating the success of the dyke network as an adaptation

Throughout the above chapter a number of Barnett and O'Neill's (2010) characteristics of maladaptation have presented themselves. The presence of maladaptation is cause for concern because of the potential it has to develop into first an emergent, and later a key risk to humanity and global ecosystems, as described by the IPCC's report (Oppenheimer et al., 2014) and in **Chapter 2**, when interacting with other development and climate change mitigation drivers of change (e.g. upstream dams). However, the mere presence of these characteristics does not necessitate a net increase in vulnerability to the system. In this case, the increases in vulnerability may take place in a variety of sectors of society (rich vs poor, riverbank vs non-riverbank) and on a variety of spatial scales (in-situ vs downstream) while in other sectors and scales benefits may be felt. At present those vulnerability increases are hypothetical and their variety and unpredictability make them difficult to measure. Some quantification is needed, and a system somewhat more nuanced than Barnett and O'Neill's (2010) maladaptation framework. In such a complex system, with multiple stakeholders, a clear strategy is required for such a process. One key first step has been identified above which could initiate an evaluation of the success of the high dyke approach to adapting the VMD: the weighing up of services provided by sediment versus the benefits of a third rice-crop.

4.4 Chapter conclusion

Calls are frequently made in the academic literature for greater clarity in the definition of adaptation that is being used when case studies are being reported (e.g. Murtinho and Hayes, 2012). This review has served to reiterate that the emergence of an adaptation, in practice, is rarely a straightforward and clear-cut process. Here, while the use of adaptation terminology begins abruptly in 2008, the dyke network's physical adoption creeps in incrementally, as the network is steadily expanded and heightened. At no point does a fully evaluated decision to expand and heighten the dyke network as an adaptation appear to have been made. The dyke network's historic flood protection objectives bare similarities to its present adaptation objectives but the issue of the moving baseline associated with climate change may not have been considered and neither the potential benefits of encouraging sediment deposition.

Abunnasr et al. (2015) discuss the implementation of incremental adaptations during windows of opportunity. Rather than in large one-off transformational actions, they suggest that allowing for the uncertainty inherent in environmental change projections and progressively implementing incremental adaptations is a cautious but effective method of adapting. Each change can be made in anticipation of an approaching tipping point in the system. Others, such as Wise et al. (2014), suggest that incremental adaptations may still lead to maladaptive pathways; specifically, incremental action may be taken to ensure continuity of the status quo rather than in anticipation of approaching thresholds. As such, incremental adaptations may function to sustain a system in an increasingly unsustainable landscape. In the case of the Mekong Delta, the adaptation objectives of the action undertaken on the dyke network are very much to sustain the status quo, despite the fact that transformational changes are already exogenously influencing the delta through climate change and upstream hydropower development. The objective of sustaining an agricultural production drive has resulted in an incremental adaptation being implemented. In the following chapters (**5**, **6**, and **7**), the systemic impacts of the adaptation are explored, with a particular focus on the sediment-related knowledge gap identified, and any consequences of the nature of its adoption are investigated and, for the first time, quantified.

Chapter 5: The Impacts of the Adaptation of the Vietnamese Mekong Delta Dyke Network

5.1 Chapter introduction

An adaptation has evolved, as documented in **Chapter 4,** with mixed objectives of development, environmental stability, and climate change adaptation, but at no point does a systemic analysis of the action's long and short-term performance as an adaptation appear to have been conducted (either pre or post-implementation). Here such a process is initiated, with a particular focus on the role and social value of sediment in the Vietnamese Mekong Delta (VMD); a specialised rice-producing social-ecological system. In many provinces, particularly of the northern delta, rice farming indirectly employs not only the farmers but the majority of society. As **Chapter 4** has outlined, a hydraulic society prevails, highly dependent on dyke networks and water regulation for a variety of services. As a result, this chapter works on the assumption that measuring the impact of the adaptation of the dyke network on society can be performed by measuring its impact on the rice-agriculture sector.

5.1.1 Chapter aim

The overall aim of this chapter is to quantify the impacts, physical and socioeconomic, of the adaptation of the dyke network on VMD's rice farming systems. This is performed through the lens of the switch from a double to triple-cropping system which the increase in the height of the dykes enforces; especially when accompanied by government production targets (as discussed in **Chapter 4**). The impacts of the adaptation are measured here in a correlational manner, by analysing the agricultural trends reported in a large (n = 434), randomly sampled, farmer survey. Comparisons are made between key trends under the triple-cropping high dyke environment (post-adaptation) operating across two thirds of the delta's rice producing area (Kontgis et al., 2015) and key trends in the remaining one third of the paddy area where double-cropping and low dykes (pre-adaptation) still operate. Subsequently, in **Chapters 6** and **7,** the causative relationships of the trends revealed here are investigated through construction of a system dynamics model and, a secondary function of the data collection and analysis outlined in this chapter is to provide data against which the model can be validated.

The survey reported herein uniquely focuses on the significance of the exclusion of deposited fluvial sediment to the local socioeconomic system. This facilitates a calculation of the tangible economic value of deposited fluvial sediment to the chosen study area (An Giang province in the northern delta). The role of sediment deposition in determining the success of the adaptation implemented is discussed, as is the relative performance of the adaptation from the perspectives of different wealth classes. Wealth inequality being, as discussed in **Chapter 2**, a key determinant of society's ability to cope with environmental change (e.g. Szabo et al., 2015).

A further contribution of this chapter is to provide evidence to inform key policy debates taking place within the VMD and its wider basin. With dam construction likely to significantly reduce the sediment load reaching the delta (Kondolf et al., 2014), there is a need to appreciate the socioeconomic services provided to society by sediment. Putting an economic value on such services is a common approach utilised to help either ensure a valuable service's preservation or, at least, to facilitate informed analysis of trade-offs implicit in decision making. Here the service sediment deposition provides by delivering free nutrients to rice cultivated on the floodplain is valued. This valuation links directly into the evaluation of the adaptation as high dykes are already known to exclude the majority of sediment deposition from the floodplain (Hung et al., 2014b). Such a valuation has been attempted on one previous occasion in the VMD. The ICEM report (2010) estimated the fertiliser costs needed to compensate for a 75% reduction in sediment-bound nutrients reaching the floodplain (due to dam trapping) would be approximately USD $24 million at 2010 fertiliser prices. Their estimate was based on the market value of the bulk nutrients carried, and deposited, by the river. But, the mechanisms which translate the nutrient content of suspended sediment into improved yields for farmers are very poorly understood, subject to complex biological and geomorphological processes and particularly human management practices. It can therefore be argued that the value produced by ICEM's approach is subject to considerable uncertainty, leaving a knowledge deficit which this chapter aims to fill. The key research questions addressed in this chapter primary relate to the second overall objective of this thesis (**Section 1.4**) and they include:

- *i.) How do key indicators of agricultural performance (e.g. yield and fertiliser application) vary between the adapted (high dyke) and non-adapted (low dyke) environments?*
- *ii.) How are the socioecomic livelihood impacts that are associated with the adaptation action distributed across wealth strata?*
- *iii.) Is there evidence of a relationship between agricultural trends and the high dykes' exclusion of fluvial sediment deposition?*
- *iv.) What is the socioeconomic role and tangible value of sediment in rice agriculture in the VMD?*

v.) *To what extent do the answers to the above questions point to a successful or failed adaptation?*

This chapter addresses these research questions through the following structure: first it reviews the various considerations which need to be made when conducting social science field research; it then justifies the chosen survey method and reports the details of its implementation; subsequently, this chapter presents (and checks against logical expectations and secondary data) the basic physical differences between the pre and post adaptation environments (e.g. inundation and sediment deposition depths between low and high dyke compartments) reported by the farmers; discusses the trends and correlations within the agricultural data obtained from the farmers in relation to the dyke height change and shift towards triple-cropping; and finally, discusses the implications of the findings on the overall performance of the high dykes as an adaptation.

5.2 Social survey methods

Within the climate change adaptation field the goal of social science research is usually to discover and value (economically or otherwise) environmental or climate services lost, or provided to, society. Here I deconstruct the processes and particularly the potential sources of error involved in collecting data of this nature.

5.2.1 Using humans as a data source

Khagram et al. (2010) describe the positivist perspective on data collection:

"In the positivist tradition, an actual external material reality exists independently of human perception, and is governed by law-like systems. This external reality can be objectively observed through direct or assisted (as with a microscope) sensory perception" (p. 390)

In practice, data is accessed through two routes, it can be measured directly (primary data), or it can be accessed indirectly through a third party that has recorded it (secondary data). There are pros and cons to either route. Direct measurement can ensure the researcher maintains complete control over the data collection process but, collecting large quantities of data may involve considerable time, effort, and money. An example might be the field sampling of sedimentation on the VMD floodplain by Manh et al. (2013). Use of secondary data foregoes a degree of control in exchange, usually, for a greater quantity of data, or data which the researcher does not personally have the tools to collect. Examples include the use of census data to investigate human-environment interactions by Szabo et al. (2015) in the Ganges-Brahmaputra delta.

In traditional contexts performing interviews or surveys with humans, as conducted herein, tends to be treated as primary data collection. Examples include when asking participants personal information such as their age or profession, or their opinion on a matter.

Increasingly, however, humans are being asked to report environmental data. Common examples include asking farmers to report their crop yield, or to estimate the number of days of rainfall they have experienced. In this context the lines between what is primary and secondary data can become somewhat blurred. A key reason for the growth in the number of studies taking such an approach is an interest in identifying whether local communities are perceiving environmental change, how they are responding, and how they might be helped (e.g. Sutcliffe et al., 2015; Thomas et al., 2007). Reliance on data acquired through this method presents under-explored reliability issues (Meze-Hausken, 2004). Specifically, because the researcher maintains control over their own data collection process, through their question design, but not that of the participant.

In the context of this thesis, in which one of the research questions being asked is a novel and relatively specific one (the socioeconomic role of sediment in agriculture) traditional secondary data sources meeting the requirements of the research (time-series data on provincial-scale sediment deposition depths) were not available. As such a social survey was performed. In addition to collection of primary data through more traditional questions, the approach described above of asking participants to report their perceptions of environmental data, was also utilised. Specifically, participant perceptions of the process of sediment deposition were included as a component of the farmer survey presented below. In the section that follows some motivations and considerations when using humans (and human perceptions of an environmental process) as a data source in such a manner are discussed.

5.2.2 Considerations when using humans as a data source

When a researcher chooses to use humans as a primary or secondary source they must do so accepting of the fact that the data they wish to obtain will be exposed to some noise before they receive it and, as with any data collection process, there is a risk that errors may occur. Even when collecting quantitative data, an awareness is needed of the rationale behind the interpretative stance on research commonly found in qualitative studies. The interpretative stance emphasises the importance of social constructs to the information which is produced by the participant as a data source and also how it is received and processed by the researcher (Walsham, 1993). Phenomena have been documented, such as the tendency for participants to overestimate losses, known as *gain/loss asymmetry* in economics (Tversky and Kahneman, 1991) and *negativity* *dominance* in psychology (Rozin and Royzman, 2001), which may alter the quantitative data produced by a social survey. The prevalence of such errors will depend on the extent, context, and design of the data collection from humans involved in the research.

When consulting a participant there are a number of factors which may affect the accuracy of any data obtained, particularly, sources of bias within the participant's reporting and limits to the accuracy of the participant's memory when reporting data. For example, while techniques such as interviews and focus groups can both operate on projects of similar scale, Kaplowitz and Hoehn (2001) suggest that they may still reveal different information. Kaplowitz and Hoehn's main conclusions were that focus groups encouraged a more speculative approach to information sharing, while in individual interviews participants were more likely to feel comfortable expressing controversial opinions which are perceived to go against more broadly held ideas (noting that opinions can be expressed in many forms, including through numbers). The authors' final recommendation, was that the two methods should be used complementarily. Cooke and Kothari (2001) go further into detail on three key problems faced in collecting data from humans either in group settings, or with individuals who are influenced by their status in a group. The first, *risky shift* involves the tendency of individuals in groups to finalise, as a collective, a more risky course of action than they would have in an individual setting. The second, *the Abilene paradox* involves the tendency of individuals to go along with group decisions on the assumption that their own view is in the minority and therefore not worth voicing when, in fact they may even be in the majority. The third, *groupthink*, phenomenon involves the tendency of a group towards an irrational decision due to the loss of independent critical thinking resulting from an overbearing sense of togetherness and common purpose (ibid; Esser, 1998).

Despite these challenges there are multiple benefits to using respondent reported data (all of which contributed to the approach being utilised herein). In physical geographical research utilising people's reported information can allow researchers to gain information on environmental processes covering very large spatial areas, and going back long periods of time; information which, if obtained via direct observation (usually with a non-human tool), might be extremely time-consuming, expensive, or indeed impossible to collect and contain different sources of error. In regions such as the VMD study participants may have been directly managing their environment (in this case for rice production) for decades, and possibly with familial ties going back centuries (Fox and Ledgerwood, 1999). Furthermore, for the majority of local people rice growing is a vocation, and their only (or main) source of income, upon which they are entirely dependent. As such, awareness of year to year shifts, trends, indicators, and environmental connections is not only present but essential for success. In similar situations information reliant on participant memory has proven to be highly accurate and detailed (Brondizio and Moran, 2008). For example, other studies within the Mekong region have successfully utilised household surveys to investigate shifts in farming systems over time (e.g. Bosma et al., 2006) and, in the region, studies have gone considerably further back into participant's pasts when asking respondents to report on medical issues they have experienced (e.g. Polimeni et al., 2014). The possible representation and legitimacy issues in collecting perceptions data, some of which were described above, can partially be addressed by effective survey design and enumerator training. The risk mitigation measures put in place for this study are described in **Section 5.3** and the implications of any unavoidable risks discussed in **Section 5.5**. These efforts can (and are) be integrated throughout the study design of a project. Study design in social science field research can vary in a number of ways; typically (as outlined in Angelsen et al., 2011), in the (i) level of participation from non-scientists (e.g. from citizen control to subject manipulation) (ii) scale (e.g. from one-to-one interviews to regional census collection) (iii) level of restriction they place on the data which can be obtained (e.g. from unstructured interviews to closed questionnaires) and the (iv) approach to obtaining data (e.g. direct or indirect). The design of the study conducted in this chapter is outlined extensively in **Section 5.3**.

5.3 Executing the survey

This survey aimed to capture data on the agricultural operations and role of sediment that was statistically robust for extrapolation to the provincial scale; and specifically to provide comparisons between socioeconomic and agricultural (including sediment) indicators in the areas behind adapted (high) and non-adapted (low) dykes. Given the common occurrence of the rice agroecological zone across the entirety of the delta, however, it was hoped that insights would be provided at the provincial level which are relevant to decisions on policy implementation across the VMD. Using translators from Can Tho University interviews with 434 heads of farming households and semi-structured interviews with the leaders of 18 commune authorities were carried out in An Giang and Soc Trang Provinces in April and May 2014 (**Figure 5.1**). The farmers were asked for basic farm characteristics, such as size and crop, and historical data (2008-2013) on: flood duration, perceived sediment deposition depth, fertiliser application, and yield achieved.

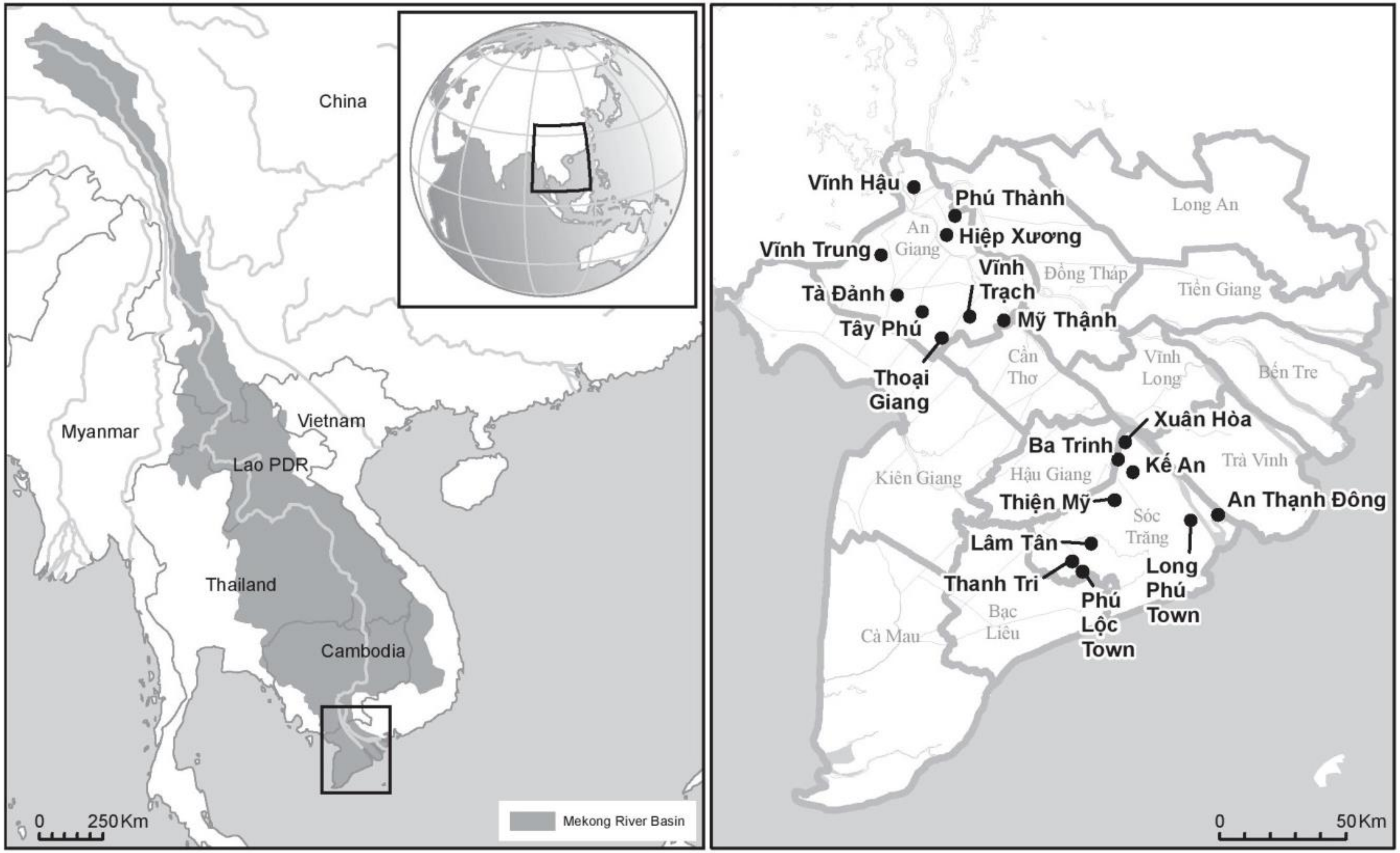


Figure 5.1 The study area (left) and the randomly selected communes visited in An Giang and Soc Trang provinces (right).

This data allows documentation of the impacts of the adaptation described in **Chapter 4**. The key data analysis is conducted utilising a regression model designed to capture rates of change and the impact of sediment exclusion on those changes. Additionally, commune leaders were asked for meta-data regarding the commune population, primary rice varieties in use, and recent issues with pests and disease. This additional data collected from knowledgable local stakeholders helped establish whether any factors linked to events or operations in each surveyed area might hinder comparisons between areas. English-language versions of the survey forms used are available in **Appendix 9.2** and **9.3** respectively. The information sheet provided to survey respondents and interviewees can be found in **Appendix 9.4**.

5.3.1 Survey preparation

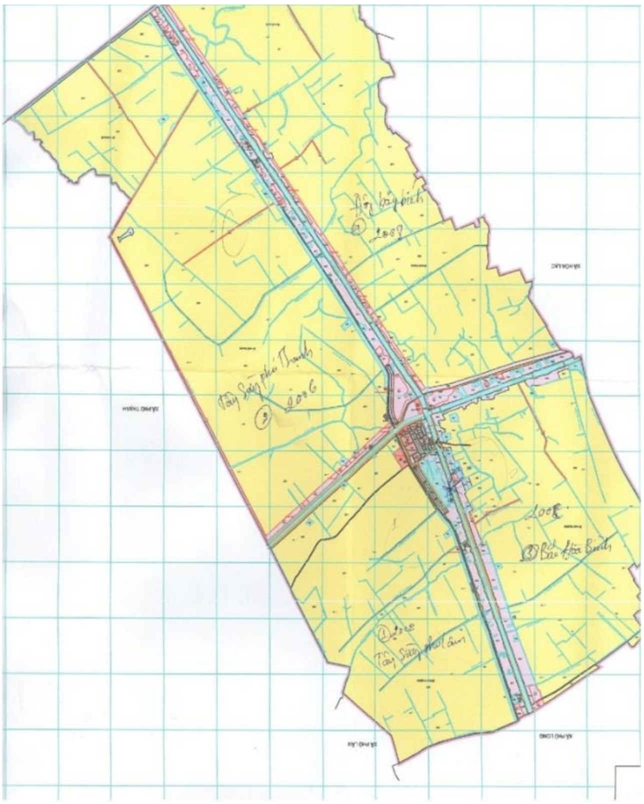


Figure 5.2 An example of a hard copy map of a commune authority which was used to perform the random-walk survey collection.

A stratified random sampling approach was performed with the Vietnamese commune level (**Table 4.2**) of administrative unit utilised as the primary sampling unit (PSU). The study area was stratified using pre-existing geographical information systems (GIS) data on the Vietnamese Government's administrative boundaries that is available in the public domain (DIVA-GIS, 2013). Within the PSU sampling was conducted via a simple random walk methodology adapted from the World Health Organization's *expanded programme on immunization* (EPI) cluster survey (Oliphant et al., 2006). The sampling method involved randomly selecting a starting location (by dropping a pin) on a hard-copy map of the commune (see **Figure 5.2**), and collecting surveys in a randomly assigned direction (by spinning a bottle) from that start point.

A requirement for participation in the survey was that respondents run a farming operation within the selected PSU. The intention was to conduct interviews in a private location in or near the selected farmer's homestead. While the selection process was adhered to, the local commune authorities had a preference for the interviews with the selected respondents to be conducted in a central location rather than at the farmers' homesteads which meant 60% of the interviews were conducted within earshot of other farmers. The implications of this issue are explored in **Section 5.5**. The objective of the random sampling approach taken both with the selection of PSUs and within the PSU was to obtain results which could be extrapolated to the provincial scale, and also to allow the valuation of sediment deposition at the provincial scale. By surveying in the provinces An Giang and Soc Trang this survey aimed to cover the two key agro-ecological zones of the VMD in which rice farming takes place: the fluvial-dominated inland area of the northern and central provinces (represented by the An Giang survey), and the coastal, tidal-dominated, region in the south and southwest (represented by the Soc Trang survey).

The survey was designed to contain the minimal amount of politically sensitive information possible, in order to reduce any potential noise entering the reported data. This meant, with the exception of one final question, it contained entirely quantitative questions on agricultural operations as these were seen as less likely to place the farmers in a politically sensitive situation. The enumerators of this survey were all native Vietnamese speakers, all had considerable experience in the execution of surveys in the rural parts of the Delta (a minimum of six previously completed), and were all postgraduate (or greater) students of agriculture and the environment at Can Tho University, located in the heart of the Delta. The interview itself was conducted in Vietnamese, and the questionnaire form completed by the enumerator was in Vietnamese. Translation of the questionnaire was performed by experts in the Natural Resources Department of Can Tho University and verified by a professional translator. Enumerator training was provided to reinforce the core principles of the survey utilising guidance from the enumerator training manual of the South African national statistics body (SSA, 2006). Important aspects included ensuring that: the farmers fully understood their right to refuse or withdraw from the survey, that their answers were uninfluenced, and that the sample selection remained random.

Information to guide the formulation of the survey design and its execution (such as on the approximate present extent of the dyke network) was obtained from sources which included: district and provincial statistical year books (AGSO, 2013), the Mekong River Commission's data portal (MRC, 2014), and data accessed through the WISDOM Project's information system (WISDOM, 2014).

5.3.2 Survey execution

A total of 195 farmer interviews were conducted in nine communes of An Giang Province, and 234 interviews were conducted in nine communes of Soc Trang Province in April and May 2014 (see

Figure 5.1 for locations). The target was to collect a minimum of 20 surveys in each commune, but the final number collected (**Table 5.1**) was determined by a number of practical aspects of data collection in the region including, the time spent with the local commune authorities, the time taken to access farmer households, and weather conditions. Assistance from members of the local commune committee, who would track down farmers in their fields and encourage them to participate, ensured around a 95% response rate. The only criterion for selection for interview was that the interviewee must hold management responsibilities over the day-to-day running of a farm within the selected commune. Further selection criteria were not utilised at this stage in order to gain as close a picture of the overall province as possible, and because high resolution descriptive statistics to more specifically target the survey were not available.

Table 5.1 A breakdown of the nesting categories used in the analysis and the corresponding number of rice farmers (fruit farmers excluded).

Status	Crop Category	Code used in figures	Province	Farmers interviewed
Low dykes (pre-adaptation)	Two crops per year	*Two*	An Giang	60
			Soc Trang	50 (excluded)
Under adaptation (recent dyke height change	Changed system during period	*Chng*	An Giang	21
			Soc Trang	21
High dykes (post-adaptation)	Three crops per year	*Three*	An Giang	74
			Soc Trang	118
	Adapted three year cycle “3-3-2”	*332*	An Giang	40
			Soc Trang	0
			Total:	384

Farmers reported data on the most recent cropping years at the time of survey, covering 2008 – 2013, in order to provide the most up-to-date picture of farming operations and trends in the study area. The choice to reach back to 2008 was made in order to collect sufficient data to reveal recent temporal trends without stretching farmers’ memories beyond what might reasonably be recollected (noting that a small number of farmers had written records). The aim was to garner one value for each year (e.g. 2012) in each of the categories: flood duration, perceived sediment deposition depth, fertiliser application, and yield achieved. In the cases of yield and fertiliser, many farmers preferred to provide two or three values per year (one for each growing season), in this case an average value was calculated for each year during post-survey processing in order to homogenise the data for analysis (the analysis methods of these data are reported in **Section 5.3.4** and the main results in **Section 5.4**). Hence, during data analysis a maximum of six values in each category were associated with each farmer. In some cases, farmers did not feel they could accurately remember (or did not have records of) figures for some years or, they had taken over the running of the farm since 2008. In these cases values were only taken for the years the farmer could confidently report and their unreported years were excluded from the analysis. Additionally, farmers reported general information on their farm (size, farm distance from canal, number of labourers, and the type of land ownership), these data are reported in the descriptive statistics **Section 5.3.3** below.

Two communes were found in Soc Trang province that operated double-cropping (a pre-adaptation system - **Table 5.1**), these communes had to be excluded from the main analysis reported below due to their use of a specialist rice variety commonly known as “Tai Nguyen” with different characteristics to the usual varieties grown in the delta. Tai Nguyen is a very slow growing variety which tends to produce lower yields but sells at a higher price as a luxury good. In this case the commune leader reported that it was selected by farmers primarily because of the higher elevation of the land and hence reduced access to water. This was the only issue prohibiting comparison between PSUs that was identified by the leaders interviewed in each commune (PSU). All of the remaining Soc Trang communes operated standard triple-cropping.

The most novel aspect of this survey was asking the farmers to estimate two physical processes: the length of the period of flood inundation their paddy experienced, and the depth of the sediment left behind on their paddy as flood water subsided. While answering the question on sediment farmers were provided with two aids. The first was a simple diagram showing different levels of sediment coverage, found in **Section 9.5** of the **Appendix**, which was designed to help farmers to estimate the percentage of their paddy which received sediment cover. This, in the end, proved to be redundant as 99% of the farmers reporting sediment deposition reported that their paddy received total coverage. The second aid, was a ruler which helped farmers to indicate the depth of the sediment which was deposited on their paddy. The limitations of this approach, and its implications for the reliability of the main results presented in **Section 5.4** are discussed in **Section 5.5**.

5.3.3 Survey descriptive statistics

The random selection process produced four primary farming systems: rice only (84%), rice and fruit (4%), fruit-only (4%), and sugarcane-only (8%). In the event that the farmer grew both fruit and rice the interview questions were only applied to the rice farming activities run on their farm, the categories of rice farmer surveyed are listed in **Table 5.1**. Given the low numbers of non-rice farmers produced by the random selection process they have been excluded from the analysis.

Rice is the dominant crop in the VMD, cultivated on around 60% of the region's surface area, and accounting for over 90% of the area in agricultural use (GSO, 2014). As such, rice drives the economy in the region and was the focus of this study. Additionally, 40 farmers in An Giang were found to be operating the 3-3-2 cropping rotation (introduced in **Section 3.3.4** of **Chapter 3**), a policy advocated but not enforced by the provincial governments in which farmers leave their paddy fallow and facilitate flooding once in every three monsoon seasons (once every nine cropping seasons).

Table 5.2 summarises some basic characteristics of the rice farmers interviewed, the full quantitative survey results can be found in graphical form in **Appendix 9.6**. Of the rice farmers interviewed for this study (n=384) 71% were growing three rice crops at the time of interview (inclusive of those on the 3-3-2 cycle - **Table 5.1**). This finding was in line with Kongtis et al. (2015) who estimated that two thirds of rice farmers in the VMD were triple-cropping. Also in line with expectations, the average period a three-crop rice farmer witnessed inundation of their field in An Giang as a result of sluice gate operation was 15 days, in contrast with the two-crop farmers who witnessed 102 days of inundation from dyke overflow and sluice gate operation. These reported inundation periods are at the lower end of the findings of Sakamoto et al. (2007) who estimated inundation periods of 10-50 days for triple-cropping areas and 90-180 days for double-cropping areas. One theory for these lower end estimates lies in Sakamoto et al.'s utilisation of satellite images, from which it may not have been possible to distinguish between a flooded paddy and a paddy with recently sown rice (which also involves large spatial extents of water coverage).

Table 5.2 A summary of the basic household characteristics which are not specific to the different cropping system categories.

Characteristic	Median	Mean	Standard Deviation	Lower Quartile	Upper Quartile
Farm Size (ha)	1.3	2.1	2.6	0.8	2.5
Number of full-time labourers per farming operation	1	1.6	0.9	1	2
	Rice	**Non-rice**	**Land owned**	**Land rented**	**Distance**
Crop (%)	89.5	10.5			
Ownership status (%)			98.6	1.4	
Average distance of paddy from nearest canal (m)					300

5.3.4 Survey results analysis

To facilitate comparative analysis between the different pre and post-adaptation categories (as shown in **Table 5.1**) the main data were divided into four categories of rice cropping system that were practiced in the region during the period reported by the interviewees (i) farmers operating three crops every year; (ii) farmers operating the 3-3-2 system; (iii) farmers who shifted from two crops to three crops during the study period; and (iv) farmers still operating two crops every year (**Table 5.1**). Where figures are presented these categories are referred to by their codes, as listed in **Table 5.1**. Categories (i), (ii), and (iii) are linked to the high dykes, and hence the adaptation action. The old two-crop system (iv) is grown in low dyke areas. Viable data on the two-crop (pre-adaptation) system was only obtainable in An Giang where it is still operated in some areas, mostly to the west of the province, and hence the majority of comparative analysis could only be performed on the An Giang data.

Statistical analysis was conducted in the R software package. Generalised Linear Models (GLMs) were utilised, as a widely accepted method of investigating the factors explaining the supply of an ecosystem service (Mouchet et al., 2014) and measuring agricultural trends over time (e.g. Dawe et al., 2000). Parametric GLMs were constructed for each of the dependent variables: sediment deposition, fertiliser application, and yield achieved (**Table 5.3**). **Figure 5.3** conceptualises the chain of influence of these variables. The general characteristics of these GLMs can be found in **Table 5.3**. Primarily, these GLMs highlighted temporal rates of change in each indicator and differences between the cropping categories listed above (targeting research question (i)). They also facilitated exploration of the influence of wealth strata on differences in agricultural indicator performance between adapted and non-adapted areas (research question (ii)). The influence of wealth on the trajectories of change in the various indicators was explored utilising farm size as a proxy for farmer wealth. Farm size was deemed appropriate for use as a proxy due both to the relative homogeneity of the rice growing compartments across both provinces and based on the advice of local experts consulted at Can Tho University (reported in **Chapter 4**), who reported that local customs directly link the size of an individual's land holdings to their status in society. In addition to the main GLM analysis some ANOVA models were built, the results of these models are presented where relevant in the results section.

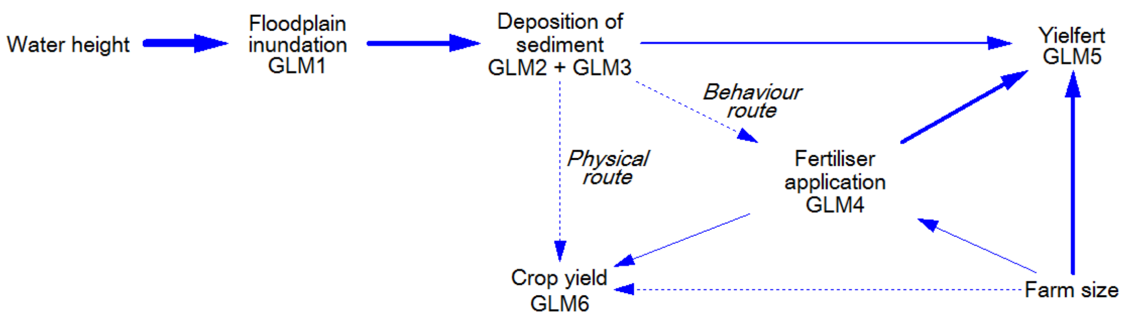


Figure 5.3 A conceptual model of the statistical models in **Table 5.3**. Each arrow represents a variable in the labelled general linear regression model (GLM). The arrow size represents the explanatory power of the model based on its adjusted R-squared value.

Table 5.3 A summary of the General Linear Models used to explain the relationships between the variables reported in the household survey.

ID	Dependent variable	Independent variables	Nesting variables	Adjusted R^2	Model P – value	Model F - statistic
GLM1	Inundation Duration An Giang	Water height - days above 1.5m and 2.5m (secondary data)	Crop Category	0.989	< 0.001	$F_{2,489}$ = 2289
GLM2	Sediment Deposition Depth	Inundation Duration	Crop Category, Province	0.487	< 0.001	$F_{15,2114}$ = 133.9
GLM3	Fertiliser	Farm Size, Sediment Deposition Depth	Crop Category, Province	0.273	< 0.001	$F_{15,1307}$ = 34.2
GLM4	Yield / Fertiliser (*Yielfert*)	Fertiliser Application, Farm Size, Sediment Deposition Depth	Crop Category, Province	0.633	< 0.001	$F_{20,1186}$ = 104.9
GLM5	Yield	Fertiliser Application, Farm Size, Sediment Deposition Depth	Crop Category, Province	0.285	< 0.001	$F_{20,1186}$ = 25

The majority of the comparative analysis was conducted on the yield/fertiliser ratio produced by the farmers' reported data, henceforth termed *Yielfert*. The *Yielfert* regression equation is shown in **Equation 1** (also see footnote[2]). *Yielfert* was seen as the indicator through which the influence of sediment would most likely be perceived as it represents the input efficiency at which the farmer operates and would hence detect any benefits brought by sediment-bound nutrients (targeting research questions (iii) and (iv)). Furthermore, the yield/fertiliser ratio was selected as its temporal trends succinctly summarise the status and sustainability of an agricultural system and it is commonly utilised to benchmark the performance of policies implemented in agricultural systems (see Khai and Yabe, 2011). As such, *Yielfert* offered the greatest insight into the differences between the pre and post-adaptation systems. The key independent variable in **Equation 1** which represented the efficiency gain farmers receive from the annual deposition of sediment on their floodplain was termed β_3. Also included was farm size (β_2), which, as described above, was utilised as an indicator of the wealth of the farmer; and finally, fertiliser application (β_1) was included which, as a key determinant of Yielfert, allowed a basic check of the model's

[2] *Note: "vu" is a Vietnamese term used hereafter to denote a rice growing season, of which there are three in a three-crop system, and two in a two-crop system*

behaviour against expectations (e.g. Witt et al., 1999). Specifically, the greater the fertiliser applied the higher the farmer operates on the production function and hence, the lower the Yielfert that would be expected. Additional independent variables were initially included which may have been pertinent to *Yielfert* (e.g. farm distance from river or canal, and the period of paddy inundation) but these (not statistically significant) variables were dropped during the model refinement process, thereby improving the fit of the model as measured by the Akaike information criterion (AIC) value (Bozdogan, 1987). The four categories of cropping system were incorporated into the GLM models as nested variables in order to allow comparison, and in all cases the process of nesting improved the explanatory efficiency,.

(1) $Yielfert = \beta_{1\,(kg/vu/ha)}\,(fertiliser\ applied\ to\ paddy) + \beta_{2\,(ha)}\,(farm\ size) + \beta_{3\,(cm/yr)}\,(sediment\ depth\ perceived\ on\ paddy) + \varepsilon_i\,(error)$

5.3.5 Economically valuing sediment

Once modelled, the influence of sediment (β_3) on *Yielfert* could be translated into economic terms by converting its relative influence on *Yielfert* into its relative influence on the yield to fertiliser income/cost ratio (which, as discussed above, provides a strong indicator of agricultural policy performance). In the field data were collected from farmers on the maximum and minimum price (VND/Kg) farmers sold rice at during the previous year, and the price of various fertiliser types (e.g. NPK, Kali, DAP). Additionally, information was collected from farmers on the combination, and relative weights, of fertiliser applied (e.g. 20kg NPK, 20kg Kali, 10kg DAP). These data were supplemented with secondary data and the utilised values are shown in **Table 5.4**. Secondary data sources were utilised where they were drawn from more robust samples than presented herein.

Table 5.4 Summary of the supplementary data used in the calculation of the economic value of sediment.

Variable	Survey estimate	Secondary data estimate (source)	Utilised
Fertiliser price	11,700 VND/Kg	8,200 VND/Kg (World Bank, 2014)	Survey
Rice price	4,650 VND/Kg	3,200 VND/Kg (FAO, 2014)	Survey
Area in 2 crop production	64,997 ha	84,259 ha (AGSO, 2013)	Secondary
Area in 3 crop production	135,755 ha	116,493 ha (AGSO, 2013)	Secondary

The *Yielfert* variable was then converted into the Dong (Vietnamese currency) received from sales of rice ($VND_{(r)}$) per Dong spent on fertiliser ($VND_{(f)}$). It is important to note a distinction in the data analysis approach between the economic calculations described here and the rest of the analysis. For the purposes of the economic calculation, the analysis was reduced to a simple double versus triple-cropping comparison. The *332* and *Chng* categories were separated out into double and triple-cropping years and compiled with the *three* and *two* categories as they were not necessary to the objective of putting an overall value on sediment. The $VND_{(r)}/VND_{(f)}$ value could then be extrapolated to the operations of all of the farmers within each cropping system across the province using Equation 2 and the additional secondary data in **Table 5.4**.

$$(2)\ Y_{(VND/yr)} = f_{(kg/ha/vu)} \cdot c_{(VND(f)/kg)} \cdot \beta_{3\ (VND(r)/VND(f)/cm)} \cdot s_{(cm/yr)} \cdot v_{(vu\text{-}1)} \cdot a_{(ha)}$$

Y = provincial value of sediment

f = fertiliser applied

c = average cost of fertiliser

β_3 = cost efficiency gain per centimetre of sediment

s = average depth of sediment

v = crops per year

a = area in production

5.4 Survey results

In this section the results of the survey are presented, accompanied by a narrative description. The structure is as follows: first the general trends associated with the adaptation are presented, second the role of sediment is investigated, third the interactions of the cropping pattern change (enforced by the adaptation) with different wealth classes are elicited and finally, the performance of the second-order action, the 3-3-2 cropping rotation, is discussed.

5.4.1 General trends in perceived sediment deposition

Across the whole dataset perceived sediment deposition depths had a significant declining trend over time (-0.07cm/yr ± 0.02, $p<0.001$). However, that trend can largely be accounted for by the subset of farmers who experienced the closing of high dykes during the period of study (cropping category “*chng*”). The mean reported decline in An Giang the year following dyke closure was 2.33cm and in Soc Trang, 1.15cm. Declines reported within the other cropping categories were not statistically significant.

5.4.1.1 Sediment in An Giang

On average two-crop paddies were receiving 2.51cm of reported sediment deposition (**Figure 5.4**), (the semi-natural regime), this value was significantly more than all other categories (ANOVA, $F=61.1$, $p<0.001$).

There were no significant differences between the other three categories. As a result of the sediment exclusion process three-crop paddies in An Giang received, on average, 1.98cm shallower deposition than two-crop paddies. The mean deposition reported in three-crop areas (high dyke rings) of 0.53cm is not dissimilar to Hung et al.'s (2014b) estimate in the neighbouring province of Dong Thap of ca. 0.6cm, but rather less than the ca. 1.2cm measured by Hoa et al. (2006) in Can Tho province in 2000-2001, both were measured using sediment traps within high dyke rings. As two thirds of rice farmers are growing three crops a year, and they account for 149,524 ha (43.5%) of the provincial land area (AGSO, 2013), this would suggest sediment and its delta building properties are being excluded from large areas of the provincial floodplain.

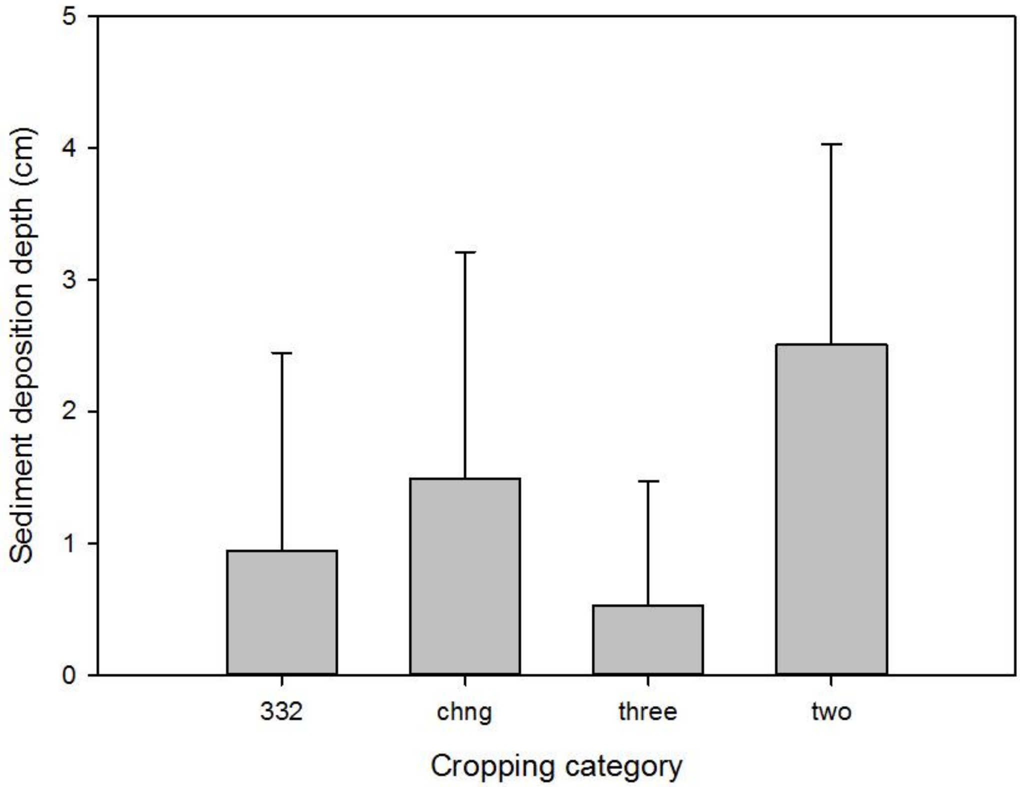


Figure 5.4 Mean annual sediment deposition depths (including standard error bars) perceived by farmers in the four categories of cropping system in An Giang. The category "two" is significantly different from "332", "chng", and "three" (ANOVA, F=61.1, p<0.001).

5.4.1.2 Sediment in Soc Trang

The sediment exclusion process was far less pronounced downstream in Soc Trang. On average, three-crop farmers reported considerably more deposition (+0.85cm, ANOVA, F=47.1, p<0.001) than their counterparts in An Giang. The reason for this difference is unknown and requires further study but, two arguments can be hypothesised: firstly, the average inundation period allowed by the three-crop farmers in Soc Trang was 7 days longer than that in An Giang and, as mentioned in **Section 5.3.5**, the inundation period was linked with sediment deposition depth across the dataset. Secondly, such a result might be attributed to the Soc Trang farmers' decision to allow flooding of their paddy during Aug-Sep after harvest of the Spring-Summer rice, as opposed to the An Giang farmers who were allowing a short flooding period in Nov-Dec after harvest of the Autumn-Winter rice (**Figure 5.5** highlights these two periods). Hung et al. (2014b) suggest the peak deposition period is in August while the peak erosion period is Oct-Nov. This, as well as the fact that the suspended sediment concentration (SSC) in the river tends to peak between Aug-Sep (**Figure 5.5**), may be factors contributing to higher deposition rates in Soc Trang.

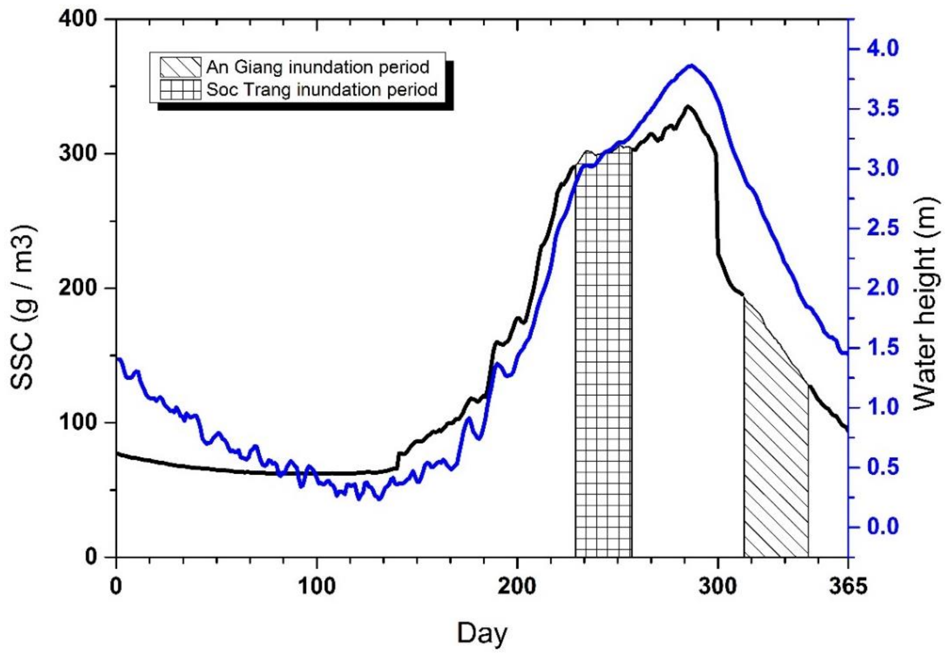


Figure 5.5 The water height and suspended sediment concentrations (SSC) entering the delta at Tan Chau with the respective inundation periods for An Giang and Soc Trang provinces highlighted.

Due to the greater intensity of flooding in An Giang some of the farmers interviewed there reported informally (outside the auspices of the survey) that facilitated flooding during the short Aug-Sep break utilised in Soc Trang would be difficult to control and hence dangerous. As such, a change to the timing of facilitated flooding in An Giang is not an option for increasing their deposition rates under the triple-cropping system.

5.4.2 General trends in fertiliser application and yield

Across the whole dataset reported seasonal fertiliser application varied little between cropping categories, with the exception of a slightly lower total in the triple-cropping areas (**Figure 5.6**). However, during the 2008-2013 study period fertiliser application increased significantly over time across both provinces ($p<0.001$) at around 13 (±2) kg/ha/vu. In An Giang, where comparisons can be made between the different systems, highly significant ($p<0.001$) increases (16 ±4 and 22

±6 kg/ha/vu/yr for the *three* and *chng* cropping categories, respectively[3]) were found within all cropping categories except the two-crop (*Two*), semi-natural, pre-adaptation system, in which there was no significant change (**Figure 5.7A**).

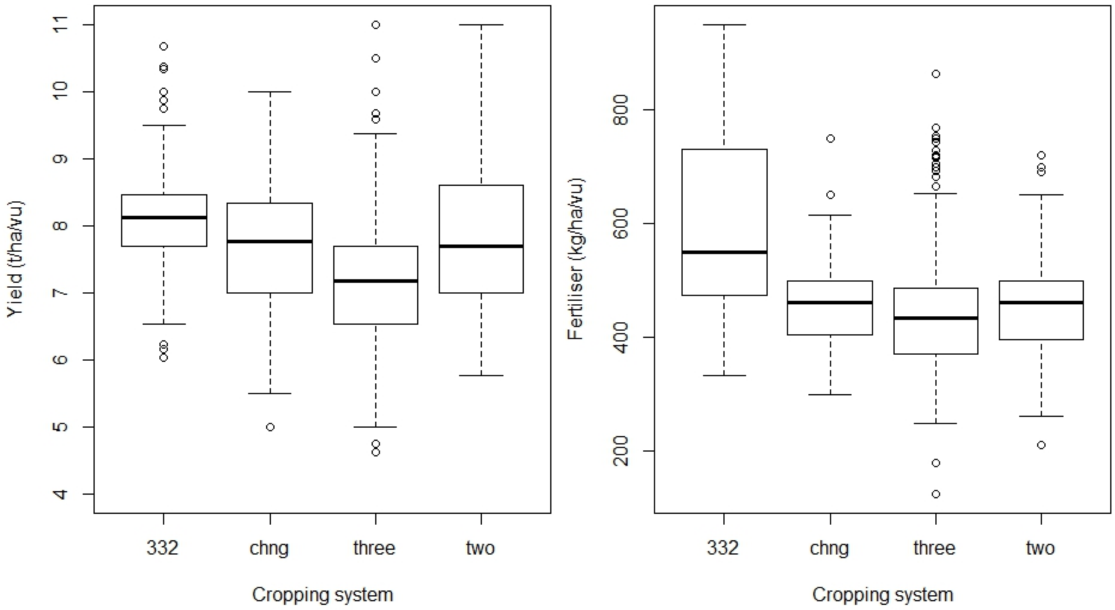


Figure 5.6 (Left) Boxplot showing the overall differences in yield achieved across all cropping categories and both provinces. The *three* category is significantly less than all others (ANOVA, F=71.5, p<0.001). (Right) Boxplot showing the quantity of fertiliser applied per season in all four cropping systems across both provinces. The only significant differences are between the "*332*" category and the other three (ANOVA, F=115.9, p<0.001).[4]

Despite applying a statistically similar (relative to other cropping categories and based on the ANOVA reported in **Figure 5.6**) amount of fertiliser per season on average, farmers in the three-crop areas were achieving significantly less yield (-0.8 t/ha/vu/yr ±0.18, ANOVA, F=71.5, p<0.001) than their counterparts in the two-crop area. This suggests that farmers were increasing fertiliser application to prevent yields from diminishing under the new system (as some farmers reported informally). Such a shift substantiates a hypothesis put forward by Berg (2002) of the development of an *open-throughout* agricultural system in the three-crop areas, a system in which agricultural productivity is almost entirely dependent on anthropogenic inputs.

[3] Note results from the 3-3-2 category are presented separately in **Section 5.4.6**
[4] All boxplots presented herein display the median, upper quartile, and lower quartile. Additionally each shows an upper and lower whisker according to a standard formula. The upper whisker represents whichever value is smallest between the maximum x-value and the sum of the upper quartile plus 1.5 times the interquartile range. The lower whisker represents whichever value is largest between the minimum x-value and the sum of the lower quartile minus 1.5 times the interquartile range.

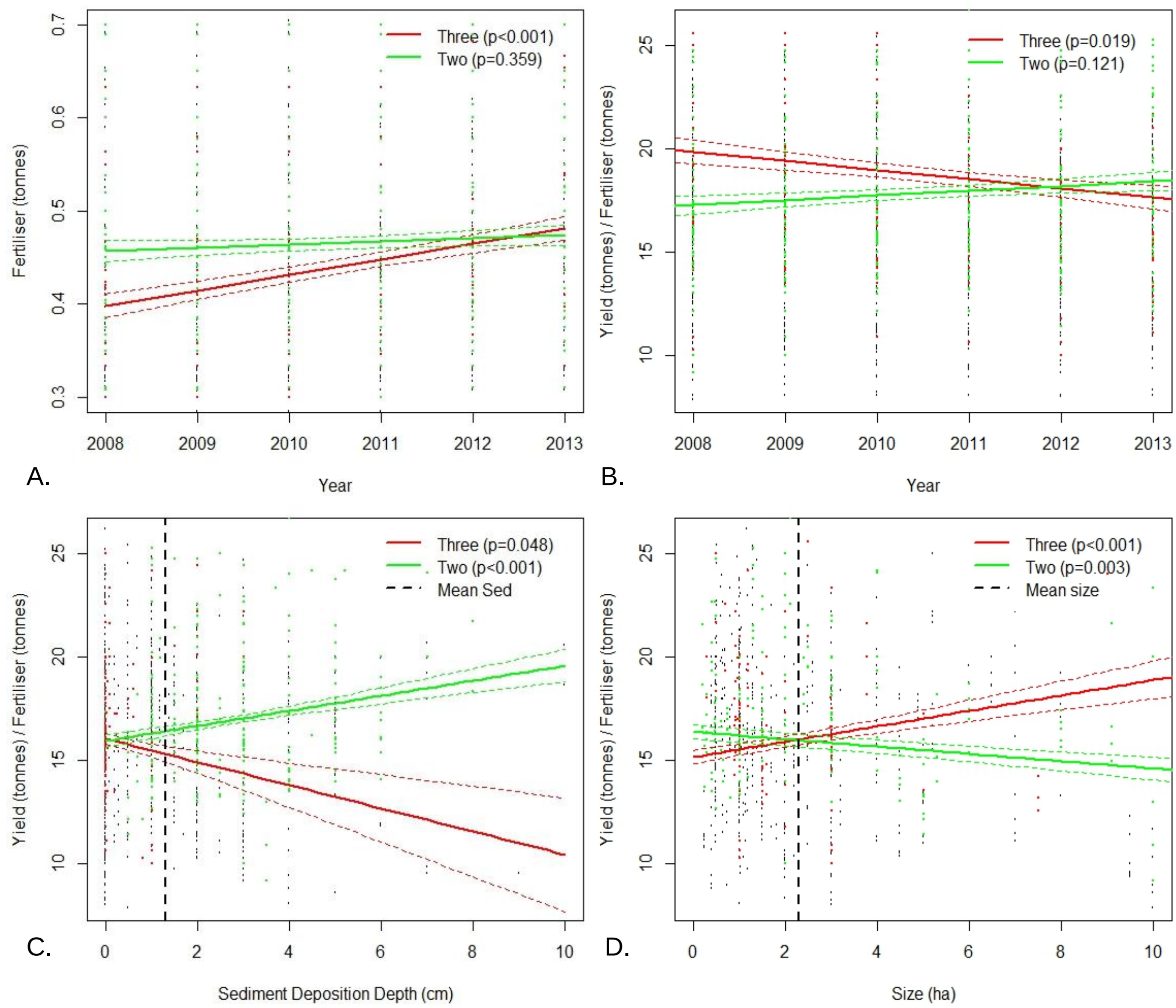


Figure 5.7 Regression lines (GLM) modelling the differences between the three and two-crop categories. P-values are labelled on each graph and standard error lines are presented. The data points corresponding to the modelled cropping category are highlighted in their corresponding colour. A. Models fertiliser over time (GLM3). B. Models the *Yielfert* ratio over time (GLM4). C. Models the *Yielfert* ratio against sediment deposition depth (GLM4). D. Models the *Yielfert* ratio against farm size (GLM4).

5.4.3 Detecting the impact of sediment

Having established that the adaptation action both excludes sediment, and appears correlated with increasing rates of fertiliser application, a substitutable relationship between the two factors was investigated. The survey data collected allowed for detection of a sediment/fertiliser-application relationship through two routes (conceptualised in **Figures 5.3** and **5.8**). First through farmer behaviour, i.e. farmers alter fertilisation levels when they perceive sediment. Second, through a biological relationship, i.e. sediment-bound nutrients improve plant health and increase yield. Evidence for each of these routes through which sediment might be detected is examined below.

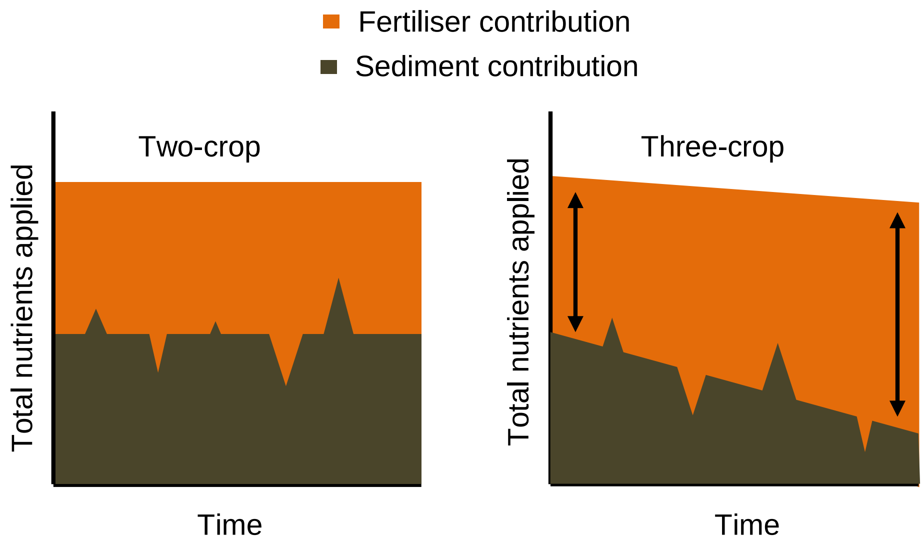


Figure 5.8 A conceptualisation of the nutrient contributions of fertiliser and sediment to the total nutrients applied to the floodplain. Highlighted, right, the increasing burden on fertiliser application during sediment loss.

5.4.3.1 Farmer behaviour

Using regression analysis (GLM3) it was possible to detect, statistically, the farmers' reported behaviour of reducing fertiliser application when perceiving sediment deposition. The regression analysis (GLM3) showed a significant negative correlation between fertiliser application and perceived sediment deposition depth reported by the farmers that changed (*chng*) system during the period (-18 ±6.2 kg/cm, $p<0.01$), and operated the three-crop (*three*) system (-20 ±9.7 kg/cm, $p=0.04$). Farmers, particularly those who changed system during the period, were able to see the difference between a year with high deposition and a year with no (or very low) sediment deposition clearly and, based on local knowledge, make an active decision to change their fertiliser application. In the two-crop system, where sediment is received every year, no relationship could be detected. The correlations reported above attest to a substitution relationship between sediment and fertiliser based in farmers' decision making. However, they do not detect a physical relationship between the nutrient contribution of sediment and the crop yield achieved.

5.4.3.2 A physical, substitutable, relationship

If sediment and fertiliser are in fact substitutable goods (i.e. they perform the same function in providing nutrients to crops), as implied by Manh et al. (2014), a decline in the sediment contribution to the overall soil fertility, and the increase in fertiliser application necessary to compensate, would manifest itself in an overall reduction in the yield to fertiliser ratio, *Yielfert*. *Yielfert* might also be regarded as the input efficiency of production, i.e. the outputs achieved from a fixed level of inputs (Khai and Yabe, 2011). Using regression model GLM4, with *Yielfert* as the dependent variable, this hypothesis was tested using the An Giang data.

There were noticeably different trends over time between the different cropping system categories (**Figure 5.7B**). Across all three categories involving the three-crop system the efficiency of agricultural inputs was declining. A portion of this trend was attributable to the law of diminishing returns which applies when increasing fertiliser to boost yield (e.g. Tilman et al., 2002) with a very strong correlation between increasing fertiliser application and decreasing *Yielfert* (-0.03 ±0.001 t/t, $p<0.001$, GLM4). However, another portion of the variance could be attributed to sediment.

The two-crop category (*two*) was the only category showing an improving *Yielfert* trend over time (0.23 ±0.15 t/t/yr, $p=0.12$). Increases might be expected as a result of advancements in components of input efficiency (i.e. *Yielfert*) not captured within this study, such as in: cultivation technology, seed varieties, climatic data availability, and education (Tran and Kajisa, 2006; Nguyen and Kawaguchi, 2002). Such advances have more than doubled yields since the late 1980's (Pingali and Xuan, 1992) and are currently contributing to an average annual increase of about 2% a year country-wide (GSO, 2014). However, GLM4 provides evidence that within two cropping categories the *Yielfert* ratio achieved benefits from sediment deposition. Within the two-crop system (*two*) each centimetre of deposition provided an additional 0.36 (±0.1) tonnes of yield per tonne of fertiliser ($p<0.001$) (**Figure 5.7C**). A similar relationship was detected in those farmers who changed cropping system (+0.41 ±0.19 t/t/cm, $p=0.03$).

For An Giang's three-crop farmers the reverse was found, a negative correlation between sediment and *Yielfert* was statistically significant (-0.283 (±0.13) Kg/Kg/cm $p=0.048$). In informal discussions An Giang's three-crop farmers linked the presence of sediment on their paddy to the phenomenon of dyke failure/breach which allowed unwanted flooding of their paddy, which provides an explanation as to why it would negatively influence their yield. The majority (51%) of An Giang sediment reports in the triple-cropping system were zero, a further 23% were negligible (≤0.5cm).

For Soc Trang's three-crop farmers, *Yielfert* was also decreasing over time (-0.3 ±0.12 t/t, $p=0.012$) and again, that decrease is primarily attributable to diminishing returns to fertiliser inputs. However, the decline in *Yielfert* is slower in Soc Trang than An Giang. As mentioned above, Soc Trang farmers, despite operating three-crops, are able to obtain higher sediment deposition due (it is assumed) to opening sluice gates during peak suspended sediment concentration periods. There is weak evidence that the influence of this additional sediment deposition on *Yielfert* was positive, as it was for An Giang's two-crop farmers. In Soc Trang's triple-cropping areas sediment was positively correlated, albeit with a high p-value, with *Yielfert* (0.12 ±0.07 t/t/cm, p=0.111).

5.4.4 Putting an economic value on sediment deposition

The survey conducted herein facilitates a calculation of the economic value of deposited sediment which is realised by VMD farmers after management practices are considered. **Figure 5.9** shows the two key *Yielfert* regression models utilised for the economic calculations detailed in **Section 5.3.5**. To facilitate the economic calculations the seasons of double and triple cropping inherent within the *Chng* and *332* categories have been merged with the *Two* and *Three* categories to leave two simple models: years in which a farmer grew two crops, versus years in which a farmer grew three crops. As such the regression coefficients reported vary slightly from those presented in **Section 5.4.3.2**.

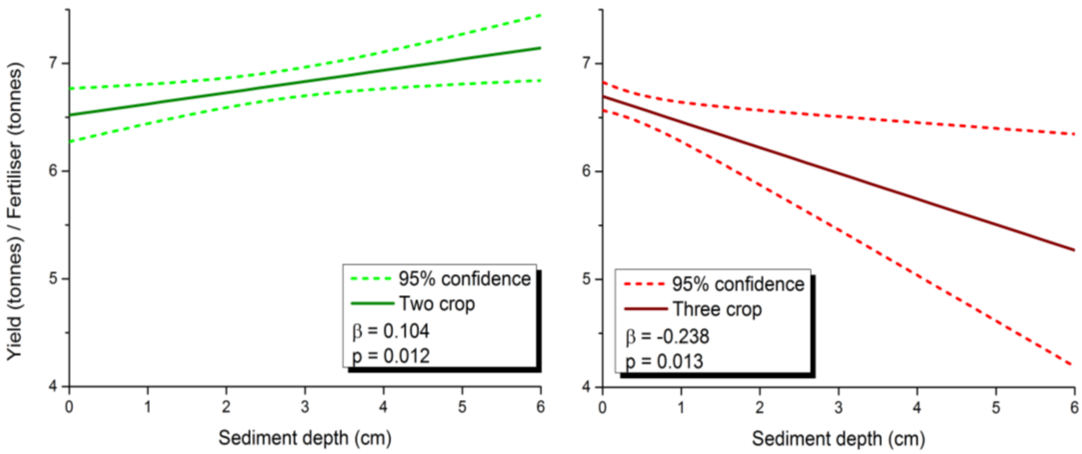


Figure 5.9 A different take on **Figure 5.7**. This time the data have not been separated by cropping pattern but into years in which two crops were grown and years in which three crops were grown regardless of cropping pattern (i.e. *332* and *Chng* have been separated). A GLM regression line has been plotted for *Yielfert* against sediment and 95% confidence intervals have been drawn instead of SE.

The regression coefficient which represents the influence of sediment, β_3, = 0.104 (± 0.036) indicates that, when allowed by double-cropping, average sediment deposition improved the average annual input efficiency by around 0.2 tonnes of rice-yield per tonne of fertiliser. This equates to an approximate 2% improvement in agricultural efficiency and applies across all crops grown in the year (intra-annual variation cannot be detected in this analysis). This gain appears minor when compared with Manh et al.'s (2014) estimate: that sufficient nutrients are contained within sediment deposits to meet half of a season's fertilisation needs. This estimate would translate into an approximate 17% gain in efficiency. But, VMD farmers operate very fine margins, and the 2% gain found herein, which would likely translate directly into profit, could be worth approximately USD $170 annually to the average farmer. At 2014 prices this represents approximately 8% of GDP per capita (World Bank, 2014).

The coefficient estimating the improvement in input efficiency attributable to sediment was then extrapolated to the provincial scale to provide an estimate of the total value of the deposited sediment's fertilisation affect. **Table 5.5** outlines the numbers used and calculated for the value (VND and USD) of sediment fertilisation. The calculation performed indicates that, if encouraged across the province, sediment deposition (of 2.53cm/yr) would have value of approximately USD $26 (±9) million per annum to An Giang farmers, thanks to the yield improvements brought by cost-free nutrients. This number represents the economic value of sediment presently reported as being realised by VMD farmers, and not the total value of the nutrients present within VMD sediment. Of this potential value, only USD $11 (±4) million is currently being realised due to sediment exclusion in the triple-cropping areas. Importantly it should be noted that this value does not include sediment's other benefits and costs to society, particularly it does not value its contribution towards countering subsidence and sea-level rise. These estimates are in the same order of magnitude as those made in the International Centre for Environmental Management's (ICEM) report in 2011, but somewhat higher when considering that ICEM's USD $24 million estimate was for the whole VMD.

Table 5.5 Calculating the economic value of sediment: s = average depth of sediment, β_3 = cost efficiency gain per centimetre of sediment, f = fertiliser applied, c = average cost of fertiliser, a = area in production. Highlighted in italics are the negative values which farmers associated with damaging dyke breach events. Also shown (highlighted in grey), the change in the economic value of sediment between double and triple cropping in An Giang (assuming a sediment depth of 2.53 cm could be achieved if all paddy compartments practised double cropping).

Province	Crops	s	β_3	SE	$f.c$ ('000 VND)	a	Seasonal value ('000 VND)	Annual value (USD[1])	SE (±USD)
AG	3	0.43	*-0.283*	0.087	5,148	116,493	*-72,978,219*	*-10,045,178*	3,088,094
	2	2.53	0.104	0.036	5,452	84,259	120,872,083	11,091,726	3,839,444
Value lost between cropping patterns		2.53	0.104	0.036	5,452	116,493	167,112,731	15,334,960	5,308,256
					Total:	200,752	**Total potential value:**	**26,426,686**	**9,147,699**
ST	3	1.27	0.052	0.032	4,996	138,842	45,808,952	6,544,136	4,027,161

[1]exchange rate correct as of 27/05/2015 at 1 (USD) : 21,795 (VND)

5.4.5 Assessing the distributional impacts of high dykes

Evidence of the impacts of the conversion to high dykes and triple-cropping (the adaptation) has been presented, and also evidence of potential negative economic impacts on society. However, another key factor in evaluating the action as an adaptation lies in how the impacts are distributed across the different strata of society.

5.4.5.1 Compensating for lost natural nutrients

Using farm-size as a proxy for wealth, a relationship between wealth and fertiliser application could be detected. Across the whole dataset, there was a significant ($p<0.001$, GLM3) correlation between larger farms and higher application of fertiliser, each additional hectare accounted for a fertiliser application increase of 5.3 (±1.2) kg/ha/vu (**Figure 5.10**). As previously discussed, such a phenomenon is commonly due to a desire among farmers to increase their yield. Given the evidence above that excluding natural sediment places more demand on fertiliser application, the capacity to apply additional fertiliser when desired would be advantageous to wealthier farmers under the input-intensive three-crop system.

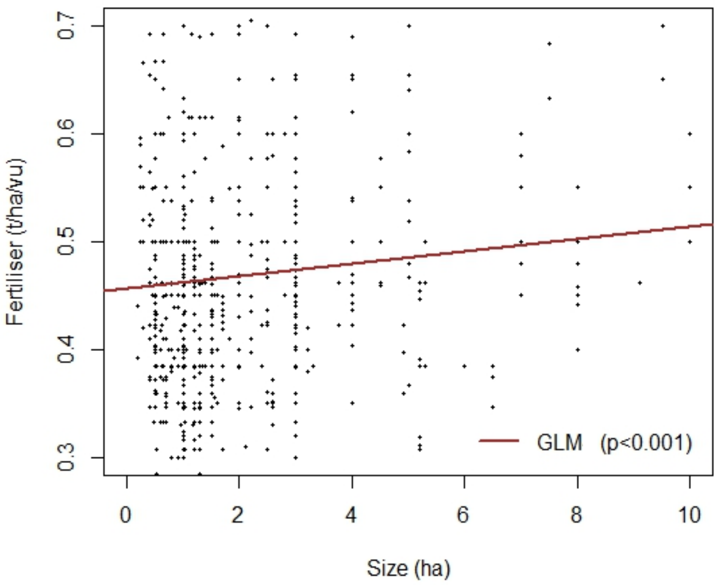


Figure 5.10 The significant relationship between fertiliser application and farm size across the whole dataset.

5.4.5.2 Input efficiency

Past research conducted on the national scale in Vietnam has shown a highly significant correlation between greater land wealth (i.e. the total value of an individual's land holdings) and higher input efficiency (Khai and Yabe, 2011; Akram-Lodhi, 2005). However, **Figure 5.7D** (modelled from GLM4) highlights that such a relationship was not present under the old two-crop farming system. Indeed, farm size (i.e. land-wealth) was negatively correlated with *Yielfert* efficiency (-0.18 ±0.06 t/t/ha, $p<0.01$). The shift to the three-crop, open-throughput system, sees a reversal of that trend (+0.37 ±0.1 t/t/ha, $p<0.001$) to fit with the evidence from Khai and Yabe (2011). Further research is required into this shift, but, the switch from natural sediment-bound inputs to anthropogenic nutrient application through fertilisation, and the concurrent workload increase, appears to be favouring those farmers with the land wealth to drive other components of input efficiency. Important factors include access to advanced technology for applying fertiliser, and education in farming practices. This apparent inequality in the shift from the two to three-crop system may also link to small scale farmers' inability to respond to increased incidence of pest and disease in their paddy, which have also been associated with the high dykes (Cong, 2011) and were reported by the commune leaders interviewed during this survey.

5.4.6 The performance of the 3-3-2 cropping rotation

The 3-3-2 cropping rotation was found to be practised in two of the nine communes visited in An Giang and none in Soc Trang. Adopting this practice might be regarded as a second-order action on behalf of the farmers, who have the freedom to adopt it if they wish to increase sediment deposition. But, as multiple farmers operate within one dyke ring, and all paddies within one dyke ring will be inundated, the decision must be made collectively among farmers. Here, the comparative performance of this system is investigated. As shown in **Figure 5.11A** the 3-3-2 farmers were, on average, applying considerably more fertiliser per season. What causes this phenomenon is unclear but it may link to the geographic location of the two communes in which the system was found (the communes Hiệp Xương and Phú Thành are both in the east of An Giang province, and are the closest of the nine An Giang communes to the main branch of the Mekong river). The 3-3-2 system farmers, in line with most others (see **Section 5.4.4.1**), reported making a visual judgment on the level of sediment deposition and adjust their fertiliser application accordingly, and this was statistically evident (-11.2 ±4.6 kg/cm, $p<0.01$). They were also progressively increasing their fertiliser application (14 ±4 kg/ha/vu/yr, $p<0.001$). However, as can be seen in **Figure 5.11C**, there was no evidence of farmers receiving a physical (yield) benefit from the presence of sediment. Furthermore, as with standard triple-cropping, within the 3-3-2 areas there was a significant benefit to input efficiency for farmers with larger farms when compared with farmers under the old two-crop system (**Figure 5.11D**).

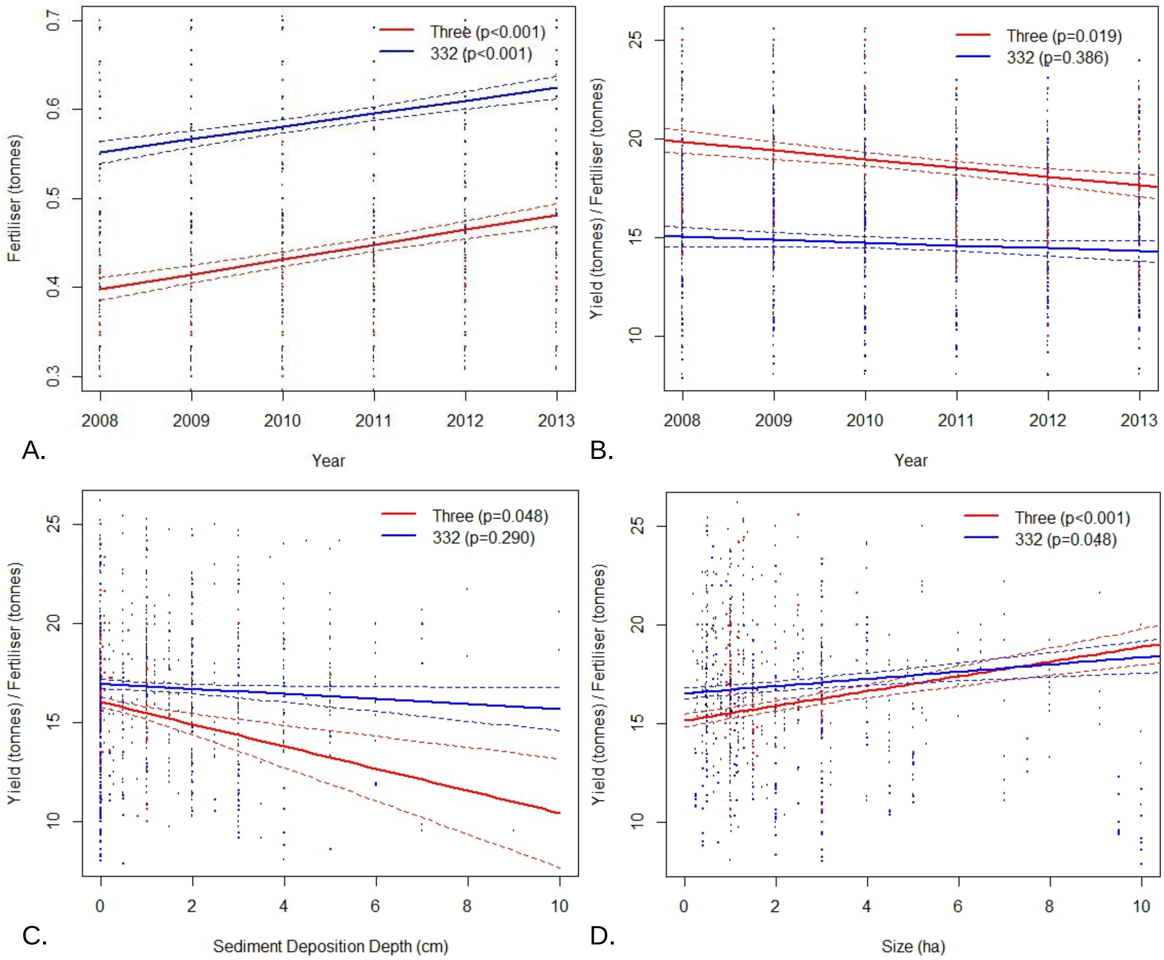


Figure 5.11 Regression lines modelling the differences between the three and 332 cropping categories. P-values are labelled on each graph and standard error lines are presented. The data points corresponding to the modelled cropping category are highlighted in their corresponding colour. A. Models fertiliser over time (GLM3). B. Models the *Yielfert* ratio over time (GLM4). C. Models the *Yielfert* ratio against sediment deposition depth (GLM4). D. Models the *Yielfert* ratio against farm size (GLM4).

5.5 Limitations of the survey data and analysis

In this section the limitations of the survey and analysis conducted are briefly discussed. Three areas are focused on, issues around the approach taken to collecting data on sediment, the potential for negativity bias in the farmers' reported data, and issues potentially presented by the Groupthink phenomenon.

5.5.1 Validating farmer sediment observations

In this section some simple validation tests are performed against the farmer reported sediment data. The results of these tests increase confidence that the farmers were, as hypothesised, capable of reporting environmental processes with sufficient accuracy as to answer the research questions posed. In the majority of cases farmers provided six responses when asked to report sediment coverage and depth, one for each year 2008-2013, the most common responses were 0 cm, 1 cm, and 2 cm, the maximum reported was 10 cm and the minimum 0 cm, hence, all of the responses might be regarded as within the realms of possibility when compared with Hung et al. (2014b) and Manh et al. (2014). Two basic logical tests and one validation test against secondary data were performed against the farmer's reported inundation periods (days) and sediment depths (centimetres) in order to validate the farmer's observations. It was only possible to perform the validation against secondary data on the subset of farmers still influenced by the natural regime (i.e. the double-cropping farmers, n=60) and operating in An Giang Province, where the double cropping system was found:

Logical tests:

- Can variance in the perceived sediment deposition depth be explained by a positive relationship with the perceived period of inundation? (expected answer: yes): yes, 0.015 (±0.001) cm (sediment)/day (inundation) (GLM2, p <0.001).
- Hence, can variance in the perceived sediment deposition depth be explained by a negative relationship with the height of the dykes? (expected answer: yes): yes, the presence of high dykes reduced deposition by 1.35 (±0.07) cm (GLM2, p <0.001).

Secondary data validation

- Can variance in the perceived period of inundation be explained by a positive relationship with the MRC's historical data on the number of days during which the water level breached 2.5m at Tan Chau? (expected answer: yes) : yes, 0.002 (±0.001) days (inundation)/day (inundation) (GLM1, p =0.066) - although the effect size is low.

Particularly, the presence here of a statistically significant (albeit weak) correlation between the farmers' reported inundation periods and the data recorded by the MRC instills confidence in the farmers' reporting. Additionally, from a statistical perspective, confidence is provided by the generally low p-values produced by the regression model outputs reported above (**Section 5.4.3**) which were associated with the trends that are key to the conclusions drawn in the discussion below. Sediment's important relationship with *Yielfert* in the double-cropping paddies was associated with a p-value of <0.001.

5.5.2 Negativity bias

A defining feature of the results reported by the farmers participating in this survey is the rapid rates of change in agricultural indicators (**Figure 5.7**), in directions which would result in economic losses for the farmers (i.e. increases in the application of fertiliser that were not matched by yield increases). In situations where participants are reporting historical losses some caution must be applied when interpreting the results. The reporting bias discussed earlier in the chapter, *negativity bias* (Rozin and Royzman, 2001) or *gain/loss asymmetry* (Tversky and Kahneman, 1991) frequently results in survey participants overstating their losses (e.g. Herley and Florêncio, 2008). This is particularly a limitation when asking participants to report on human environment interactions, and the utilisation of environmental services (e.g. Karanth et al., 2013). Commonly researchers will simply attempt to compensate for the bias this creates in the data by increasing the number of respondents (e.g. Karanth et al., 2012) however, if a bias is widespread, taking such a step may only reinforce the error's influence on the research outputs. Here, the number of surveys collected in the field was maximised only in order to achieve a number sufficient to satisfy most statistical reliability tests. Another way of dealing with negativity bias is to statistically validate participants' reports against secondary data from another source. Unfortunately, as very little data exists on fertiliser application in the delta and accessing fertiliser sellers was beyond the scope of this project, this could not be performed in this project. Rather, the particularly steep declines reported, which are seen especially during the period of cropping system change, should be approached with some caution.

5.5.3 Groupthink

Of the interviews conducted in An Giang and explored in the results section 60% were conducted within earshot of other farmers. A large body of past research provides evidence that such conditions, in which separate actors can pass judgement over interviewee responses, can induce noise in the data reported by interviewees (Esser, 1998). In order to account for this, each individual interview conducted in what was defined as a group setting was recorded and the impact of this condition on the statistical analysis of the other variables was tested. All five regression models were initially constructed including the interview setting as an independent binary variable (group/individual). The fit of none of the five models was improved by the inclusion of the group variable and hence it was dropped from the main analysis. However, it should be noted that, separately, there was a statistically significant increase in farm size when farmers were interviewed individually against interviews that were conducted in the group setting of 0.7 ±0.4 ha (ANOVA, $F=16.92$, $p<0.001$). No explanation can be offered for this difference. As this had no apparent impact on any of the regression models constructed, and particularly the key

Yielfert model which was utilised to detect the role of sediment, it is not considered a significant threat to the validity of the conclusions drawn from the data and discussed below.

5.6 Implications of the survey

The latest development of the VMD dyke network (primarily towards high dykes) began in the early 2000's as part of an effort to drive agricultural production in the region (Sakamoto et al., 2009). The policy was later assimilated into a climate change adaptation strategy in around 2008 and left to the poorly-equipped provincial governments to implement (as recognised by the MDP, 2013 and discussed in **Chapter 4**). It might be argued that, through mixed motives of agricultural intensification and adaptation, this start has resulted in an adaptation which has significant negative impacts. Above, notable differences between key agricultural trends in the pre and post-adaptation areas of the delta have been revealed (note particularly **Figure 5.7**). To take those differences and distill from them a conclusion on the relative success of the action as an adaptation is a challenging task (Bours et al., 2014). In **Chapter 2** a variety of existing approaches to this problem were critiqued and none stood out as suitably systemic in outlook. However, with a number of issues identified in the process by which the adaptation became policy (outlined in **Chapter 4**), there may be a benefit to drawing a conclusion on the action's success, i.e. to highlight the consequences of the inadequacies in the adaptation's development on it's latter performance. As such, in the following section the maladaptation framework is applied to the findings documented above and used to draw out some key implications of those findings (meeting research question (v)). The maladaptation framework, presented in **Chapter 2**, is perhaps the most commonly applied framework in adaptation evaluation. The framework was chosen because it is the most operable, specifically it provides a selection of indicators against which the action taken in the VMD can be evaluated. Commonly, maladaptation is attributed in the presence of one or more of the five characteristics presented by Barnett and O'Neil (2010), as presented in **Chapter 2**. Each of those characteristics is discussed below. The weaknesses in the maladaptation framework lie particularly in its inability to allow for trade-offs between indicators and its reliance on non-stakeholder selected success criteria for systemic adaptation evaluation, their implications are discussed below and then addressed with further work in **Chapters 6** and **7**.

5.6.1 Evidence of disproportionate burdening of the vulnerable

There is evidence above to suggest that switching from the double-cropping system to the triple disadvantages land-poor farmers. A trend which previously meant farm size had a marginally negative impact on the efficiency of agricultural inputs has been reversed, and the three-crop system appears to favour land-wealthy farmers. Correlational evidence suggests this shift is part-linked to the move away from the use of the environment's naturally available agricultural inputs (nutrient bound sediment) and towards human inputs, penalising the poor with less capacity to purchase those inputs and who also have reduced access to the technology required to apply those inputs efficiently. These findings, which suggest current practices are increasing inequality, are directly relevant because of the known link between inequality and vulnerability to climate change (Adger, 1999). Recent research has found this source of vulnerability to be particularly important in deltaic regions (Szabo et al., 2015).

5.6.2 Evidence of reduced incentives to adapt

The move from two crops per year to three adds considerably to a farmer's workload (even when considering the additional workload of the farmers' off-season activities). With the burden of declining input efficiency the effort required to apply fertiliser increases, and is continuing to increase, by a factor greater than the 1.5 which would be expected across the year if farmers shifted to triple-cropping under perfect conditions (based on the fertilisation levels reached by 2013 in **Figure 5.7**). Nevertheless 9% of the rice farmers interviewed for this study converted to the system during the study period 2008-2013. A key impact is the loss of diversified income streams. In the past farmers would mix their rice-growing activities with other wet-season ventures, such as fishing or livestock cultivation (Cong, 2011). The 274 three-crop farmers that were visited for this project spoke frequently of the strain of growing more and more rice to keep up with falling rice prices and the increasing agricultural input demands. The result is a positive feedback loop, which discourages diversification, a key element of adaptation in the region (Renaud et al., 2014). Such feedback loops were previously linked to maladaptive practice by Fazey et al. (2011). Importantly, on this maladaptive trait, it should be noted that in Vietnam some farmers do not have the freedom of crop choice (Markussen et al., 2011).

5.6.3 Evidence of path dependency

Building on the qualitative summary in **Chapter 4** this chapter presents further evidence that the VMD's social-ecological system, particularly in the northern province of An Giang, is becoming increasingly rice-specialised. The loss of the intrinsic increasing trend in the yield/fertiliser ratio in the high dyke areas highlighted by this research points to issues with the fertility and condition of the soil. It is possible that, as Hoa et al. (2006) predicted, the long term nutrient buffer within the soil which was provided by the deposited fluvial sediment is diminishing or lost. This hypothesis requires further research however, if proved correct it would come at a high price. Removing the natural fertility of the soil would make diversification of crops/land uses more difficult, particularly in the early years of establishing a new crop. In addition, farmers have lost the time they had under the old double-cropping system (reported at 102 days by the surveyed farmers) to develop and diversify their skill-sets. Indeed Garschagen et al. (2012) estimate the triple-cropping system requires ca. 269 days of labour per year, a level equivalent to greater than a full-time workload (ca. 250 days per year). The Farmers in the VMD are becoming dependent on a path determined in the 1990's but reinforced by action explicitly defined in policy documents as climate change adaptation.

5.6.4 Evidence of a high opportunity cost

There is now strong evidence to suggest that exclusion of deposited fluvial sediment from large reaches of the delta is taking place as a result of the heightening of the dykes. Deposition of fluvial sediment is important for countering the natural subsidence of the delta body (Syvitski et al., 2009). Therefore, when put in the context of the 0.6cm/yr of relative sea-level rise calculated by Syvitski et al. (2009), the 1.6cm/yr of subsidence calculated by Erban et al.(2014) for the region, and the potential loss of up to 96% of the suspended sediment in the river due to dam trapping (Kondolf et al., 2014), there is a clear stimulus for further in-depth research into the relevance of high dyke closure to relative sea-level rise. The likelihood is that the construction of the high dykes across the delta will be a contributor to major future land preservation challenges similar to those currently being experienced in the Mississippi Delta (Blum and Roberts, 2009) and hence the adaptation action may come at a very high, but unknown, opportunity cost. Recently, alternative strategies (potentially with lower opportunity cost) to dyke-based approaches to large scale delta sediment management have been proposed, such as the "rising grounds" (p. 8) strategy put forward by Ibáñez et al. (2013), which involve strategic facilitation of sediment deposition. The high dykes and triple-cropping system in place in the VMD, and the continuing trend towards it, are directly at odds with this strategy.

5.6.5 Evidence of increased emissions of greenhouse gas

The production, transport and application of fertiliser are notoriously Green-House Gas (GHG) intensive processes that are contributing considerably to global emissions (Snyder et al., 2009). Indeed, reducing fertiliser use in agriculture is a key component of the Vietnamese Government's (2012) "Sustainable Development Strategy for 2011-2020":

"…apply cultivation techniques in order to mitigate the use of fertilizer and chemical substances in agricultural production." (Vietnamese Government, 2012, online)

This chapter highlights both a disproportionate (>1.5×) increase in fertiliser application when moving from two to three-crop systems and evidence to suggest the efficiency of fertiliser use is also declining over time in the three-crop areas. As such, it could be assumed that the shift to a triple-cropping system which is directly facilitated by the government's policy of adapting the VMD's dyke network is both producing rice less GHG efficiently and emitting a higher total amount of GHGs. At very least this higlights a contradiction in government policy, but subject to a propor lifecycle assessment it is also potentially an indicator of maladaptation.

5.6.6 Second-order adaptation

There is evidence that all five of Barnett and O'Neil's (2010) maladaptive traits may be associated with the action undertaken in the VMD but, whether (and the ease with which) those traits can be alleviated through second-order action is important to the evaluation process (as discussed by Birkmann, 2011). Presented in the results section was evidence that the 3-3-2 rotation successfully increases average sediment deposition over the three-crop system (**Figure 5.11**). But, some of the negative trends present under triple-cropping are retained, there is weak evidence that the 3-3-2 cycle, like triple-cropping, has a negative impact on the yield/fertiliser ratio over time, and also that it favours land-wealthy farmers more than the traditional two-crop system (**Figure 5.11**). Further work is required to evaluate this strategy more comprehensively, and also to seek and evaluate alternative options. Such an evaluation needs to focus on the system dynamics which are determining the patterns and trends seen in these survey results as well examining the system more broadly than is possible with the indicators discussed here. Such an investigation is conducted in **Chapters 6** and **7**.

5.6.7 Emergent risk

The latest iteration of the IPCC's report introduced emergent risks: those arising from the unforeseen negative interactions of adaptation and mitigation actions with development (Oppenheimer et al., 2014). A key descriptor is that such risks are new and result from systemic links that were not foreseen. While only offering correlational insights, this study is the first to assess the role of sediment in underpinning deltaic agriculture from the farmers' socioeconomic perspective. As such, newly identified risks have been associated with the exclusion of sediment through the use of high dykes. Issues such as the exacerbation of the land-rich vs land-poor divide, sediment-exclusion's contribution to the declining fertility and sustainability of rice agriculture, and implicit second-order impacts such as the increased level of specialisation and workload necessitated by the shift might be regarded as maladaptive charcteristics. Such maladaptive characteristics seem to have occurred due to conflicting objectives of climate change adaptation and agricultural development in land-management plans. Those traits may represent an emergent risk to communities in the VMD at least, until responses (second-order adaptations) such as the 3-3-2 cropping system and others (e.g. a return to double-cropping or diversification) have been explored in more detail.

5.7 Conclusions from the survey

A framework for evaluating an adaptation has been applied to data collected in a novel survey investigating the socioeconomic implications of an adaptation and the role of sediment in the VMD socioeconomic system. There is clear evidence of maladaptive characteristics associated with the switch to high-dykes in the Vietnamese Mekong Delta. Furthermore, the use of the maladaptation framework has helped identify an emergent risk in this context. There are new short-term threats to human security identified in this chapter in the diminishing efficiency of agriculture, economic losses due to sediment exclusion, and the disproportionate burdening of the vulnerable. Additionally there is an evolving long-term threat in the potential acceleration of RSLR through the exclusion of sediment. As is required by the IPCC's definition of emergent risk (Oppenheimer et al., 2014), these threats result from a complex interaction between climate change adaptation and local development pathways (particularly agricultural intensification).

To fairly evaluate the action implemented greater understanding of the operational mechanisms producing the correlations documented herein is required. First and foremost without such knowledge it is unclear whether the trends identified are avoidable under present and future system conditions. Once such knowledge has been developed an evaluation of second-order courses of action might be conducted. With the 3-3-2 cropping-rotation the An Giang provincial government have already succeeded in both doubling the average annual sediment deposition and improving the trend in yield/fertiliser efficiency against the three-crop system. But, the maladaptive trends described above appear to still be present under this system. At present the 3-3-2 rotation is only running in 22% of the communes in the province. Further study is now required in order to evaluate whether or not it should be expanded to the rest of the province/delta. With operational knowledge developed, efforts can also be made to investigate alternative second-order adaptation strategies capable of alleviating undesirable dynamics, and particularly those dynamics which appear to be differentiating the impacts between the poorer and richer portions of society. But, to do so the preferences of the relevant stakeholders will need to be utilised in order to classify what constitutes a desirable future for the system.

This challenge is taken up in **Chapter 6** through the development of a System Dynamics model, and in **Chapter 7** second-order policies and corresponding trajectories of change are evaluated and prioritised. If it is possible to alleviate the maladaptive traits of the first-order adaptation with systemic second-order adaptation which targets the sources of the undesirable dynamics, the likelihood of this emergent risk progressing into a serious threat to VMD livelihoods may reduce. However, it is worth noting that all of the above factors need to be considered in the light of other exogenous climate change drivers, such as sea-level rise, which may ultimately limit the life and potential of the VMD as a social-ecological system, as well as exogenous development initiatives such as dam construction with potentially similar implications.

Chapter 6: Trajectories of Change and System Dynamics under the Influence of the Adaptation Part I: Model Development and Validation

6.1 Chapter introduction

6.1.1 Chapter aim

This chapter reports on the development of a system dynamics model built, in principle, to investigate the trends reported in **Chapter 5**'s farmer survey. In **Chapter 7** the strengths of system dynamics modelling in providing operational insights into a system will be utilised to address a number of objectives. Those include, to elicit the causes of the shift in dynamics (identified in **Chapter 5**) brought about by the adaptation implemented, i.e. the heightening of the dyke network and concurrent shift to triple-cropping. To identify the sources of vulnerability which threaten the adapted social-ecological system's resilience moving into the future. Finally, once weaknesses are located, the ability of second-order policies, including the 3-3-2 cropping cycle documented in **Chapter 5**, to alleviate those weaknesses can be explored.

The System Dynamics approach is interdisciplinary and aims to encompass all of the diverse aspects of a system that are important to addressing a certain question about its functioning. The approach requires a researcher to draw on knowledge and evidence from a wide variety of sources, which can be of varying reliability, and sometimes a large degree of uncertainty must be dealt with. In order to substantiate the model outputs presented in **Chapter 7**, in the face of some uncertainty, this chapter outlines the process of model construction, parameter evaluation, validation, and sensitivity testing in some detail. The chapter finishes by discussing some insights into the system's functioning gained from the model construction and evaluation process itself. First however, a background and justification for the selection of the System Dynamics methodology, and the particular modelling software package chosen, is provided.

6.2 Reviewing system dynamics modelling

6.2.1 What is system dynamics modelling?

System Dynamics Modelling (SDM) is the physical realisation of the process that is more broadly termed *systems thinking* (Forrester, 1994). Users, interested in investigating the dynamics of a real world system build their model in a freeform icon based SDM package such as STELLA (ISEE systems, 2015) or Vensim (Ventana Systems, 2013) which provides a platform for the investigation of a system over a specified time period. Sometimes described as *mediated modelling* (Fraser et al., 2011) model parameters are produced drawing on a huge variety of inputs, ranging through educated guesses, expert opinions, to field observations and published academic research. Most commonly, SDMs revolve around stocks (i.e. accumulation points, such as the stock of nutrients held within the floodplain) and flows (also called rates, as represented by the differential equations which define how the level of a stock varies over time). But ultimately, the model created, and how accurately it reflects the true system's dynamics are entirely determined by the efforts of the builder. The modelling packages and the field of research itself aim to encourage the creation of models which are interdisciplinary and which reveal most about the more challenging nonlinear dynamics within the system of interest (Sterman, 2001). They also aim to make SDM as open and accessible as possible, to both the producers and consumers of research. Particularly, by removing the need to master a complex programming language prior to starting and by producing transparent and accessible outputs. A common approach to the reporting of SDM is through the telling of the narrative or story of the model, and the dynamics that prevail as the system moves through time (Martinez-Moyano and Richardson, 2013). Such an approach ensures the accessibility of the modelling work performed, but also encourages the researcher to approach the problem from an operational rather outcome oriented perspective.

6.2.2 A background to SDM

The roots of the system dynamics approach (in environmental modelling) can be traced back to Lovelock and Watson's (1983) Gaia hypothesis and the accompanying "daisyworld" simulations. Daisyworld, a system dynamics model itself, revolutionised our understanding of planet earth, illustrating how the environmental feedbacks hidden within Earth's natural systems allow a degree of self-regulation and provide a buffer to changes in external forces almost akin to a living being. Concerns about the effects of environmental feedbacks instigated by anthropogenic climate change would later become one of the greatest scientific questions of the 21st century (Bony et al., 2006). SDM of natural systems did not gain widespread application until Prof. Robert Costanza published a trilogy of special issues in the journal *Ecological Modelling* (Costanza et al., 1998; Costanza and Gottlieb, 1998; Costanza and Voinov, 2001). Two main conclusions were derived from these three special issues: (i) that SDM of the environment is no longer restricted to modelling (programming) specialists, and as such; (ii) the method itself, facilitated by software programmes such as STELLA, has strong potential for addressing global policy questions.

SDM is unusual as a modelling technique in that it has enjoyed very broad take-up across a range of disciplines and sectors, including business management , NGO projects, academia, and government (Costanza and Voinov, 2001; Sterman, 2001). However, in recent years the focus of many papers using a system dynamics methodology has become highly specific and more policy question driven (e.g. Roy et al., 2010), with many exemplar studies having used the approach to help achieve sustainable levels of production and consumption of goods (e.g. Hassanzadeh et al., 2012; Qi and Chang, 2011). As a result, the true impact of SDM may be underestimated by traditional academic impact measures.

Efforts are being made to improve the documentation of SDM projects and their successes, which may over time provide stronger evidence for some of the above assertions. Rouwette and Ghaffarzadegan (2013) report on the progress of a case repository project which is bringing together the work of academics and non-academic practitioners alike. Their repository is documenting the huge number of projects in fields including: health, education, and economics that have contributed to sustainable decision making around the globe. They also note the direct line between many SDM studies and policy making and evaluation, serving to highlight how appropriate its use is for environmental sustainability studies aiming at maximum impact. At the time of writing (09/03/2016) there were 53 projects documented in the repository, guiding policy for organisations such as Coca-Cola Inc, UK Department of Health, Centre for Disease Control and Prevention, US Coastguard, and General Motors.

6.2.3 Why choose system dynamics modelling?

The early policy discourse on reducing the harmful effects of climate change impacts was dominated by what is known as the predict then act philosophy (Lempert et al., 2004). Advancing empirical forecasting techniques and supporting research aimed at reducing uncertainty in earth system models was seen as a prerequisite to effective adaptation decision making (Füssel, 2007). These mathematical/statistical models focus primarily on the biophysical relationships which control earth systems. However, many claim the tendency is for such models to morph into *black box* (correlational) models as they develop (Blöschl and Montanari, 2010). The internal examination of black box models is clouded by complexity and the result can be models from which it is difficult to identify the causation of troublesome behaviour (Jorgensen, 2008). This weakness of complex modelling research is often considered to be something which precludes translation of its outputs into policy (Panayotou, 1997). In addition to accurate forecasts, knowledge about the controlling (and internal) socioeconomic system dynamics are required in adaptation decision making (Fraser et al., 2011). In any case, with climate change pressures growing rapidly it is now accepted in some spheres that the sheer complexity of earth systems, and the confounding effects of multiple other anthropogenic influences causing environmental change, will preclude the accurate forecasting needed to recommend a single adaptation choice (Ford, 2010).

Rather than preventing adaptation action, most suggest (e.g. Adger et al., 2009) the uncertainty in climate change forecasts simply demands a change of direction towards *robust decision-making*. A robust adaptation decision is one which affords protection to a social-ecological system across a spectrum of different impacts and impact magnitudes (Lempert et al., 2004). Lempert and Collins (2007) find, the greater the uncertainty, the greater the chance that a robust decision will ultimately be preferable to a policy which attempts to achieve an optimal outcome under one set of forecasted assumptions. The information required for such a decision is different to that of the predict-then-act approach and does not relate only to climate changes. To understand what outcomes are possible from different actions a greater focus on process is required. Systems must be examined to find key relationships, feedbacks, and thresholds within all sectors of the system, with a specific focus on finding (potentially multiple) unstable pillars which threaten a system's resilience under environmental change (Fraser et al., 2011). As Adger et al. outline:

"Adaptation is a continuous process which influences the location of a system in relation to thresholds. In order to evaluate the influence of adaptation activities there must be sensitivity to changes, or feedbacks, in the system. Sensitivity to feedbacks relates both to the timing as well as where these feedbacks occur." (Adger et al., 2011, p. 762)

It is in the understanding of feedbacks that SDM has its strength. SDM allows exploration of the internal workings of a system and communication of a system's feedback and momentum (Ford, 2010; Simonovic and Li, 2004). The development process allows construction of interdisciplinary system relationships which, ultimately, can challenge assumptions made about the sources of vulnerability and risk in the system (Costa et al., 2011; Fraser et al., 2011) and help find problematic behaviour (Simonovic and Li, 2003). Furthermore, system dynamists have developed a method for identifying the (tipping/leverage) point at which a system loses resilience and begins a transition to a new state. Stemming from the field of loop polarity dominance research (Richardson, 1995), Dyke and Weaver (2013) explore the idea that an environmental system loses resilience at the point when the dominant feedback loop switches from negative to positive and ceases to self-regulate. System dynamic modelling specialises in modelling those feedback loops. Positive feedback loops often carry the momentum required to move a system into a new stable or *homeostatic state* (ibid). Bueno (2012) suggests that this same logic applies to social-ecological systems, such as that in **Figure 6.1.** Locating the causal processes of such shifts is likely to be extremely useful for planning targeted policy.

Social-ecological systems are extremely complex and each of the components of the conceptual model, such as in **Figure 6.1,** could be divided into several interdependent micro-systems. Within any of those micro-systems could be a variable at a magnitude close to its threshold and therefore liable to destabilise the system and force it into positive feedback. To find this variable requires examination of social, physical and ecological systems and it is a feature of SDM that it is capable of modelling these multi-disciplinary systems and their respective sub-systems in an integrated manner (Ford, 2010).

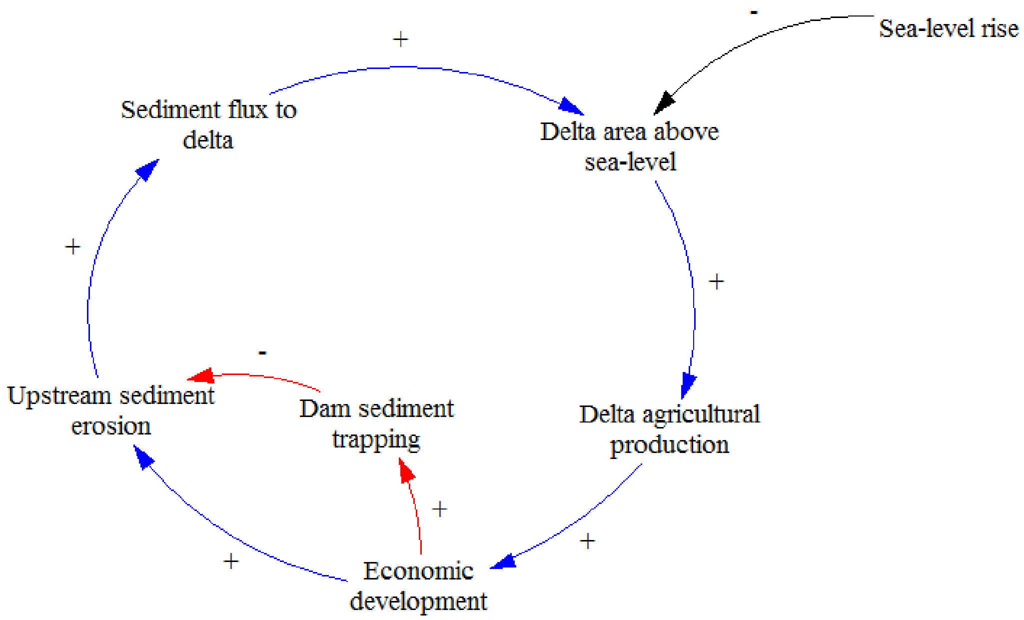


Figure 6.1 An example of a feedback loop in a social-ecological system, subject to external drivers (black arrow), and internal alterations (red arrows).

To allow model structural clarity and integration of cross-disciplinary systems, system dynamics models should be as simple as possible. As illustrated in **Figure 6.2,** this sometimes results in a lesser degree of detail and the inclusion of fewer processes, which may lead to a lack of forecasting power. This simplicity is a difference but not necessarily a weakness. Advocating simpler models Blöschl and Montanari (2010) explained:

"There is not only the advantage of reduced model uncertainty due to fewer parameters; there is also the advantage that the processes modelled can be more readily understood by the modeller. Unless we understand why an impact study predicts changes in a given [...] variable we cannot trust that the results are valid" (p. 378)

The reduced accuracy and precision of the model might mean poorer validation results (though this is not a rule) than other models achieve but, as many commentators point out, since no model can truly be validated, a better question to ask is: 'is the model useful?' (Ford, 2010). There is a long history of debate over the validation of system dynamics models. A strong case has been put forward by the SDM community that their models should be validated for purpose, not forecasting performance (Barlas, 1996).

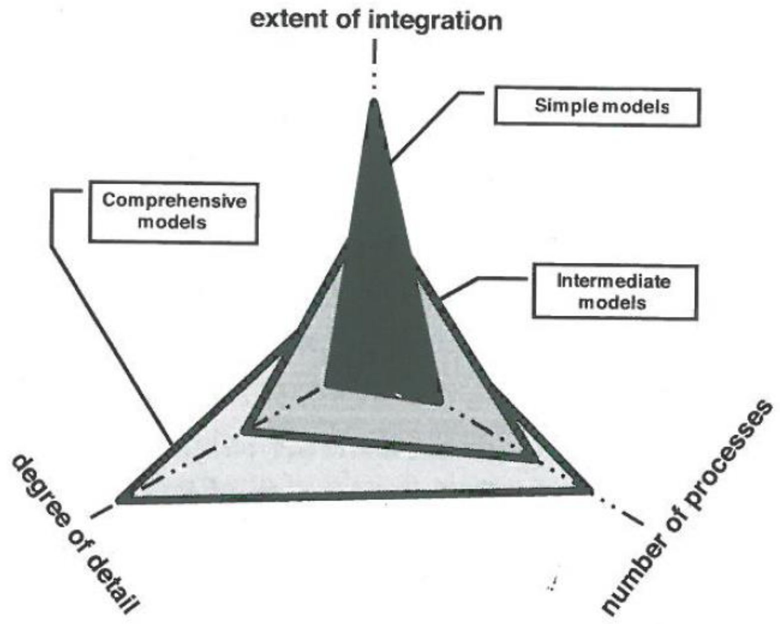


Figure 6.2 The trade-off between level of integration, detail, and the number of processes (Ford, 2010).

With the shift in emphasis in adaptation policy away from reliance on forecasts and towards robust decision making the contribution system dynamics modelling can make to the process of policy evaluation has grown. A robust decision will be one which considers impacts across many sub-systems and scenarios and SDM is increasingly being seen as a technique which has the flexibility for exploratory modelling of such scenarios (Kwakkel and Pruyt, 2013). The superior integrating power and clarity of system dynamics models makes them ideal for this purpose and mean they can fulfil different roles compared to, for example, climate models and coupled climate models. However, at present, the number of published studies explicitly implementing the SD approach to evaluate adaptation policy is still small (e.g. Gies et al., 2014).

Valuing model simplicity also has some useful by-products. The system dynamics methodology has garnered a reputation for improving public participation and awareness in environmental decision making (e.g. Garedew et al., 2012; Beall and Zeoli, 2008; Stave, 2002). This strength has especially been utilised to deal with water management issues (Van Den Belt et al., 2013; Wei et al., 2012; Tidwell et al., 2004; Stave, 2003; Ahmad and Simonovic, 2000). Creating a system dynamics model is an iterative and transparent process affording opportunities for stakeholders to provide their input into model design and scenario analysis (Ford, 2010). Many SDM packages (e.g. STELLA and VenSim) are highly visual in their presentation, and any changes made to a model through stakeholder engagement processes can be implemented immediately and shown to participants (Susnik et al., 2012), providing a far more interactive experience than traditional public hearing methods (Stave, 2002). This accessibility not only benefits the wider public but also makes system dynamics models highly beneficial to the public policy process, as non-expert policy makers can grasp complex dynamics and traditional assumptions can be challenged (Fraser et al., 2011; Ghaffarzadegan et al., 2011; Sterman, 2001).

This strength in stakeholder engagement is useful for the process of prioritising adaptation action in social-ecological systems. What is perceived as a risk or benefit by a scientist might be very different to what is perceived to be a risk or benefit by a community within the system (Dessai et al., 2004). What constitutes human wellbeing is an entirely subjective concept and hence the perceptions of the stakeholders are of importance in determining priorities for a system (Owens, 2000), making SDM advantageous on multiple fronts. This issue of stakeholder priorities for a system is revisited in **Chapter 7** as it is also an advantage of multi-criteria decision analysis. In the current context of rapidly intensifying climatic and development pressures this strength in fast and effective stakeholder engagement to set priorities, better understand a system, and inform policy is of value, and played a role in the selection of the system dynamics modelling method for this thesis. Due to the academic nature and importance of physical systems in the SDM constructed herein full participatory modelling was not deemed necessary or appropriate. However, various forms of stakeholder engagement do inform the process, as report in **Chapter 4** and **5**. In addition, the accessibility of the modelling technique holds significant advantages for ensuring policy impact for the findings presented, and allows further iteration of the model beyond this thesis, potentially to responsively test further policies proposed as and when appropriate.

6.2.3.1 Alternative methodologies

The term SDM is a broad one, with unclear boundaries, frequently it is treated as encompassing all nonlinear differential equation models of systems (Rahmandad and Sterman, 2008). Furthermore, within the field of SDM there is a considerable range of approaches that, as earlier described, vary in their complexity and transparency. That said, two alternative methodologies have evolved that are distinct from SDM and may be utilised to tackle similar problems (see **Figure 6.3** from Borshchev and Filippov, 2004).

Like SDM, the field of discrete event modelling (DEM) looks at systems from an operational perspective, its strengths lie in breaking down and describing in detail the micro-level operational, step-by-step, process which leads to an outcome (Borshchev and Filippov, 2004). DEM’s forecasting power may well be greater than SDM, but it is a linear approach, not well equipped for investigating feedbacks. Similar to SDM, the field of agent based modelling (ABM) approaches systems from the perspective that systems may be more than just the sum of their parts. ABM examines how the behaviour of individual agents (e.g. organisms, or businesses) creates collective behaviour that cannot be understood when only one agent is observed. In comparison with SDM, ABM places greater emphasis on understanding an individual agent's decision making behaviour and its relationship with collective/aggregate decision making behaviour. SDM works primarily with the aggregate behaviour, and aims at understanding how that behaviour operates within a wider social-ecological system, unclouded by the nuanced influence of lower-level agents (Rahmandad and Sterman, 2008).

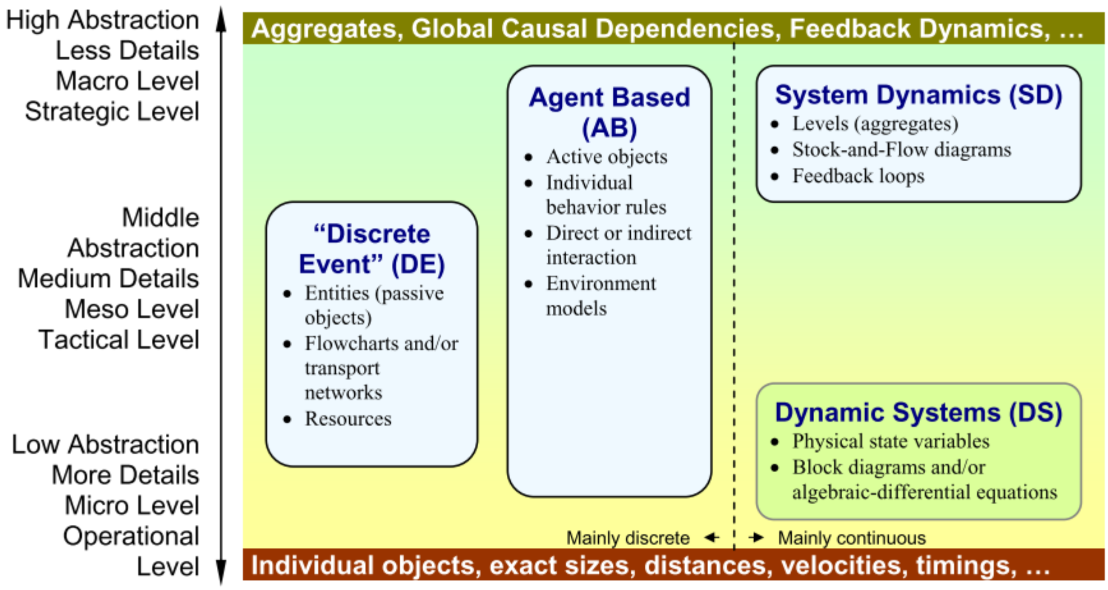


Figure 6.3 The roles and specialities of various approaches to systems modelling (Borshchev and Filippov, 2004).

The SDM and ABM methodologies are not exclusive, and indeed, system dynamics models may contain agent based ideas, and vice-versa, as cross over is not restricted by the software commonly utilised in either field (Ford, 2010). Indeed Rahmandad and Sterman (2008) suggest the differences in results achieved from utilising a SDM methodology over an ABM one may be less than those caused by parameter uncertainty. Ultimately, the choice of approach depends on the question being asked. As **Figure 6.3** suggests, SDM tends to be preferred where feedback loops (and their manipulation) are of particular interest.

In this project the SDM approach was preferred over other options because the focus of the project is not solely on the decision making processes of VMD farmers, though they are important, but on the feedback in the loop connecting the farmers decision making with the economic system and the physical system of floodplain sediment deposition. The indicators against which system performance might be measured are spread around the different sectors of the model and are not focussed on one agent moving through the modelled environment.

Furthermore, there is only one decision making agent (the farmer) internalised within the model constructed in this chapter, rather than multiple interacting agents (although other agents, such as government policy makers, do exogenously drive the system). That single internalised agent, is furthermore a strongly homogeneous one. The rice farmers within An Giang province operate in a homogenised environment, producing the same crop within the same dykes, and with similar levels of dependency on that crop between farmers. This would not be the case in other VMD provinces, such as Soc Trang, where multiple crops are grown, using different water management techniques. To a degree, this agent homogeneity takes the focus of the model off the agent and places it on the system.

6.2.4 Choosing a modelling package

A SDM package provides a modelling environment within which the user creates a model. As such, the software package chosen is of lesser importance to a project than the complexity, clarity, and accuracy that the modeller is capable of simulating. However, as a result of the prevalence of SDM in business management and planning there are a large number of software packages available. Each of these packages will contain nuanced biases associated with a wide variety of factors, such as layout, programming language, and computing power, which will influence the model throughout its creation, and may be difficult for the user to detect (Rizzo et al., 2006). For example, Seppelt and Richter (2005) created the same model in six different packages and ultimately obtained six marginally different results. They attribute the differences to *"embedded numerical models [which] are insufficient and inadequate to treat the mathematical models involved"* (p. 1547). However, Seppelt and Richter (2005) are keen to point out that this does not detract from the worth of system dynamic modelling; its ability to produce analytic rather than black box models, even when simplification has been performed, is vital for a model to be meaningful.

Rizzo et al. (2006) identify two primary choices involved in the process of package selection. The first is a straight forward decision between icon based packages (e.g. STELLA, Madonna, Goldsim with flows, and Vensim) and language based programmes (e.g. MATLAB, Simulink, and Goldsim with expressions). The icon based packages provide a better conceptual understanding (through visualisation) of the system and a more user-friendly interface while the language based programmes allow greater customisation of formulae. The second decision is a simple trade-off between computational (forecasting power) and ease of use and clarity (see **Figure 6.4**).

The packages Goldsim and Simulink were not developed with the main purpose of exploring system dynamics and therefore are generally disregarded by environmental modellers (Ford, 2010). This project aims to maintain accessibility, such that the causality behind dynamics of interest is explicitly clear, and hence policy implementation is simple, with easily measurable impacts. Furthermore this project does not deal with a problem that is excessively complex in terms of the individual relationships between parameters. As such, a language based modelling packages was deemed inappropriate. This left a decision between STELLA, Vensim, and Madonna. All three packages are extremely similar and their primary differences come down to presentation and price. A strength of Vensim over both Madonna and STELLA is that its most basic package is available for free download. For a project such as this, based in a developing country, this is useful for sharing ideas, collaborative modelling, and accessing project outputs. However, STELLA is by some stretch the most widely used software package meaning it has greater potential for collaboration among researchers and institutions.

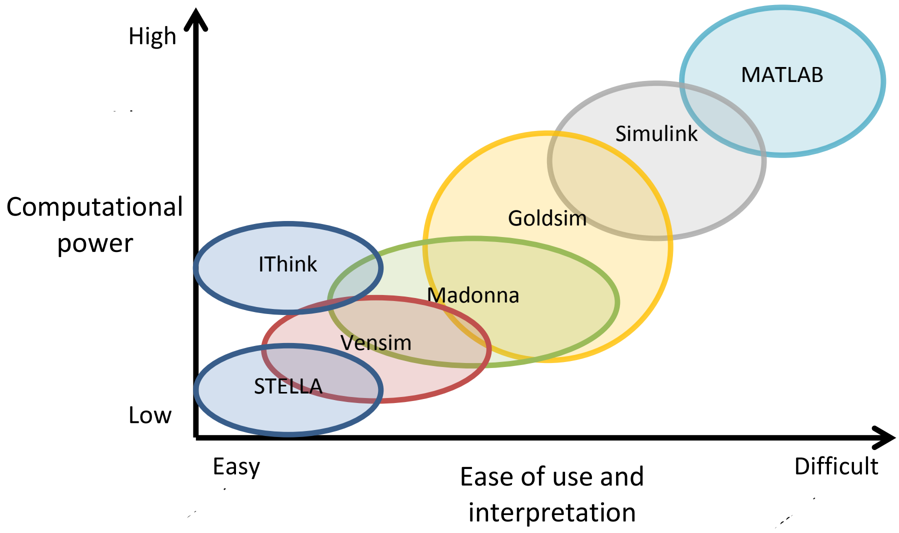


Figure 6.4 The trade-off between ease of use and interpretation and computational power for a variety of software packages, adapted from Rizzo et al. (2006).

Both Vensim and STELLA were utilised during this project. Vensim was used to design the core causal loops. The version of STELLA known as IThink (ISEE Systems, 2015) was used to build the functional model, IThink, which is ISEE Systems' most powerful version of the STELLA software, offered the best balance between accessibility and computational power.

6.3 Model development methods

6.3.1 Model construction methods

Ford (2010) describes eight steps as vital towards developing a system dynamics model capable of imitating system behaviours of interest. The process laid out by Ford has since established itself as best practice in the field in Martinez-Moyano and Richardson's (2013) review of approaches. The steps in the standard process are divided into the qualitative and quantitative parts of the process in **Table 6.2**; the table also serves as a map for the SDM side of this project. **Table 6.2** highlights that there are seven key steps which need to take place before any policy analysis can be performed, these steps are either presented in this chapter or have already been presented in **Chapters 4** and **5**. Methods for completion of steps 1-4 are described in **Table 6.2**. The methods for implementation of steps 5, 6, and 7, are briefly discussed below, while step 8 constitutes the bulk of **Chapter 7**.

6.3.2 Parameter estimation methods

A considerable amount of data were required to inform the relationships and parameters within the broad, interdisciplinary, model that was constructed to simulate the dynamics of the adaptation evaluated in this thesis. Wei et al. (2012) and Qi and Chang (2011), who performed similarly broad water resources management-system dynamics projects highlight the huge number and variety of primary and secondary data sources that must be utilised to define such a wide ranging system's parameters. The careful selection of data sources is an highly important step in the process of model construction as, in sensitive models subject to feedbacks and thresholds, small inaccuracies can have important implications (Santos et al., 2013). As system dynamics models are designed for developing system understanding and not forecasting, a large variety of possible data sources can be considered in order to ensure that all of the important components of the system are included. Ford (2010) describes an information spectrum of source types, shown in **Table 6.1**. In **Table 6.1**, both qualitative and quantitative sources can be considered and indeed construction of a systemic model can sometimes be impossible without utilisation of stakeholder and expert knowledge about the system's structure, functions, and parameters (Luna-Reyes and Andersen, 2003).

Table 6.1 Ford's (2010) information spectrum for informing System Dynamics Models.

Physical laws	**Controlled** experiments	**Un-controlled** experiments	**Statistical** information	**Case** studies	**Expert** judgement	**Stake-holder** Knowledge	**Personal** intuition
Hard ←							→ Soft

Table 6.2 The steps in system dynamics model construction, which are designed to be an iterative process, adapted from Ford (2010) and Martinez-Moyano and Richardson (2013).

No.	Step	Practicalities	Project work
Qualitative processes			
1	Problem familiarisation:	Review literature on the system under investigation. Meet system experts and stakeholders. Investigate existing and proposed policies for the system.	Literature review, in **Chapter 2**. Policy background and key informant interviews in **Chapter 4**
2	Problem definition	Establish a time horizon and reference mode associated with the behaviour of interest	Reference mode and behaviours of interest established in **Chapter 5**
3	Model formulation	Construct a stock and flow diagram. Establish where the policy variables lie, and where performance is measured.	Model stock and flow diagram, and accompanying narrative presented in **Section 6.4.3**
4	Causal loop formulation	Construct a causal loop diagram	Causal loop diagram presented in **Section 6.4.1**
Quantitative processes			
5	Parameter estimation	Establish an information source for each relationship and its associated parameters. Estimate their value/equation.	Parameters established and evaluated in **Section 6.4.2**
6	Simulate (and validate)	Run the model. Compare the model's behaviour with the reference mode and other known behaviours of the system.	Model run and statistically compared with the reference mode in **Section 6.5**
7	Sensitivity analysis	Test the sensitivity of the model's outputs to variations in its parameters, and test responses to extreme conditions	The model was tested for sensitivity to the weak parameters in **Section 6.6**
8	Policy analysis	Run the simulation changing the values assigned to the policy variables and assess the impact of the policy	Policy analysis takes place in **Chapter 7**

6.3.3 Model evaluation methods

This section discusses the processes that are involved in the evaluation of a system dynamics model and how those methods are executed here. The goal of model evaluation in ecological modelling (Rykiel, 1996) and especially SDM (Barlas, 1996) is to determine whether the model is fit for purpose. In SDM that purpose is invariably not forecasting, but rather policy-design through structural understanding, a caveat which strongly influences and adds complexity to the evaluation process (ibid). Barlas (1996) contends that traditional validation in which, for a known set of inputs, model outputs are compared against real-world data records, plays a lesser role versus other structural tests. In **Figure 6.5** Barlas (1996) presents a summary of the available model evaluation methods which, along with Sterman's (2000) "tests for the assessment of dynamic models", has become a key point of reference in the field. Those more traditional validation methods involving comparison with secondary data are categorised under *behaviour validity* and are preceded by a host of structural and behavioural tests, such as extreme condition testing. These tests primarily take place during the iterative process of model construction in order to guide the evolution of the model, rather than providing results which can be used to judge a model's validity post-construction.

Sensitivity tests also play a key but complex role in the evaluation of a system dynamics model. Testing model sensitivity is one way of validating a model, under a similar premise to that of extreme condition testing, however, sensitivity analysis can also be a useful tool for learning about a system. Below are the methods used in the three important phases of model evaluation which provide data which can be used to judge the performance of the model in its final iteration.

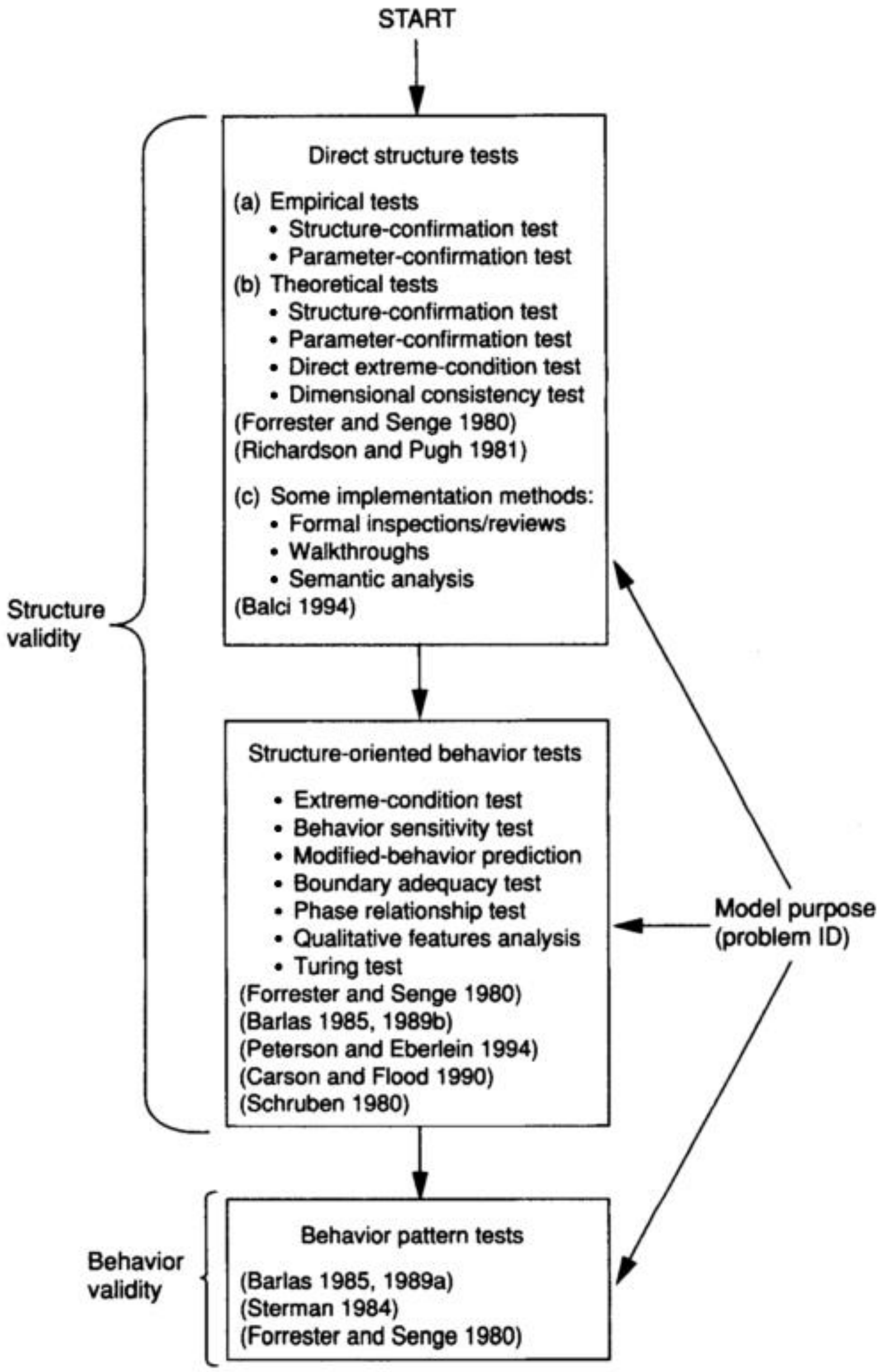


Figure 6.5 Validating a system dynamics model for purpose (Barlas, 1996).

6.3.3.1 Parameter assessment

The use of what, in other research projects, might be considered unusual data sources opens the model up to unusual sources of error. As such, parameter assessment is an important component of Sterman's (2000) *"tests for the assessment of dynamic models"* (p. 859). The most common approach, a judgemental method, is applied to the sources informing each parameter/combination of parameters later in this chapter. As the assessment of parameter reliability/strength is unavoidably a normative process no accepted standard or approach has been established. For the purposes of this project a simple framework for scoring a parameter source's reliability was developed, as shown in **Table 6.3**. The approach began from the assumption that, at the outset, all of the sources in Ford's (2010) information spectrum (**Figure 6.1**) are of equal standing, and that their reliability can be determined from their performance against a few key indicators, which included: transferability of source location, transferability of source spatial scale, quantity of evidence/sources, and the statistical confidence associated with the source (where appropriate). Once identified, parameters with weak sources were targeted in sensitivity analysis (**Section 6.6**) to establish how significantly their uncertainty impacts on our ability to draw wider conclusions from the model's outputs.

6.3.3.2 Validation by comparison

Model validation through comparison with secondary data is performed, in SDM, through comparisons of the model output with what is known as the *reference mode*. The reference mode is the behaviour of interest being modelled, and the reference mode is usually, though not exclusively, established from observed field data. Usually, the system behaviour described by the reference mode is in some way problematic and the modellers wish to locate its source and investigate methods of manipulating it (policies). Model outputs may be compared against the reference mode statistically, most often through significance testing, but with some caveats.

Barlas (1996) outlines the debates surrounding the issue of validation through statistical significance testing. Primarily, Barlas argues that statistical significance testing should be approached with caution in SDM for (i) practical reasons and (ii) philosophical reasons. Practical reasons include: that SD models are not serially independent and are cross-correlated; they do not have a single output variable (one indicator may perform well while others may not); and they are highly prone to measurement errors. The philosophical reasons revolve around the arbitrary level at which the null hypothesis is rejected. Judging all findings above an arbitrary p-value invalid may reduce the potential for learning from a model.

Table 6.3 A spectrum of information types and the factors controlling their reliability.

Information type	Physical **law**	**Score**	**Controlled** experiments	**Uncontrolled** experiments	**Statistical** information	**Predictive** models	**Expert/stakeholder** knowledge	Personal **intuition**
Transferability of location	N/A	3	Within study area	Within study area	Within study area	Local model	Specialises in study area	Specialises in study area
		2	Comparable environment	Comparable environment	Comparable environment	Regional model	Specialises in comparable environments	Specialises in comparable environments
		1	Poorly comparable environment	Poorly comparable environment	Poorly comparable environment	Global model	Specialises in the field only	Specialises in the field only
Transferability of spatial scale	N/A	3	Study scale	Study scale	Study scale	Study scale	N/A	N/A
		2	Similar scale	Similar scale	Similar scale	Similar scale		
		1	Incomparable scale	Incomparable scale	Incomparable scale	Incomparable scale		
Quantity of evidence/studies	N/A	3	High number of experiments	High number of experiments	High number of surveys	High number of models	Comprehensive sample frame	N/A
		2	Multiple experiments	Multiple experiments	Multiple surveys	Multiple models	Representative sample frame	
		1	Single experiment	Single experiment	Single survey	Single model	Selective sample frame	
Statistical confidence	N/A	3	P < 0.001	P < 0.001	P < 0.001	P < 0.001	N/A	N/A
		2	P < 0.05	P < 0.05	P < 0.05	P < 0.05		
		1	P-value not provided	P-value not provided	P-value not provided	P-value not provided		

In summary, system dynamics models may be traditionally validated, and systematic errors may be present, particularly due to the difficulties of parameterising social-ecological systems. But, a model's performance should be judged in the knowledge that such errors do not necessarily preclude a model from providing useful insights into the functioning of the system under observation (Ford, 2010).

The objective of secondary data validation in SDM is to test the model's ability to simulate system behaviour. In this project comparisons between the model outputs and the collected data were made using the *Yielfert* variable (Yield (t) / Fertiliser (t)) also utilised in **Chapter 5**. *Yielfert* was chosen as the primary indicator for comparison between the model and the real-world for several reasons: first, because its temporal trends succinctly summarise the status and sustainability of an agricultural system; second, because it is commonly utilised to benchmark the performance of policies implemented in agricultural systems (see Khai and Yabe, 2011); third, because it is a lens through which to perceive the nutrient contribution of sediment i.e. the addition of sediment-bound nutrients should increase *Yielfert*; and finally, because it provides insights into system dynamics (as opposed to indicators such as *Yield*, which would more test the model's forecasting ability).

The *Yielfert* reference mode against which the model's outputs were compared was built from the data reported in the farmer survey detailed in **Chapter 5**. This data can be found in full in **Appendix 9.6**. It should be recognised that the farmer reported data is subject to its own uncertainty, as discussed in **Section 5.5**. From the farmer-reported data a *Yielfert* time-series was built spanning the six-year reporting period (2008-2013). Three models were built, one for each of the three key system conditions found in the field: double-cropping farms (*Two*), farms which were in the process of changing system from two to three (*Chng*), and triple-cropping farms (*three)*. For comparison with these three reference modes, three equivalent model set-ups were simulated, each subject to 100 Monte-Carlo runs (see **section 6.4.3** for further discussion of Monte Carlo simulation). From the Monte-Carlo model runs a six year time slice was cut which would temporally correspond with the six year period reported on by the farmers, and another regression model was built. First, the model and farmer reported regression models could be visually compared, and second statistical comparisons were made.

Two forms of statistical test were performed on the data. First, an ANOVA model (F = 19.45) *(i –* **Appendix 9.7 Table 9.2***)* was built to test for a statistically significant *difference* between the *mean values* of all the modelled and reported datasets, and a second ANOVA model (F = 9.98) *(ii –* **Appendix 9.7 Table 9.3***)* was built to test for a statistically significant *difference* between the mean *rates of change* in all the modelled and reported datasets (i.e. the data was transformed to find X_t/X_{t-1} for each datapoint). Second, for further information, a general linear regression model was built with all the modelled and reported *Yielfert* data collated as the dependent variable. The Adjusted R^2 values were then calculated to show the amount of variance explained by a categorical dummy variable which separated the modelled and reported data.

6.3.3.3 Sensitivity analysis

As discussed above, parameterisation of ecological models which try to simulate the variability of nature is perhaps the greatest challenge of the modelling process (Van Nes and Scheffer, 2005). Ultimately, models may produce strong traditional (secondary data) validation results but, their parameterisation may still be poor, and the strong results may be for the wrong reasons (Rykiel, 1996). If the model's parameters have been estimated to the greatest obtainable degree of accuracy and uncertainty is still present, sensitivity analysis is usually the preferred method for investigating the relative influence of uncertain parameters over the model. – though it is generally considered only a part of a wider process of monitoring, simplification and comparison (Van Nes and Scheffer, 2005). Sensitivity analysis can help determine which parameters are key to producing the observed behaviours. The findings of such a process can either point to a deficiency in a model or an insight into the modelled system's functioning. Commonly, simple sensitivity analyses can be conducted within the SDM packages themselves.

While the process of analysing the sensitivity of a parameter in a model is relatively simple its application can vary in nuanced ways between studies. Ford (2010) treats sensitivity analysis as a part of the iterative construction process, performed prior to policy analysis. The objective of Ford and other researchers utilising this approach (e.g. Guo et al., 2001) is to ensure the model is not overly sensitive to the value of certain parameters which are subject to greater degrees of uncertainty. Other researchers utilise sensitivity analysis post-model construction and post-policy analysis, as a piece of supplementary information which may help inform robust decision making rather than the physical design of the model (e.g. Xu et al., 2002).

A key issue with performing traditional sensitivity analysis techniques on system dynamics models is that they provide only a static, time-independent, guide to the relative influence of model parameters on outputs. System dynamics models run for a time period during which fluctuations involving complex dynamics take place and therefore the relative importance of individual parameters might shift temporally. Statistical screening is a method, developed and recommended by Ford and Flynn (2005) and Taylor et al. (2010) which aims at discovering the changes in the relative importance of parameters on output sensitivity throughout the simulation. This method is, however, in its infancy, and is very time consuming and resource intensive to perform and hence is rarely utilised in applied projects

Guo et al. (2001) and Zhang et al. (2008c) present what might be considered a practical and robust approach to sensitivity analysis which would appear to be establishing itself as the discipline standard in applied, published, SDM projects (e.g. Liu et al., 2015). While not as comprehensive as statistical screening, their method analyses multiple levels of alteration in key parameters against multiple key outputs. Zhang et al.'s (2008c) approach stands in contrast to many other SDM studies which have applied a more random and selective approach to sensitivity analysis, testing only a small number of parameters against an individual output (e.g. Talyan et al., 2007; Anand et al., 2006). In Zhang et al. (2008c)'s method a sensitivity degree (S_Q) is calculated using **Equation 1** for each parameter alteration/indicator change combination, where $Q_{(t)}$ represents the system output *Q* at time *t* and $X_{(t)}$ represents the parameter under investigation, *X*, at time *t*. All of the values produced for each level of variation and each indicator combination for one parameter are then averaged to produce the general sensitivity degree (GS_Q). The smaller the GS_Q produced the less impact alterations to the parameter in question have on the overall model outputs. A GS_Q =1 would imply that a fractional change in one parameter of *z* would result in an equal fractional change in output *Q* of *z*, averaged across all time steps of the simulation. An equal level of change between one parameter and one output (GS_q = 1) would be a very high level of variation in a complex dynamic system. In general, GS_Q vales of <0.1, i.e. a 10% sensitivity, are accepted in published studies (e.g. Wei et al., 2012; Zhang et al., 2008c; Guo et al., 2001).

$$(1)\ S_Q = \left| \frac{\Delta Q_{(t)}}{Q_{(t)}} \cdot \frac{X_{(t)}}{\Delta X_{(t)}} \right|$$ (Zhang et al., 2008c)

6.4 Constructing the model

6.4.1 Qualitative development

Chapters 4 and **5** report both on scientific research in its own right but also on the process of problem familiarisation and stakeholder analysis which formed the first phase of model construction, and a key phase in the development of a functional System Dynamics model. Key model structures were uncovered during the process, such as the local farmers' active decision to limit fertiliser application following high sediment deposition events, and extraneous limiting factors such as the high degree of governmental control over farmers' crop selection.

Once a high degree of understanding of the system had been obtained the problem could be defined:

The problem:

A complex set of dynamics surround the transition made by Mekong delta farmers from a double to triple rice-cropping system, which is synonymous with the construction of high dykes (the adaptation). Those dynamics have the potential to elicit negative impacts (maladaptive traits) which may result in a net detriment from the transition, when measuring certain indicators. Those dynamics require investigation such that their causal process is understood and their impacts might be alleviated through second-order adaptation action.

With this aim in focus a Causal Loop Diagram was developed to summarise the dynamics of interest that the model aims to investigate (**Figure 6.6**). The CLD highlighted that the system being modelled could be divided into three key sectors: the physical system, the economic system, and the decision making system. These divisions informed the model design and construction process and offered an avenue for improving the visual presentation of the model.

6.4.2 Quantitative development

The model's stock and flow structure was built iteratively. Each iteration of the model was subjected to informal behaviour tests and peer evaluation until a format was finalised. Peer evaluation was provided by system dynamics modelling experts in the System Dynamics Group at the University of Bergen, Norway.

6.4.2.1 Parameter estimation

The model's parameters were estimated using qualitative and quantitative evidence distilled from a wide reaching search of the academic and grey literature. In cases where such data was not available, which was particularly the case for the parameters in the model which represented farmer decision making processes, data was utilised from experts and stakeholders consulted in the field, as reported in **Chapter 4**. The data utilised within the model is static (non-time dependent) and should be clearly distinguished from the time-series data which was collected in the farmer survey (presented in **Chapter 5**) and is used later to help validate the model. The model's parameters can loosely be divided into the external model-driving parameters (**Table 6.4**) and the parameters which constitute the system processes internalised within the model (**Table 6.5**).

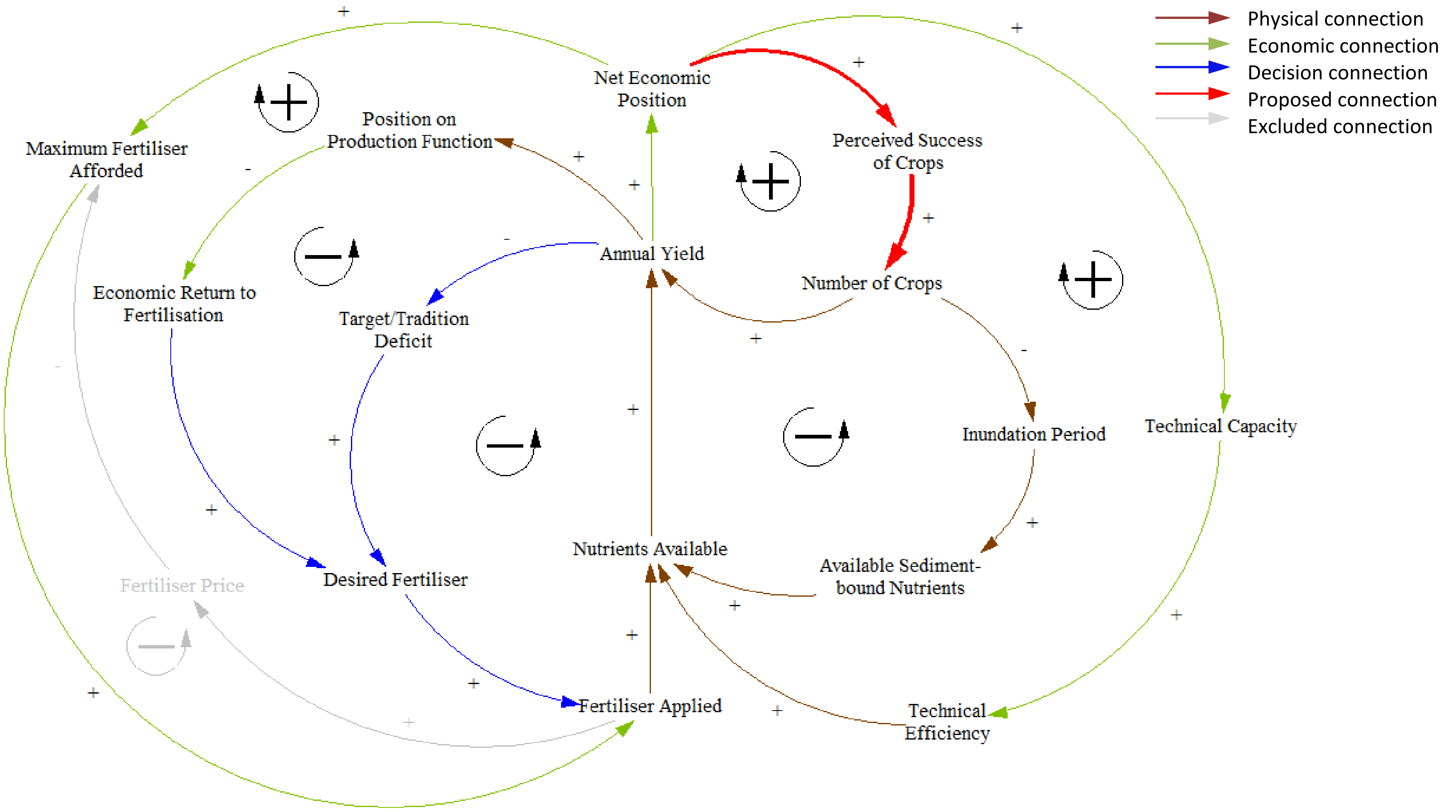


Figure 6.6 A casual loop diagram (CLD) showing the modelled connections, their nature, their individual polarity, and the overall loop polarity. Included is one example of a feedback loop excluded from the model, otherwise this diagram also represents the boundaries of the model.

Table 6.4 The (exogenous) model driving data and the values for each which were used to initiate the model, their sources, information type, and an assessment of the source's reliability. 'Overall score' represents the aggregated source reliability score based on the system set out in **Table 6.3**. Highlighted, are the components which were taken forward for sensitivity analysis.

Data	Source(s)	Information Type	Units	Initial value	Overall score
Inter-annual variability of suspended sediment concentration	SIWRR, 2013 (daily time series 2005-2011); Shreshtha et al. 2013 (predictions)	Statistical / Modelled	Fraction (standard deviation)	0.2	89%
Dam trapping efficiencies (end of simulation sediment reduction)	Kummu et al. 2010; Kondolf et al. 2014	Modelled	Fraction	0.84	69%
Total nutrient content of suspended sediment (N, P, K)	Manh et al. 2014	Uncontrolled	Kg/ha/yr	300	78%
Variability of rice prices	FAO, 2014 (monthly time series 2008-2014), Survey data	Statistical	Fraction (standard deviation)	0.05	78%
Rate of change of rice prices	FAO, 2014 (monthly time series 2008-2014)	Statistical	%/ha/yr/yr	1	78%
Variability of fertiliser prices	World Bank, 2014 (monthly time series 2000-2014), Survey data	Statistical	Fraction (standard deviation)	0.1	78%
Rate of change of fertiliser prices	World Bank, 2014 (monthly time series 2000-2014)	Statistical	%/ha/yr/yr	1.05	33%
Growth rate of rice yields due to rice variety development	Laborte et al. 2012; Ray et al. 2012 ; Tran and Kajisa, 2006	Statistical / Case study	%/ha/yr/yr	1.01	89%
Non-rice income achievable	Bosma et al. 2005	Statistical	'000 VND/yr	4800	78%
Exogenous variability of rice yield	GSO, 2014 (seasonal time series 1995-2013)	Statistical	Fraction (standard deviation)	0.1	78%
Rice price	Survey data	Statistical	'000 VND/Kg	4.5	78%
Fertiliser price	Survey data	Statistical	'000 VND/Kg	6	78%
Minimum wage level	Vietnamese Government, 2013	Law	'000 VND/person/yr	7200	100%

Table 6.5 Endogenous modelled processes (key micro-systems within the model), their sources, information type, and an assessment of their source's reliability. 'Overall score' represents the aggregated source reliability score based on the system set out in **Table 6.3**. Highlighted, are the components which were taken forward for sensitivity analysis.

Modelled processes	Source(s)	Information Type	Overall score
Sediment deposition process	Manh et al. 2014; Hung et al. 2014	Uncontrolled	75%
Floodplain nutrient accumulation process	Tsheboeng et al., 2014	Uncontrolled	58%
Nutrient fixing and leaching process	Liang et al., 2013; Phong et al., 2011	Controlled / Uncontrolled	67%
Rice nutrient requirement (production function)	Pham et al. 2004; Witt et al. 1999	Controlled	83%
Technological advancement process	Reardon et al. 2014; Rutten et al., 2014	Statistical / Modelled	58%
Technical efficiency rate	Khai and Yabe, 2011; Hueglas and Templeton, 2010	Statistical	75%
Technological investment return	Tin et al., 2008; Tran et al., 2000	Statistical	75%
Sediment perceived versus fertiliser applied decision process	Survey data	Stakeholder	100%
Fixed cost variation between cropping patterns	Survey data	Stakeholder	83%
Pesticide cost variation between cropping patterns	Survey data	Stakeholder	83%
Fertiliser subsidy policy	Tran, 2014	Expert	67%
Farmer's propensity to invest	Personal Intuition	Personal Intuition	-
Farmer's fraction of funds kept as contingency	Personal Intuition	Personal Intuition	-

6.4.3 Random variation

A number of variables within the constructed model are subject to temporal variation which, within the boundaries of the system under examination, is random. The price of fertiliser is one, others include: the price of rice, the precise sediment concentration of inundation water, the impact (and hence cost) of crop pests and disease, and the exogenous conditions that affect rice yield, such as air temperature and rainfall. Including such variation in the model adds a degree of realism to the model, and, importantly, ensures the model is subjected to extreme conditions which might exert different dynamics to those experienced under average conditions. The "RANDOM" function which is built-in to the IThink software was used to simulate this variation. The function produces normally distributed variation, and requires a standard deviation value to be provided. Standard deviation values were calculated from the available secondary data for all of the above variables and can be found in **Table 6.4** along with all of the initial values of the exogenous variables. The standard deviations of rice and fertiliser prices were calculated from World Bank data (World Bank, 2014), yield deviation was calculated from data provided by Vietnam's General Statistics Office (GSO,2014), sediment concentration deviation was calculated from data provided by the Southern Institute of Water Resources Research, Vietnam (SIWRR, 2013) and a crude estimate of the cost of pests and disease was calculated from the data provided by commune officials in semi-structured interviews during the data collection process outlined in **Chapters 4** and **5**.

Applying random variation means that capturing a representative sample for the exploration of scenarios and policies in **Chapter 7** requires analysing multiple runs of the model, each with a different random variation scenario applied. This form of stochastic modelling is termed Monte Carlo simulation. Sufficient Monte Carlo runs must be performed to gain a general picture of the dynamics under investigation and to avoid making generalisations from rare examples of extreme behaviour. Ford (2010) suggests a sufficient number of runs is a number at which adding more runs would provide no new information or insights. Ford highlights that in other studies (e.g. Ford, 1990) only 40 runs have been required to provide useful insight. As the objective of system dynamics modelling is not to forecast values but to reveal important dynamics, the numbers of runs required are commonly lower than the number required in other environmental modelling studies, and especially climate studies. Here, 100 runs per model-setup was deemed a sufficient number to ensure no important dynamics were missed.

6.4.4 Spin-up

The model runs over a user-defined time period. However, before analysis can be performed on the model outputs a *spin-up* of the model was required. Spinning-up a model is common modelling practice, the model is run for a period prior to the point at which its outputs are examined; this is in order to ensure any behaviour associated with the specific starting conditions chosen does not exert a disproportionate influence on the model's outputs. In this case the model was initiated with the exogenous forcing variables set at substantially below-present-day levels (in this study present-day levels are the average values of the year 2013). From visual inspection it was estimated that the influence of the initiating values had significantly diminished after 10 years (30 time steps) of simulation, as highlighted in **Figure 6.7**. However, the model took a period of 18 years, or 54 time steps to spin-up to present-day levels, at which point policy testing began. The model's correlation with present-day levels was determined using a visual inspection of the fertiliser prices and rice yields being produced by the model. After 18 years, these indicators were deemed to be in-line with the real-world data reported by the World Bank (2014) and the commune authorities in the field. **Figure 6.7** shows, for reference, the output of a General Additive Regression Model performed on the data which was produced by a set of 100 Monte-Carlo simulations (each subject to normally-distributed random variation), over a 48-year model time period.

6.4.5 Model narrative description

A common component of the reporting phase of a System Dynamics Modelling project is a model narrative, or story, which presents the causal chain within the model as a logical progression of events. Conducting such a process is frequently cited as best-practice in SDM, for it ensures that the modelling process remains transparent to all stakeholders and encourages operational thinking about dynamics which may not necessarily be intuitive (Martinez-Moyano and Richardson, 2013; Guhathakurta, 2001). What follows is the story of this model. For clarity, the model is separated into three modules roughly divided into the physical, economic, and decision making components.

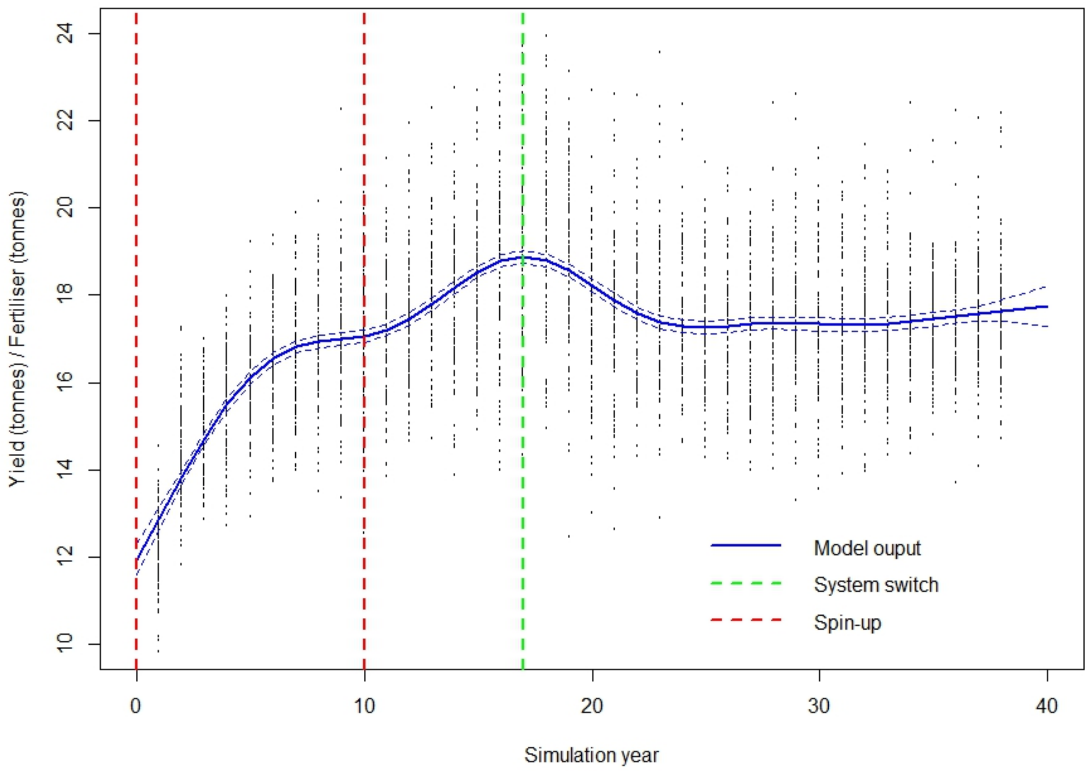


Figure 6.7 The output of a general additive regression model (denoted by the solid blue curve, which is the mean of the 100 Monte Carlo simulation results, the latter being indicated by the data points), across a 38 year time period. At the 'system switch' point, the farmer converts to triple-cropping. The dotted blue lines represent the standard errors. Highlighted between the red lines is the spin-up period and by the green line the year at which the system switched from two to three rice crops per year.

6.4.5.1 The economic module

The story of this model begins with the rice farmer. The farmer operates a farm of size *S*, employing *N* people. During the model spin-up period they cultivate two rice crops a year and, during the fallow monsoonal season, they obtain a small non-rice income. At the onset of the data-recording period (2013), dependent on the policy being applied they may remain double cropping or they may switch to three rice crops per year and sacrifice their non-rice income for the additional rice sale profits, alternatively they may operate a variant of the three-crop system.

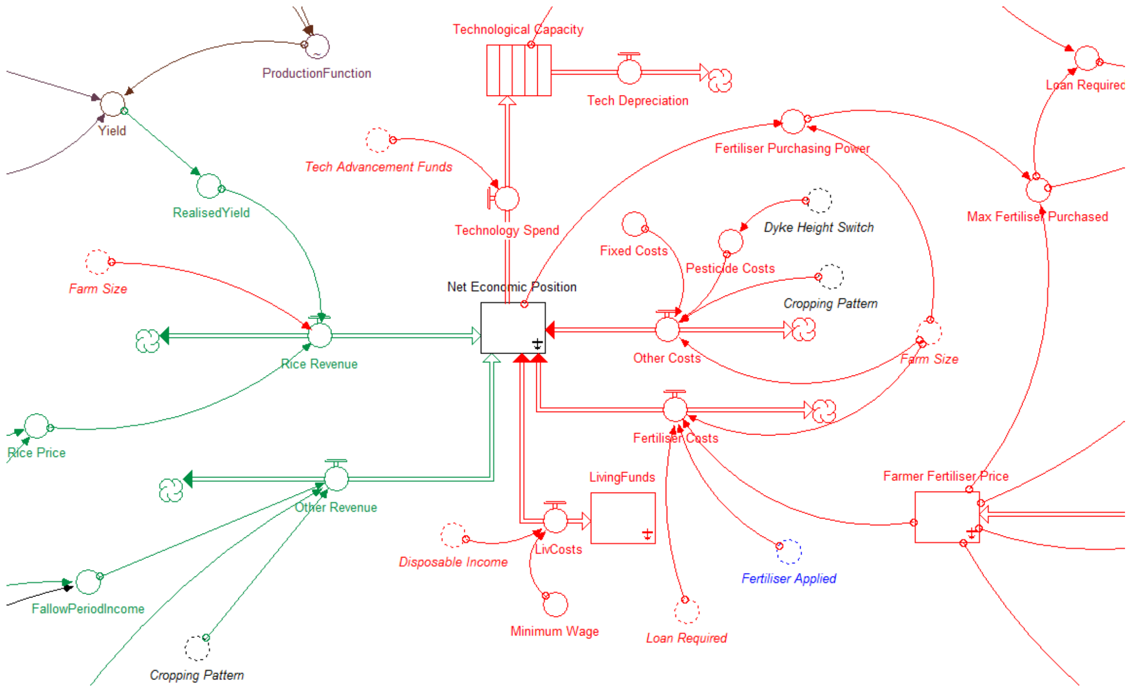


Figure 6.8 Graphic representation of the economic module of the system dynamics model.

The rice farmer's economic position is a function of their income, which constitutes the total of their rice sales (subject to the sale price of rice which fluctuates over time), plus their non-rice income; and their costs, which constitute their base living costs (calculated based on the Vietnamese minimum wage), their fixed farming costs, their pesticide costs, their expenditure on the upkeep of technology, and their expenditure on fertiliser (**Figure 6.8**). Should the farmer have a profit remaining after the books have been balanced they have the option to utilise that profit as disposable income or to invest it in technological advancement (e.g. advanced machinery or farm facilities).

The incentive for farmers to invest in their technological capacity is that it will improve the efficiency of their agricultural inputs (**Figure 6.9**). For example, they may improve the ratio of nutrients applied to the paddy (with fertiliser) versus the nutrients applied which actually become accessible to the crop or, they may improve the efficiency of sowing. The formulae determining the benefits of technological advancement are based on Tran

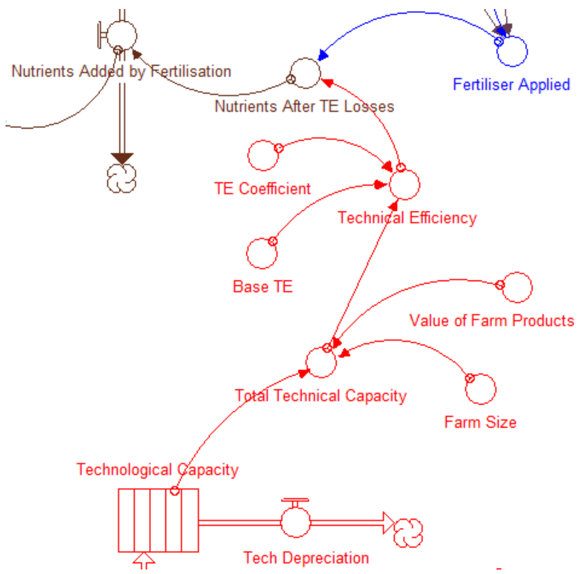


Figure 6.9 Graphic representation of the technical efficiency system in the system dynamics model.

et al. (2000) whose Vietnamese case study shows how adoption of modern farming technology can increase production by up to 116%, which, against only a 100% increase in farming costs, results in a considerable net benefit to adopting farmers.

A further factor affecting the input-output ratio achieved is the farmer's technical efficiency. Technical efficiency (TE) (Debreu-type) is described by Tzouvelekas et al. (2001) as:

"the ratio of the observed to maximum feasible output, given the production technology and observed input use"

TE differentiates the efficiency and hence is a key factor in the profitability of different farming operations. In the Mekong region an example of a key differentiating variable is the education level of the head farmer. Informing the model is work by Hueglas and Templeton (2010) who document in detail how farmers with lower education levels are less likely to adopt recommended efficiency-improving measures and will hence operate at a lower level of TE. Key to the model is Khai and Yabe's (2011) finding that this relationship reveals itself through a highly significant correlation between the value of a farm's products (effectively the wealth of the farmer) and the level of TE achieved. Khai and Yabe's correlation is used to determine the farmer's TE when the model is initiated. This is a simplification which was made for expediency, which results in larger farms beginning the simulation with higher TE. There are likely several variables affecting farm TE through complex relationships, but the nature of these relationships is not well understood not the subject of this investigation.

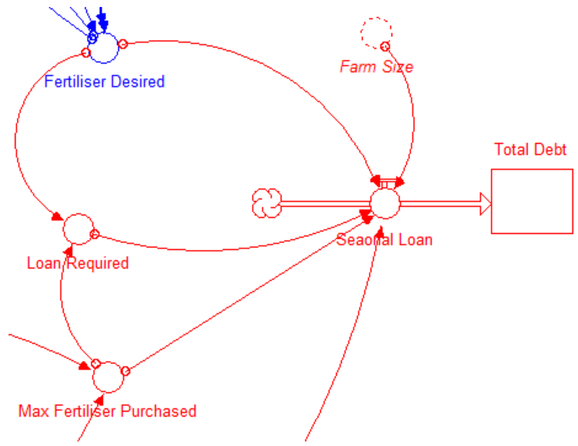


Figure 6.10 Graphic representation of the loan system in the system dynamics model.

Since wealthier farmers operate both higher base TE, and can afford greater technological capacity, strong returns to scale would be expected within the agricultural sector in the region. Indeed, Diep (2013) describes an increasing trend in the returns to scale between 1998 and 2010, i.e. large-scale farming operations are gaining an increasing efficiency and profitability advantage over small scale operations. However, the dynamics of this relationship are subject to later investigation, as the analysis in **Chapter 5** suggested this may in fact be a result of the switch from double to triple cropping, which favours larger farms.

The final component of the economic module is the debt system. A crude debt accumulator operates in this model (**Figure 6.10**). Simply, after other costs have been accounted for, if the farmer does not have the funds to purchase the quantity of fertiliser they believe they require, they still obtain the fertiliser, but its value accrues to their debt stock. The objective of this model is not to go in-depth into the systems of micro-credit and social lending operating in VMD agriculture, but rather to facilitate comparison between the impacts of the different policies tested on the debt accrued by the farmer. As such, the stock "Total Debt" is more of an indicator of the stress the farmer's system is under than an operational debt system; stress which would either force farmers into debt, or reduce their household expenditure to below the poverty line.

6.4.5.2 The decision-making module

The decision-making module proved both the hardest to model, and the module for which most difficulty was encountered sourcing data and evidence to substantiate the parameters. This issue arises again in the post-construction parameter assessment. The aim of the module is to simulate the mental processes which ultimately determine the quantity of fertiliser applied by the farmer.

In summary, five key processes were constructed in the model (**Figure 6.11**):

First, is the farmer's yield target. It was assumed that most farmers will have a target yield they wish to obtain and, in the knowledge that additional fertilisation can increase yields, they will incrementally increase fertilisation until they meet this target.

Second, is the tradition component. Most farmers have a long memory of what yields they have achieved in the past, knowing what it is possible to achieve, it was assumed that they will use additional fertilisation as one mechanism to compensate should yields, for whatever reason, fall below traditional totals.

Thirdly, the price effect. The current price of fertiliser, in relation to the farmer's income (rice price), will affect the farmers disposition towards increasing their fertilisation. High costs will dissuade farmers from fertilisation and vice-versa.

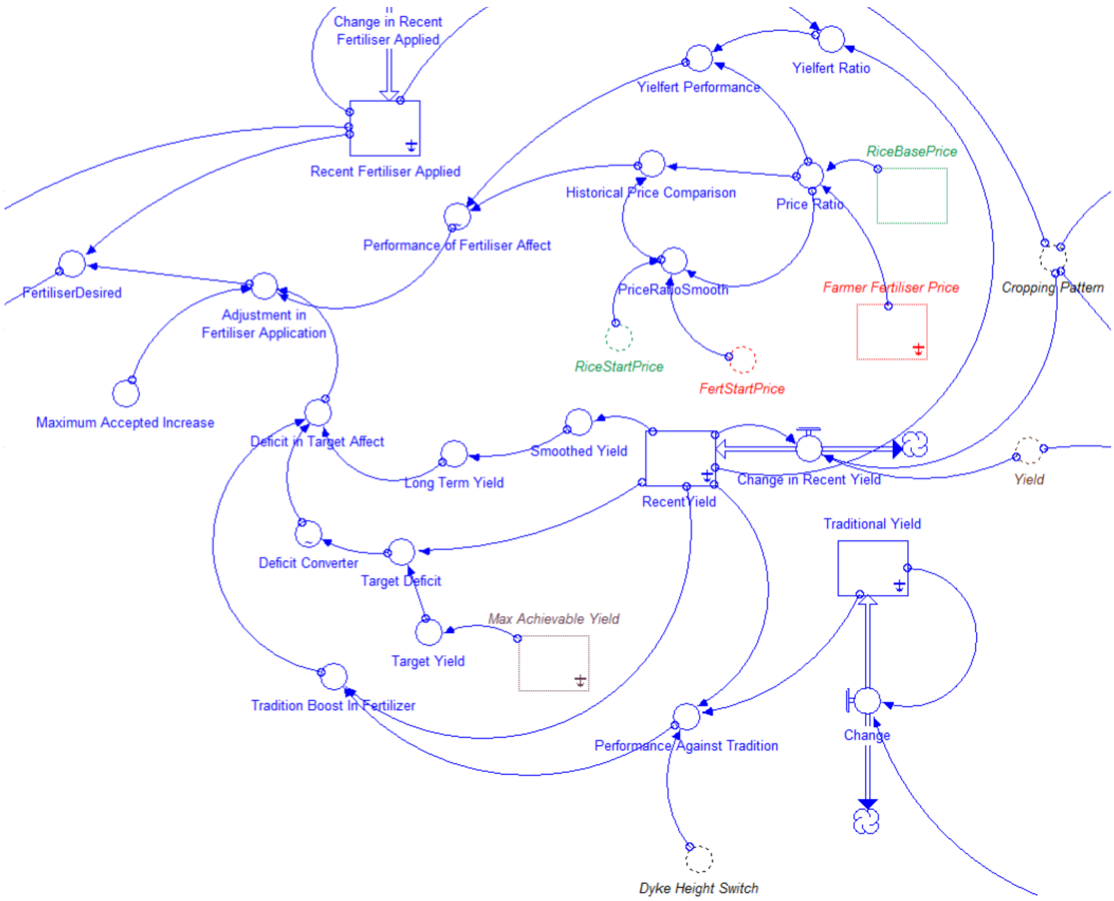


Figure 6.11 Graphic representation of the decision making module of the system dynamics model.

Fourthly, the economic performance of fertiliser was accounted for. Farmers' memories of recent practises will allow them a crude appreciation of the relative returns they are receiving from their level, or change in level, of fertilisation. At higher levels of yield the relative performance of additional fertiliser will decline, and this must be accounted for to prevent the model simulating irrationally high levels of fertilisation.

Finally, the sediment effect. Farmers are aware of the nutrients brought by deposited fluvial sediment and hence, in years of deposition, they will reduce their own fertilisation in order to save on unnecessary costs. To a certain degree, farmers even distinguish between years of proportionally higher and lower deposition and reflect this in their fertiliser application rates.

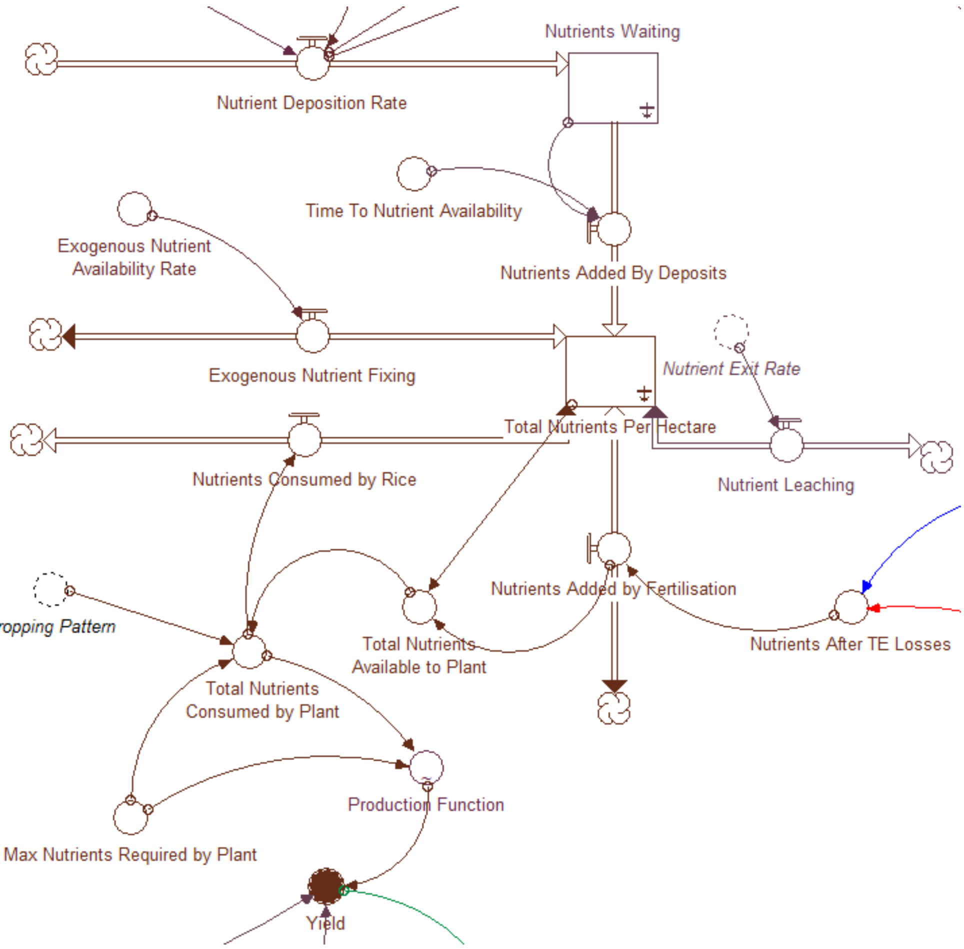


Figure 6.12 Graphic representation of the physical module of the system dynamics model.

6.4.5.3 The physical module

A final level of fertilisation is determined by the above processes, that level is then tempered by the TE level the farmer is operating at (e.g. 80%), what remains feeds into the physical module. The key stock around which the physical module operates is the nutrient content of the farmer's paddy (**Figure 6.12**). Feeding into that stock are the fertilisation applied (after TE losses), the sediment-bound nutrient deposits, and what is considered exogenous nutrient fixation (for the purposes of this model this constitutes all fixation not resulting from sediment deposition or artificial fertiliser application). Feeding out of the paddy's nutrient stock are the nutrients taken up by the crop, and the nutrients that leach away (which accounts for the vast majority of any over-fertilisation by the farmer). The quantity of nutrients contributed by sediment deposits is subject to three factors (**Figure 6.13**): the cropping pattern determines whether deposition takes place at all, and the rate of upstream dam trapping may reduce the quantity of nutrients available for deposition, and finally a delay is built into the model between the deposition event taking place and all of the nutrients deposited becoming available for uptake by the crop. Work by Tsheboeng et al. (2014) suggests a period of time passes before all of the nutrients deposited by the sediment are fixed into a format accessible to the plant, however, this is an area in which research is lacking.

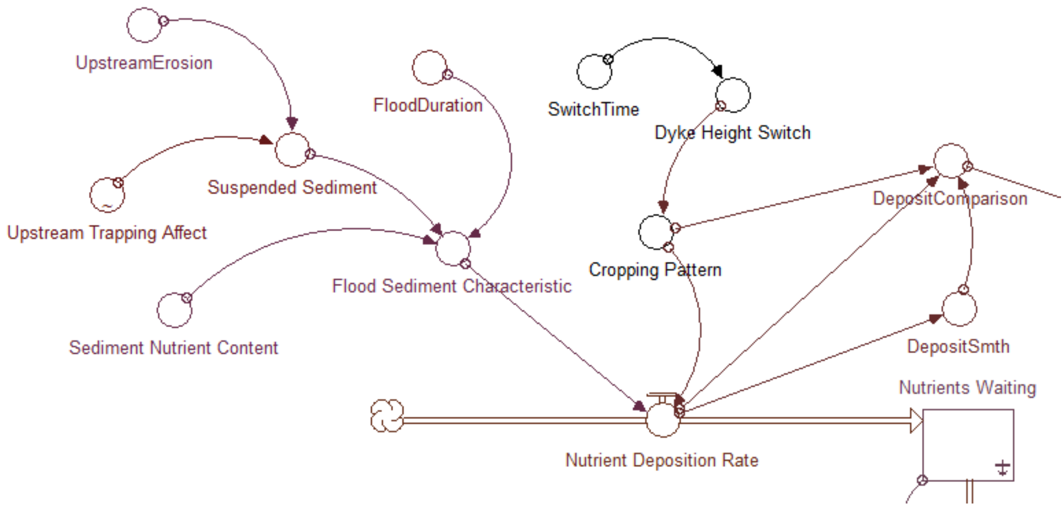


Figure 6.13 Graphic representation of the physical inputs to the system dynamics model.

With the level of nutrients available to the crop determined, the final step is for this to be converted into a yield level. The yield of the crop is simply determined by the production function for irrigated rice, which is a well-researched area. However, some variability is applied to the value produced by the production function, based on data recorded by the General Statistic Office of Vietnam (GSO, 2014) to replicate the exogenous variables, primarily weather related, which affect yield. Finally, an annual 1% rate of increase is applied to the yield attainable via the production function to simulate advancements in rice seed variety which are driving yields globally, again, a well-researched area. The final yield total is then multiplied by the current rice price and enters the economic module as income.

6.5 Evaluating the model

Multiple avenues are available to researchers wishing to evaluate their system dynamics models. These range from personal, expert, and stakeholder judgement, to extreme behaviour testing and statistical comparisons with real-world data. These evaluation techniques can be applied not just on completion of the model (as in the case of most predictive models), but during the construction process itself. The data informing the model parameters may come from a varied selection of primary and secondary sources, and in many cases those sources will already have been validated, in which case they can be evaluated for their reliability during the process of model construction. This section reports first on the parameter assessment conducted and second on the results of the statistical validation by comparison with real-world data collected in the survey reported on in Chapter 5. In the subsequent section, **6.6**, the model's sensitivity is analysed.

6.5.1 Parameter assessment

Tables 6.4 and **6.5** show the reliability scores of the sources informing each parameter relationship within the model. Overall, the sources which guided the construction of the model scored well for transferability of location (for example, studies within the Mekong Delta were often found), and well on the transferability of spatial scale (studies were conducted at a similar, regional/provincial scale), but poorly for the quantity of studies (in many cases only one or two studies were available and their scope was limited) and the statistical confidence (many studies were not forthcoming with the statistical confidence in the relationships they described). The process of evaluating confidence in data sources identified five parameters against which there was notably greater uncertainty (scoring one standard deviation below the mean or more). The parameter relationships identified were those representing: fertiliser price rate of change (%/season), the farmer's desire to invest for the future (%/season), the fraction of the farmer's income kept as contingency (%/season), the time from sediment-bound nutrient deposition to availability for plant uptake (seasons), and the rate of depreciation of farming technology investments (%/season). These are highlighted in **Tables 6.4** and **6.5**. The key parameters in these relationships were brought forward for sensitivity analysis.

6.5.2 Two crop validation

In the two-crop simulation in **Figure 6.14** the mean value of the model outputs is offset from the reported data by 0.95 ± 0.58 t/t , which amounts to a relative error (RE) of 5.3% ($p<0.001$ *(i)* and $R^2 = 0.020$). However, the rates of change are offset by only 0.001 ± 0.023, with RE of 0.1%, with a p-value of greater than 0.999 *(ii)* and an R^2 of -0.001, which both suggest the two datasets are highly similar in terms of their dynamics.

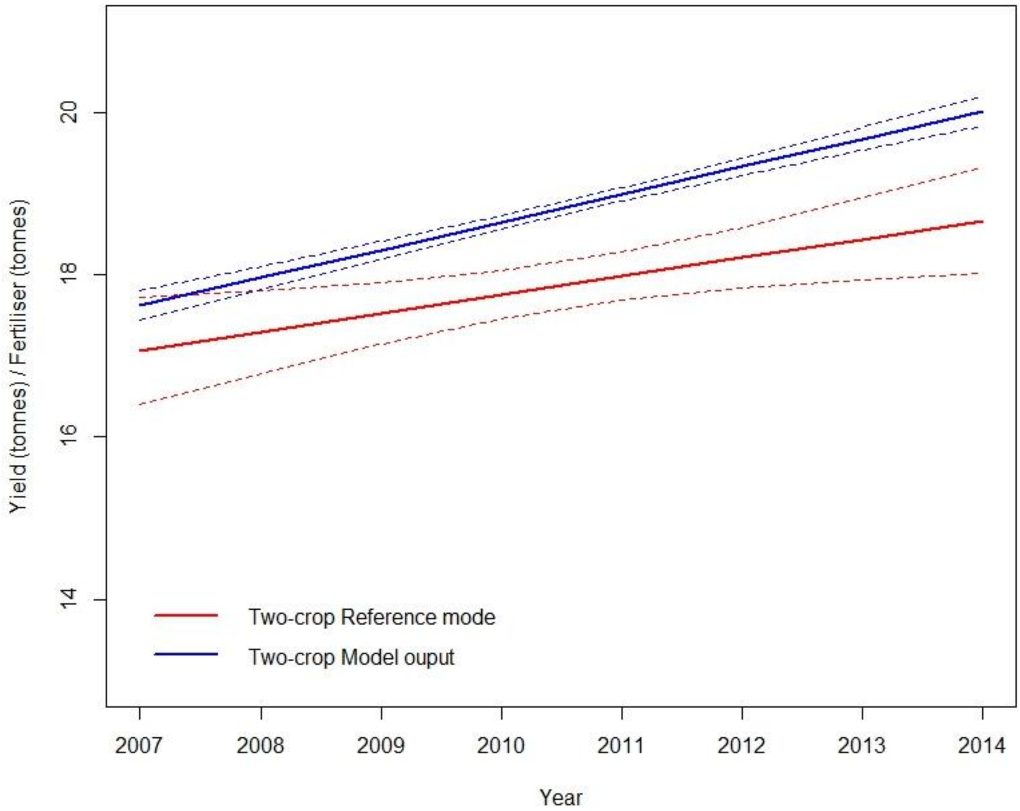


Figure 6.14 Regression models (GLM) performed on the data reported by farmers operating a two-crop system (red), and the model outputs under the same conditions (blue).

6.5.3 Change of system

Figure 6.15 compares the period of the model during which the shift from two to three-crop farming took place against those farmers who had undergone the same process in the field. With regard to the mean value of the data the model outputs hold a systematic error of 1.14 ± 1.00 t/t, RE = 6.3% (p=0.013 *(i)* and R^2 =0.023) and the rate of change was offset by 0.039 ± 0.039 (RE = 3.9%) with a R^2 of 0.012 and a p-value of 0.058 *(ii)*. Such a p-value would commonly be treated as a borderline case for declaring the two datasets significantly different.

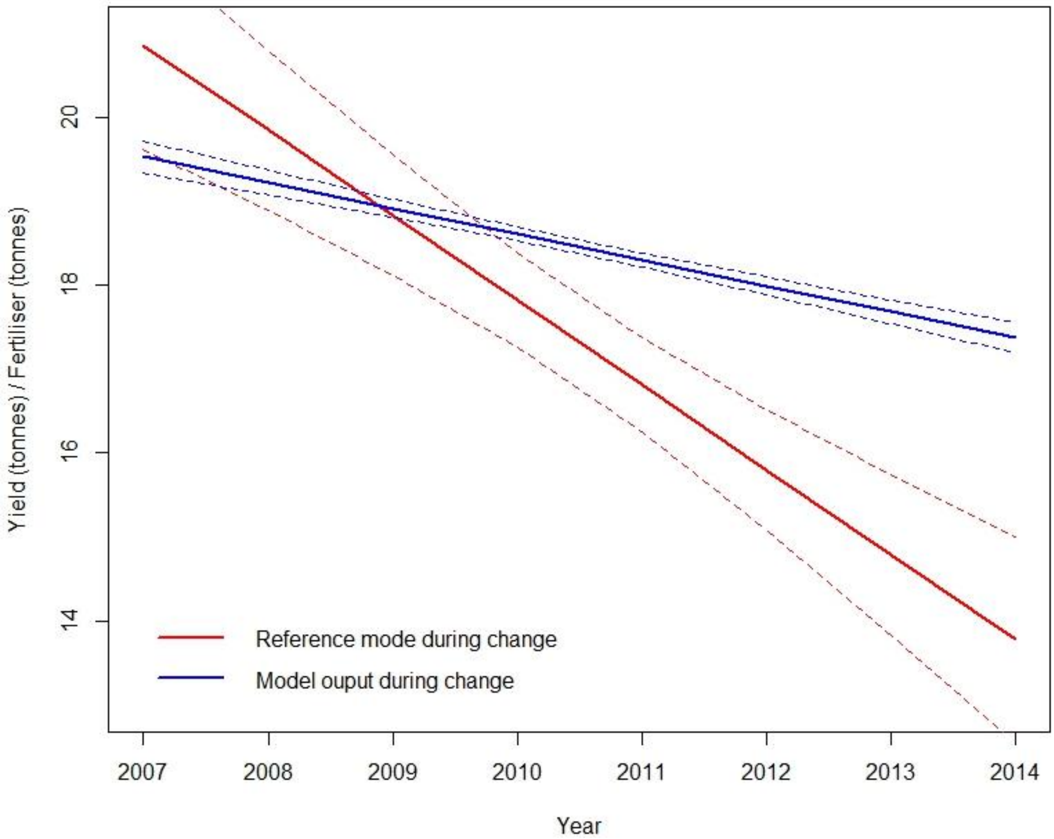


Figure 6.15 Regression models (GLM) of the data reported by farmers who experienced a change of cropping system during the reporting period (red), and produced by the model under the same conditions (blue).

6.5.4 Three crop validation

Finally **Figure 6.16** depicts the regression models of farmers fully under the triple-cropping system. The model carries a mean systematic error of -1.36 ± 0.70, RE = 7.3% ($p<0.001$ and $R^2 =0.031$). Once again the model has a smaller offset against the mean rate of change of 0.019 ± 0.028, with a RE of 1.9%, the p-value of 0.354 would usually be insufficient evidence to declare the datasets different. The R^2 value of 0.005 also suggests low level of variance between the reported and modelled data.

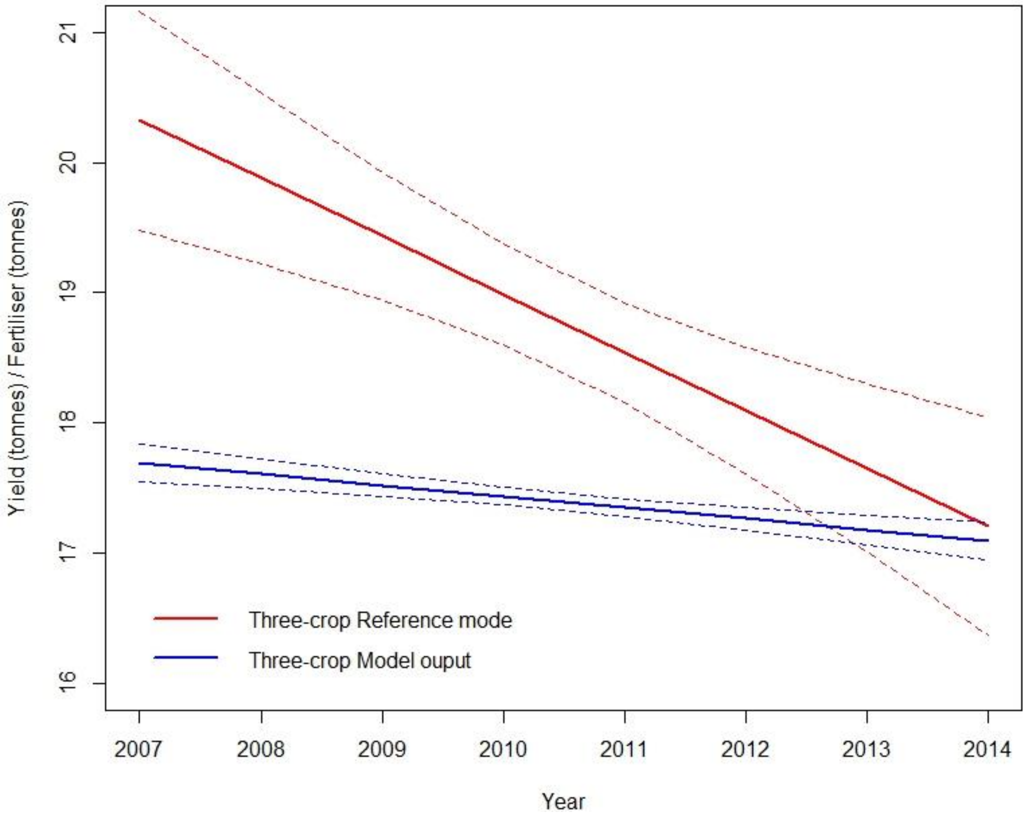


Figure 6.16 Regression models (GLM) of the data reported by farmers who were operating a triple-cropping system (red), and the modelled data produced by the same conditions (blue).

6.5.5 Model performance

Table 6.6 summarises the results reported above. One conclusion that can be drawn from these results is that the model is a poor tool for predicting the precise value of the *Yielfert* that the farmer will achieve, with a statistically significant systematic error (offset) in all three cases.

Table 6.6 A summary of the results of the statistical tests used to validate the model outputs against the farmer-reported data. SE = systematic error, RE = relative error.

Cropping category	Absolute *Yielfert* values				Rate of change of *Yielfert*			
	SE (t/t)	SE P-value	RE (%)	R^2	SE (t/t/yr)	SE P-value	RE (%)	R^2
Two	0.95 ± 0.58	<0.001	5.3	0.020	0.001 ± 0.023	0.999	0.1	-0.001
Chng	1.14 ± 1.00	0.013	6.3	0.023	0.039 ± 0.039	0.058	3.9	0.012
Three	-1.36 ± 0.70	<0.001	7.3	0.031	0.019 ± 0.028	0.354	1.9	0.005

The objective of any System Dynamics model is to simulate the behaviour of a system, and the causes of that behaviour, rather than to forecast values. In none of the three time slices can the differences in *rates of change* between the model and the reported data be classed as significantly different (under traditional assumptions that $P<0.05$ constitutes the threshold), suggesting the model is capable of simulating the system's dynamics. Indeed, the RE values reported, even in regard to the mean values, are within the region of RE values deemed acceptable in other SDM studies (e.g. He et al., 2015; Liu et al., 2015; Zhang et al., 2008c; Kato, 2005; Guo et al., 2001) and in some cases lower (e.g. Wang et al., 2014). In **Figures 6.15** and **6.16** it can be seen that the farmers were reporting more dramatic declines than the model simulated. While it is possible that this is due to inadequacies in the model's design, it may also be due to some of the biases influencing the farmer-reported data, as discussed in **Section 5.5**. Particularly, the model's underestimation of declining *Yielfert* trends would fit with there being a negativity bias in the farmers' reporting. In any case, the implications of this underestimate for the policy analysis conducted in **Chapter 7** are discussed.

6.5.6 *Yielfert* vs farm size

One of the key trends found in the farmer reported data that was described in **Chapter 5** is the relationship between the *Yielfert* ratio achieved and the size of the farm operated by the farmer (a proxy for the farmer's wealth). A distinct difference was found between the two-crop areas and the three. In the case of two crop farming, greater farm size was found to disadvantage farmers in the *Yielfert* ratio they achieved, under the three-crop system greater farm size was found to be a significant advantage. Testing whether the model replicates this relationship is one method of further validating the model's ability to simulate dynamics and, if the model is capable of simulating this trend, it may help us understand the dynamics causing it.

Monte-Carlo simulations (100 repetitions) were performed at farm sizes increasing incrementally from 0.75ha to 4ha in both the three, and two-crop models. In each simulation, the *Yielfert* value was recorded shortly after policy implementation, at a static time slice in the simulation equivalent to the mean year at which farmers reported the *Yielfert* data in the field (step 60). A linear regression model was then built between farm size and *Yielfert* for each cropping pattern, producing **Figure 6.17**.

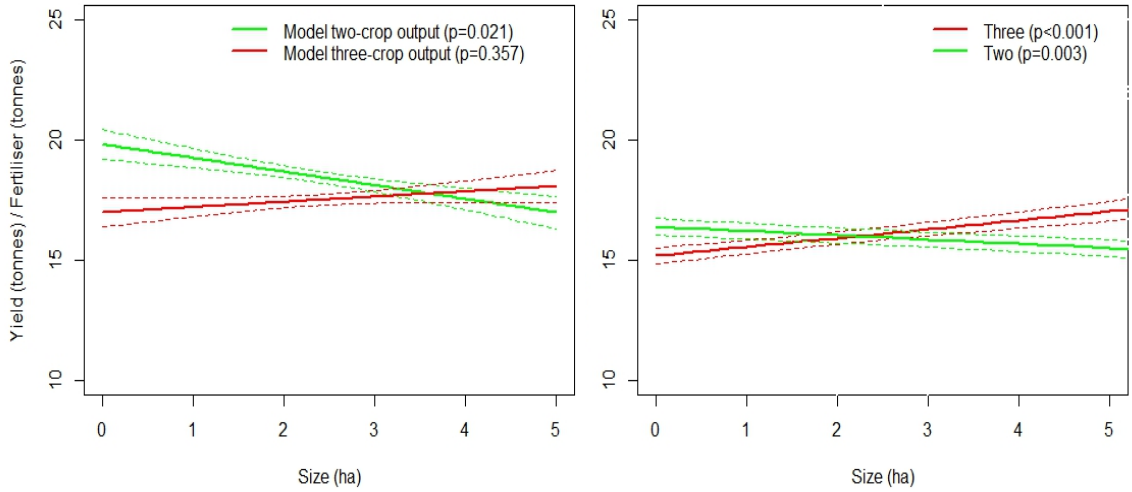


Figure 6.17 Left, linear regression lines built around the output of 100 Monte-Carlo-style model runs from the two and three-crop models at time step 60. Right, linear regression lines plotted through the farmer reported data.

Visual examination of **Figure 6.17** indicates the model is in agreement with the reported data with regard to the directions of change. However, when the same process is applied to the data with the temporal restriction removed (i.e. including data from all of the simulated time steps), these trends are somewhat ironed out. **Figure 6.18** suggests that over the wider time-frame of the whole simulation period the distinction between the three and two-crop systems in terms of *Yielfert* efficiency is less clear-cut. A statistically significant (p=0.028) increasing trend is found in triple-cropping areas (still in-line with the survey data) but, no trend is significant in the double-cropping areas (p=0.372). As a failure to disprove the null hypothesis does not prove the hypothesis, this evidence cannot be used to substantiate the survey's findings. As farm size is a time-independent variable in the model the difference between the temporally restricted model (**Figure 6.17**) and the temporally unrestricted model (**Figure 6.18**) suggests the relationship is being affected by a third variable (or several variables) containing temporal variability and affecting the system around the time of the cropping pattern switch. One candidate would be the role of sediment in the system, which is making a key transition during the period covered by **Figure 6.17**. This is subject to further investigation in **Chapter 7**.

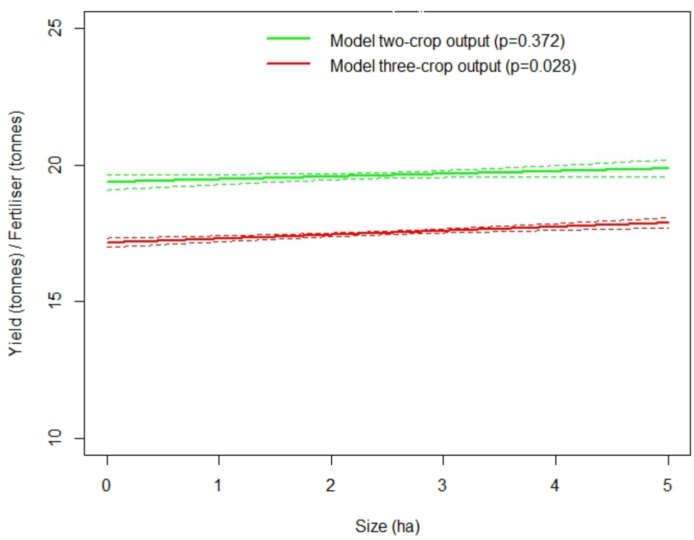


Figure 6.18 The output of 100 Monte-Carlo style model runs from the two and three-crop models. The regression lines have been drawn through the data produced across all time-steps.

6.6 Model sensitivity

In the following section the model's sensitivity to variation in the model parameters is tested. The parameters tested are those established in **Section 6.4.2.2** as having the weakest evidence base. Sensitivity analysis is conducted according to the method set out by Guo et al. (2001) and Zhang et al. (2008c) in similar environmental management/system dynamics modelling contexts and outlined in **section 6.3.3.3**.

6.6.1 Sensitivity analysis

The five parameters established as requiring further examination in **Section 6.4.2.2** were altered four times in either the positive or negative direction in increments of 10%. Observations of the system were taken at each parameter level and at four intervals during the period (after model spin-up) over which policies are being tested (time steps 53, 73, 93, and 113), totalling 16 observations of each parameter. The impacts of these alterations to the model's parameters were measured through observation of four outputs. Those outputs were selected for their importance to the policy questions being asked, and because they operate in different sectors of the model, they were: the level of fertilisation desired by the farmer (DF); the rice yield achieved (RY), the cash profits obtained by the farmer (CP), and the level of technical efficiency the farmer operated at (TE). For purposes of clarity the normally-distributed random variation usually applied to the model was switched off, and testing was conducted with the model set up to switch to the triple-cropping system at the start of the analysis period (time steps 54-113).

The value of S_Q was calculated for each time point and under each level of alteration (± 10, 20, 30, or 40%). In **Table 6.7** S_Q has then been averaged across all time steps and levels of alteration to calculate the general sensitivity degree (GS_Q) of each output, against each parameter (the raw un-averaged data can be found in **Appendix 9.8**).

Table 6.7 A summary of the general degrees of sensitivity, GS_Q, between five parameters and four output variables: desired level of fertilisation (DF); rice yield (RY); cash profit (CP; and technical efficiency (TE). Values greater than 0.1 are outlined in bold.

	Indicator			
Parameter	**DF**	**RY**	**CP**	**TE**
Fertiliser price rate of change	**0.085**	**0.011**	**0.648**	**0.048**
Farmer's desire to invest	**0.035**	**0.003**	**0.115**	**0.034**
Farmer's backup fund fraction	**0.008**	**0.002**	**0.001**	**0.006**
Time to nutrient availability	**0.015**	**0.000**	**0.017**	**0.003**
Technological depreciation rate	**0.051**	**0.008**	**0.004**	**0.044**

Table 6.7 shows that in all bar two cases the GS_Q value was less than 10%, implying low sensitivity. Such sensitivity levels are similar to those deemed acceptable in other SDM studies (e.g. Wei et al., 2012; Zhang et al., 2008c; Guo et al., 2001), or indeed slightly lower (He et al., 2015). Of the two cases highlighted in **Table 6.7**, one relationship stands out as being notably influential, that is, the impact of the rate of change of fertiliser price on the farmer's cash profit. **Table 6.8** breaks down GS_Q into the 16 S_Q values from which it was averaged.

Table 6.8 A breakdown of the sensitivity degrees (S_Q) representing the fertiliser price parameter's influence on farmer cash profit as the level of parameter alteration increases and recorded at different time steps in the simulation.

	Time step			
Change in parameter level	**53**	**73**	**93**	**113**
-10%	**0.064**	**0.422**	**0.918**	**1.714**
-20%	**0.062**	**0.466**	**0.906**	**1.384**
-30%	**0.060**	**0.836**	**0.719**	**0.988**
-40%	**0.059**	**0.669**	**0.673**	**0.912**

From **Table 6.8** it can be seen that the influence of changes in the parameter representing fertiliser price increase grows as the simulation progresses, such that by the end of the simulation its influence is especially high (in two cases greater than 1). **Figure 6.19** shows this progression over time for a fixed level of parameter alteration (-10%).

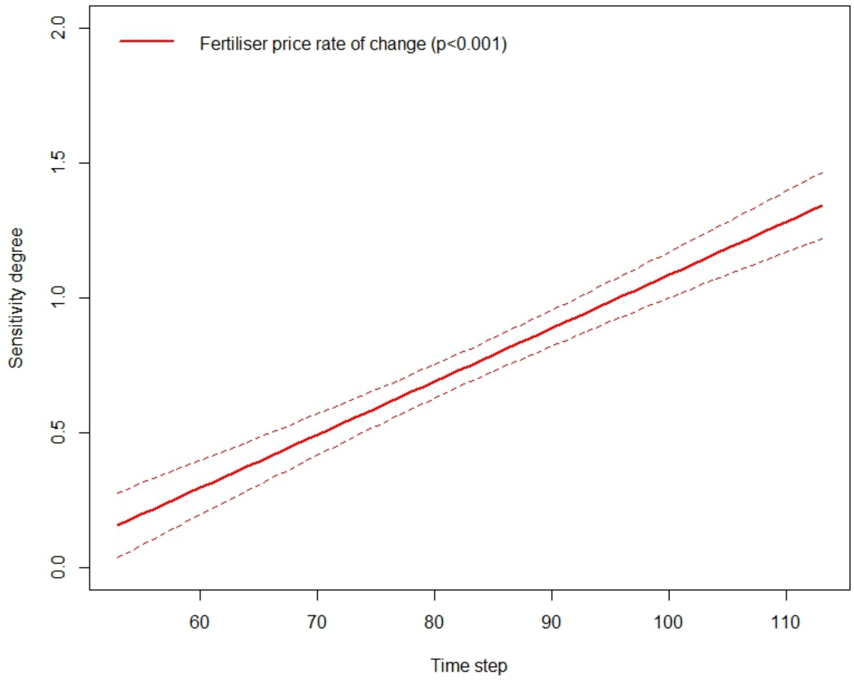


Figure 6.19 The output of a general linear regression model (GLM) performed on the sensitivity data produced by a 10% reduction to the fertiliser change rate. The graph shows how the sensitivity increases over time. Standard error lines are shown by dotted lines.

In practical term this means that changes in the price of fertiliser have an especially strong influence over the farmer's economic success, which grows over time. If this high sensitivity were down to an error in the model structure then reformulation of the model would be required. However, this behaviour is believable, i.e. it fits with the verbal evidence reported by farmers in the field. For instance, farmer no. 13 (survey data) commented that the loss of sediment caused by high dykes was an issue because "the price of farm products is not stable", and other similar comments were common. As such, the alternative, and accepted, assumption to be made from the model's sensitivity to fertiliser prices is that the finding is in fact an insight into the system rather than an error in the model's design. Indeed, this sensitivity to fertiliser prices may be a clue as to a positive feedback loop, or threshold, in the system. For instance, in **Table 6.8** we see that for greater levels of parameter alteration the proportional impact of the change reduces. This phenomenon suggests that the relationship between (CP) and the fertiliser price rate of change is not linear, and is controlled by other parameters in the model. The dynamics of fertiliser prices and their interactions with other model parameters are explored further in **Chapter 7**.

Establishing this high degree of sensitivity increases the importance of estimating the parameter representing future fertiliser price change accurately. Unfortunately, it is unlikely that this will be possible. Speculation on the future prices of commodities is a notoriously difficult exercise, and while data on past changes is available, making accurate future predictions would be an extremely challenging task. This finding has an influence on the applicability of any results presented in **Chapter 7**, and suggests, perhaps, that they should be approached with some caution. However, one step was taken to account for this uncertainty. The level of fertiliser price is one of the components that is subject to normally distributed random variation throughout the model, restricted by a standard deviation extracted from the World Bank's (2014) records on global fertiliser prices.

6.7 Discussion on the model construction process

The final model, even prior to policy analysis, provides some interesting insights into the dynamics of the double to triple cropping shift. The model agreed with the survey results in predicting that under double-cropping there would, at least initially, be an improving *Yielfert* ratio. Early exploration of the model suggests the causation of this trend lies in three key factors: the improvements seen in the farmer's technical efficiency as they invest in technological and education based improvements; the yield gains they receive from the slow introduction of higher yielding rice varieties; and because farmers are dissuaded from over-fertilisation by the increasing price of fertiliser. However, this is explored further in **Chapter 7**. Following the cropping pattern shift the model agrees with the farmer reported data in predicting that the *Yielfert* ratio begins to decline. Two intrinsically linked factors drive this decline: the loss of the free sediment-bound nutrients and with this the desire of the farmer to maintain yields at past levels without those nutrients; and the greater exposure to variable fertiliser prices due to the increased fertiliser application burden.

The sensitivity analysis has highlighted the importance of fertiliser prices in determining the success of the system as measured by some key indicators. Fertiliser prices will increase regardless of which cropping pattern is followed however, the sensitivity analysis also revealed that the influence of fertiliser prices over the model grows as time passes. Indeed, towards the end of the simulation the influence of a fertiliser price change on the model is proportionately greater than the change itself. This indicates that fertiliser prices are part of a reinforcing feedback loop within the system which becomes more dominant as time progresses; hence, fertiliser prices will need to be given special attention in the policy analysis.

6.8 Conclusions from the model construction process

A functional system dynamics model has been constructed. While the model has a systematic error affecting the absolute values it predicts, it performs well in simulating observed behaviours of the system. The process of evaluating the model has itself provided some insights. In some areas, a dearth of evidence informing the relationships in the model points to the need for further research. A particular gap was found in the knowledge about the processes translating deposited deltaic sediment bound nutrients into crop yield gains, and the decision making processes which define a farmers socioeconomic operations also proved challenging to model. However, these areas were not found to be key sensitivities of the model constructed. A key area of sensitivity was found in the model in terms of the response of farmers' profits to variability in the rate of fertiliser price change. Uncertainty in the parameters representing fertiliser prices and their rates of change was high, but a greater level of certainty would have been difficult to establish due to the challenges associated with forecasting global market movements. Instead, the high sensitivity of the farmer's economic prosperity to fertiliser prices was treated as an insight into the functioning of the system worthy of further investigation through the analysis of policy scenarios conducted in **Chapter 7**. Furthermore, farmer sensitivity to fertiliser price changes was reported by farmers in the field during the survey conducted in **Chapter 5** meaning this finding functions as a further post-hoc validation of the model. Exploration of the adaptation and different second-order policies proceeds in **Chapter 7** with due regard to the weaker areas of the model identified herein.

Chapter 7: Trajectories of Change and System Dynamics under the Influence of the Adaptation Part II: Policies and Scenarios

7.1 Chapter introduction

7.1.1 Chapter aim

With a functional system dynamics model constructed and substantiated in **Chapter 6**, **Chapter 7** presents its utilisation for the evaluation of the VMD dyke network as an adaptation. The model aims to investigate the causation of negative socioeconomic trends associated with the adaptation of the VMD dyke network in **Chapter 5** and to analyse the system dynamics of the system under a set of government policies and physical scenarios of sediment supply change. The key variables which drive changes in the dynamics of various indicators of system performance under different policies are sought; and, further, the comparative desirability of those policies, when scored against the objectives of different stakeholders, is explored.

This chapter is structured as follows: it begins by reviewing the methods integrated, System Dynamics Modelling (SDM) and Multi-Criteria Decision Analysis (MCDA); subsequently, the scenarios of physical change and land management policies (second-order adaptations) to be tested are outlined; the results of the model policy simulation are then presented in the form of a narrative description of the key dynamics controlling each scenario/policy combination; and finally, the various policy/scenario combinations are weighted and ranked for desirability based on the various objectives for the system of different stakeholders which were distilled in **Chapter 4.**

This evaluation of first and second-order adaptation policies and their comparative preferentiality has two particular foci, based on the findings of previous chapters. First, following findings in **Chapter 5** that the triple-cropping system may be exacerbating wealth inequality, this chapter examines the implications of different policies for farmers in three different wealth classes and investigates the role of sediment in local wealth inequality. This inequality focus was additionally prompted by the existing literature which has identified the ability of wealth inequality to reduce society’s resilience to environmental change, e.g. Szabo et al. (2015). Second, the implications of different scenarios of sediment flux decline for policy in the delta are discussed. This second focus is driven by three factors: the potential for dramatic changes in sediment delivery to the delta due to climate change and particularly dam construction (e.g. Kondolf et al., 2014); the current oversight of sediment issues in local policy that was identified in **Chapter 4**; and sediment's role in agricultural productivity and profitability - as highlighted by the survey in **Chapter 5**.

7.2 Reviewing policy comparison methods

This section introduces the hybrid SDM and MCDA methodology which is used first to explore the dynamics of the deltaic rice-sediment system, and then to analyse and provide greater significance to the policies tested. This section briefly: describes the processes involved in MCDA; outlines and evaluates recent developments in the integration of MCDA with SDM; and describes the particular MCDA technique that is utilised in this thesis.

7.2.1 Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis (MCDA) is a methodology well-established in both the academic (particularly environmental management) and policy literature. MCDA is used to evaluate policy decisions in social-ecological systems, such as the Mekong Delta, that are subject to multiple and contrasting stakeholder needs (Kiker et al., 2005). The methodology can be linked to the recognition among modern scientists that most decisions taken in the research process are to some degree normative and therefore, for science to inform policy, two key questions must be addressed, as described by Munda (2004):

*"…to reach a ranking of policy options, there is a previous need for deciding about **what is important for different social actors** as well as **what is relevant for the representation of the real-world entity described**…"* (p. 663)

The broad decision making methodology of MCDA can be divided into a number of sub-methods, the choice of which is dependent on the context and goals of the project, see **Figure 7.1**. All of the tools in **Figure 7.1** aid policy makers with nuanced policy decisions but the tools vary in the degree to which they actively prescribe a preferential policy option. The common case in which a finite number of policy alternatives with commensurable (can be traded between) traits are to be ranked is commonly described as Multi-Attribute Decision Making (MADM), a sub-category of MCDA (Tompkins, 2003).

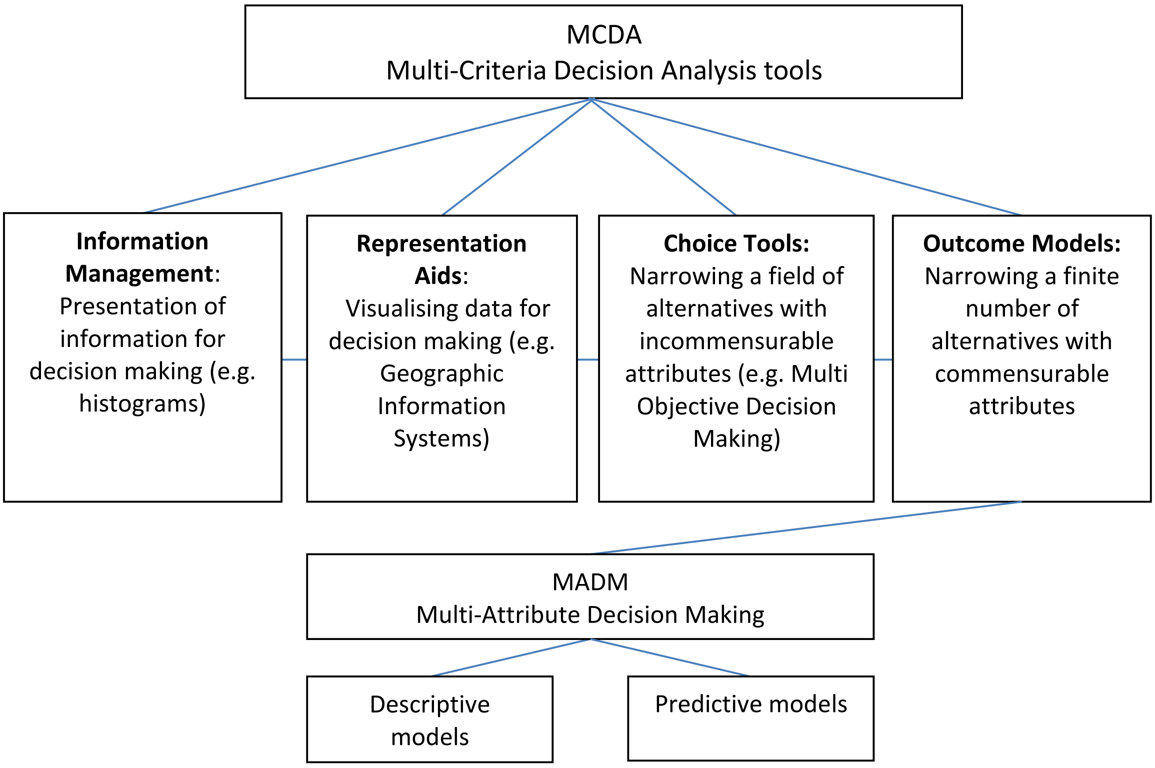


Figure 7.1 Classifying different MCDA support tools, adapted from Tompkins (2003).

The MADM methodology has traditionally been used to address conservation and development conflicts (e.g. Van Huylenbroeck, 1995; Bodini and Giavelli, 1992) and specialises in establishing societal priorities from heterogeneous information on what are now commonly termed ecosystem services (Kiker et al., 2005). The MADM methodology has emerged as a direct alternative to economic cost-benefit analysis (CBA), which has traditionally informed policy decisions (Joubert et al., 1997). MADM has gained popularity in light of a number of concerns about CBA, particularly its inability (at least in its traditional financial form) to account for (both positive and negative) attributes that are difficult to put in monetary terms. In environmental contexts such attributes are termed *externalities* (e.g. air pollution), and there has been considerable discussion of the inadequacies of the economic techniques developed to integrate those externalities into CBA (Wegner and Pascual, 2011). Indeed, pertinent to this thesis, is the fact that such critiques of CBA have been used against its application to the evaluation of dams, entities with a potentially high number of externalities (Doyle et al., 2003; Rosenthal and Nelson, 1992). Often, difficulties arise when trying to capture the values of the public with regard to an environmental service, especially those services with a somewhat intangible or unquantifiable link to society, such as existence value (Fisher et al., 2009). Another broader concern is whether heavy reliance on CBA for decision making encourages equity and sustainability in societies, particularly whether a decision is always ethically right because the calculated costs outweigh the benefits (Atkinson and Mourato, 2008). Particularly, as Krutilla (2005) identifies, the use of the net CBA output for decision making overlooks what may be an uneven distribution of gains and losses within the system. Krutilla addresses this issue with the Kaldor-Hicks Tableau, which effectively sums the costs and benefits accrued by each individual actor/stakeholder within the system. While such mechanisms can ensure actors are financially compensated for losses they incur from a policy choice, again, this methodology tends to encourage the measuring of wellbeing through primarily financial mechanisms, at least in Krutilla's (2005) original form. Wegner and Pascual (2011) discuss a number of routes through which services of financial value to the poor might end up being undervalued in CBA; particularly, they discuss a phenomenon termed *resigned preferences* in which citizens who have consistently been deprived of a service are not able to place a representative economic value on it.

According to Joubert et al. (1997) theoretical advantages of MADM over CBA are that it involves ranking on an abstract (multi-dimensional) rather than monetary (one-dimensional) scale, and that, as a result, market valuation of environmental services is not required and MADM can focus on a wider range of trade-offs. Furthermore, MADM provides a systematic method of incorporating stakeholder preferences into an appraisal (Macharis et al., 2012), a function which is essential if the subjective nature of most human-environment research is recognised (Munda, 2004). Furthermore, the integration of stakeholder weightings as a fundamental part of the process ensures analysis of the distribution of a policy's impacts is an intrinsic step (Hermans and Ericson, 2007). A practical advantage of MADM is its suitability for stakeholder involvement. Specifically, CBA's primarily technical and quantitative approach, it might be argued, is not as strong as MADM's in terms of its ability to structure a problem and integrate all available sources of information, and indeed to do so in a transparent manner (Stagl, 2006).

However, MADM studies may employ stakeholder engagement to very varying extents, some (e.g. Makowski et al., 1996) prefer to focus on running model simulations of scenarios and developing quantitative decision aid methods for optimisation, the results of which can then be presented to stakeholders (predictive models). Others (e.g. Brown et al., 2001) prefer to integrate stakeholders throughout the process with a particular focus on ensuring that decision making stakeholders are fully informed of the functioning of the system when entering the process of determining their (potentially unconscious) weightings of indicators (descriptive models).

It is due to some of the advantages listed above that MADM was selected over CBA for this thesis. As outlined in **Chapter 4** the decision making context in the VMD is one of recent decentralisation, with power delegated to departments with reasonable technical competency but perhaps lacking in systemic understanding (as also identified in the MDP, 2013). MADM was seen as having a suitable level of accessibility in this context but also as a method allowing more systemic analysis than would be possible with CBA. Specifically, the difficulties which would be associated with attempting to monetise all of the benefits brought by the complex sediment system in the delta were sidestepped. For example, while the fertilisation benefits of sediment may be quantifiable, its contributions to mitigating flooding would be far harder to monetise in a CBA. The Mekong context is one of urgency (rapidly encroaching climate change impacts); at present major decisions are being made which will have fundamental impacts on the long-term integrity of the VMD both physically and in terms of the social-ecological system it supports. As such, the objective of incorporating a MADM element into this thesis was less to make profound advances in the theoretical field of MADM, and more to ensure the insights provided by the survey and model are useful rather than abstract. Adding meaning to the flooding/sediment/livelihood choice trade-offs modelled by exploring different stakeholder weightings, it was hoped, would help ensure the project outputs were easily translatable into policy. Finally, with policy objectives being captured which are so integral to human life within the study region, and the known challenges which poorer groups face coping with environmental change (e.g. Szabo et al., 2015), a method capable of placing greater emphasis on the distribution of policy impacts was desired.

The MADM approach is not without its critics. There are perhaps two fundamental issues which are often used to challenge the legitimacy of MADM studies (criticisms which may equally be levied against other trade-off analysis approaches). The first involves Arrow's impossibility theorem (Arrow, 1950). Kenneth Arrow challenged society's understanding of rationality when he posited that, when faced with three choices, the preferences of a group for one policy (A) against another (B) could not be assumed from knowledge about their preferences between A and C, and B and C. Such a conclusion fundamentally challenges the ranking systems used in MADM, which often make such an assumption (Franssen, 2005). MADM researchers have addressed this issue principally through the development of more nuanced decision aids (discussed further in **Section 7.2.2.5**) i.e. the mechanisms through which policy preferentiality is calculated. Aids such as the outranking method, consider policy performance more than just the sum of a number of component parts that does or does not outscore another. Instead they allow nuanced, often stakeholder defined, requirements. For example, a stakeholder might set a requirement that a policy score no worse in a set of criteria, and significantly better in one criterion for it to be deemed acceptable, thereby avoiding the need to be rigidly restricted by absolute aggregate scores (Greening and Bernow, 2004).

The second challenge faced by MADM is again one commonly faced in decision analysis (Howarth and Norgaard, 1993) and concerns the equity and sustainability of decisions made using the technique. In terms of the emphasis policy makers put on the needs of future generations versus the emphasis they put on existing generations (to whom they are held to account), many question whether the MADM approach encourages short-termism (Kunsch et al., 2007). The issue of short-termism is most clearly seen in the selection of a level of discount rate to scale the value of income in the future vs income in the present. The debates surrounding the selection of a discount rate in social-ecological evaluations are discussed further in **Section 7.3.3**.

Other more procedural challenges and risks faced in MADM include: double counting, in which different criteria bring the same benefit to society but are both weighted for that benefit; the dominant influence of weightings, which are unavoidably subjective and difficult to quantify, over the conclusions drawn from a MADM process; and finally risks of assumed relationships and causation, information users may assume that if one outcome takes place in one scenario then the conditions associated with that scenario are the root of causation when, in fact, without further exploration causation cannot be assumed (Dodgson et al., 2009). However, it might be argued that as the system dynamics approach (utilised herein) specifically aims to investigate causation rather than the forecasting of future system conditions it is particularly well placed to overcome the third of these issues (explored further in **Section 7.2.3**).

7.2.2 The Multi-Attribute Decision Making process

The core steps of MADM, as adapted from Dodgson et al. (2009), Guitouni and Martel (1998), and Olson (1996) include:

7.2.2.1 Establishing a set of governance objectives

This step is perhaps the most common point at which stakeholder stakeholder engagement is utilised. A variety of different engagement methods (e.g. focus groups or surveys) can be used with a variety of different stakeholders (e.g. decision makers or end users) to establish the governance objectives of the system in question. This will then set the targets against which each scenario's performance is measured in the *performance matrix* (a table cross-referencing scenarios, policy options, and policy performance ratings on single or multiple criteria). Commonly, the participants or researchers will also weight/rank the importance of the different objectives identified for the system, allowing the priorities of different stakeholders to be accounted for when each policy's score is aggregated. The extraction of stakeholder weights, however, is subject to the risks and challenges of collecting social data (as discussed in greater detail in **Chapter 5**).

7.2.2.2 Establishing criteria for measuring progress towards each objective

The criteria are the indicators which will be used to measure progress towards the objectives set in **7.2.2.1**, some may be straightforward and others may be highly technical. As the selection of the criteria/indicators of progress will influence the final outcomes of the project it may also be performed through stakeholder consultation but, ultimately, it is down to the researcher to decide an appropriate mechanism. The subjective nature of the indicator selection process is another debated and criticised area of the MADM process in much the same way the issue of indicator selection is debated within the resilience and vulnerability (of social-ecological systems) research fields as discussed in **Chapter 2**. However, as Dodgson et al. (2009) discuss, steps can be taken to mitigate such issues, particularly by accompanying a MADM with a sensitivity analysis outlining the dominance of the weightings over the final outputs.

7.2.2.3 Establishing a selection of possible policy scenarios

Policy scenarios are most commonly derived from real proposals for the system under study put forward by either governing institutions or other stakeholders. In this project there are three scenarios of physical change (sediment flow) associated with the exogenous influence of dam construction. Locally, however, there is limited control over these scenarios, with both physical processes (erosion) and politics taking place outside of Vietnamese borders (Grumbine et al., 2012). Additionally, there are a selection of locally controllable policies on the course of second-order adaptation action pursued which are introduced in **Section 7.3.2**.

7.2.2.4 Establishing each scenario's performance against each objective

Establishing scenario performance commonly involves use of either field observations or environmental modelling techniques to produce the desired information (e.g. Makowski et al., 1996). Each scenario's performance under each objective is measured using its selected indicator/s. If environmental modelling is utilised, model parameters must be manipulated in order to simulate the different policies being tested. The Monte Carlo technique (introduced in **Chapter 6**) is most commonly utilised when simulating scenarios and policies. Simulations are repeated multiple times with stochastic variation of exogenous driving variables where appropriate. Adding random variation to model inputs and performing multiple runs helps take account of the uncertainty present in social-ecological systems, and test the impacts of rarer extreme events on the chosen performance indicators. For instance, as discussed in **Chapter 2**, deltas can be subject to rare, but catastrophic, extreme environmental conditions and the severity of such events may mean they have significant influence over the preferentiality of different policies.

7.2.2.5 Aggregating each scenario's performance across all objectives

The unique step in the MADM process is the direct comparison/ranking of heterogeneous information from model outputs relating to different objectives which have usually been presented in a performance matrix. While on occasion a preferential policy will be clear on inspection (direct analysis) of the performance matrix, an aggregation procedure will often be required to combine the indicators of performance on different criteria into one total score for each policy.

A number of sub-methods have been proposed for this part of the process, sometimes referred to as Multi-Criteria Decision Aids (MCDAs). Each sub-method has situation specific pros and cons and there has been extensive discussion, debate, and review of the application of different sub-methods (see Mendoza and Martins, 2006). Polatidis et al. (2006) suggest some key factors influencing the decision between methods include: the number of indicators and policy alternatives being evaluated; the occurence of incommensurable traits; and how temporally dependent the indicators of performance are. A further, important, choice-determining factor can be the presence of co-dependent criteria (i.e. the situation where a certain level of B is only desirable if A is at a certain level). Some MCDAs can cope with this issue better than others (Dodgson et al., 2009). However, Guitoni and Martel (1998) claim that, for the sake of expediency, sub-method choice is often actually guided by the researcher's personal expertise rather than a thought out evaluation of the pros and cons of different sub-methods.

Below are summaries of some of the MCDAs drawn from Dodgson et al. (2009):

(i) *Linear additive models:* are perhaps the simplest of the MCDAs but also the most widely utilised and have a strong track record of informing robust policy. Linear additive models can be applied when the selection criteria are preferentially independent (i.e. one criteria cannot only be determined once another has been determined) and the MCDA tool itself is not required to provide an uncertainty estimate (this can be established in step **7.2.2.4**). The value of each of the criteria is simply multiplied by its weight, standardised against the values produced by the competing policies (e.g. on a scale out of 100), and finally the individual criteria scores are added together to give a total scenario performance score.

(ii) *The analytical hierarchy process:* is a development of (i) and similar in all but the method of determining the weight. In (i) weights are determined by independent investigations. In (ii) the weight of a criterion is determined only comparatively against another criterion. However, in this method Arrow's impossibility theorem poses particular problems as preferences for certain criteria are unavoidably determined from relationships between others.

(iii) *Outranking methods:* outranking is a newer concept which combines elements of (i) and (ii). A scenario must be comparatively better than another scenario in the majority of weighted criteria to outrank it but it must also not be comparatively worse than another scenario (when weighted independently) in any individual criteria to any extreme extent. In such a case, a scenario outranks the other. All scenarios are ranked against each other and an order of preference can be established based on scenarios' ability to outrank others. Problems arise because defining what an extreme extent (i.e. the extent of difference between indicators at which the conditions of outranking have been met) constitutes is often arbitrary.

(iv) *Multi-attribute theory*: perhaps the most complex of the MCDAs, multi-attribute theory involves the conversion of criteria scores to utility (U), which is frequently used in economics to represent the inherent value a decision maker looks to maximise when faced with a choice. The process of conversion is a complex one, first explored by Keeney and Raiffa (1993) but one which allows integration of uncertainty and co-dependent criteria. For an in-depth discussion of multi-attribute theory see Dodgson et al. (2009).

7.2.2.6 Establishing a preferential policy

In this final step the overall scores of the various scenarios can be compared with each other and the scenarios ranked. In most cases analysis will involve direct comparisons between numerical scores. However, in some more complex situations (particularly where the criteria are not independent) this step may be incorporated into the previous aggregation step.

Sensitivity analysis is now established as a key component of MADM and the establishing of a preferential policy (Dodgson et al., 2009; Butler et al., 1997). Practitioners of MADM commonly find the biggest sources of disagreement between stakeholders on the outputs of an MADM study are due to uncertainty in the judged or modelled performance of individual criteria in selected scenarios (Bojorquez-Tapia et al., 2005). One way for researchers to address this is to provide decision makers with a sensitivity analysis alongside the performance matrix which demonstrates the relative impact changes in individual criteria have on the ranking results and the final outcome. Alternatively, the researcher may perform multiple iterations of the model, exploring both different inputs and different weights simultaneously (Butler et al., 1997).

7.2.3 Further development with System Dynamics Modelling

Figure 7.1 divides the MADM process into (i) predictive and (ii) descriptive modelling approaches. System Dynamics Modelling can perform either of these functions when integrated into a wider MCDA framework, but the implications of the chosen pathway are significant. Considerable debate exists as to whether SDM can stand up to academic scrutiny as a predictive, quantitative, modelling technique but it is widely acceptable as a descriptive tool (Fraser et al., 2011).

The argument for use of SDM as a descriptive tool is straightforward. As previously discussed, coping with co-dependent criteria is a challenge to MADM. More broadly, MADM can be a very output-focused methodology which puts low emphasis on discovering internal, outcome determining, system processes (Mendoza and Prabhu, 2003; Santos et al., 2002). Focusing too heavily on individual indicators without understanding causative processes may give users unrealistic expectations about the way the system can be manipulated, and such relationships may not be illustrated by sensitivity analyses. Mendoza and Prabhu (2003) suggest that investigation of *"interactions, connections, linkages and relationships"* (p. 330) between indicators are of high importance for the long term sustainability of a policy choice made using MADM. In other words, a descriptive analysis of the system structure is required. Mendoza and Prabhu (2003) recommend the use of SDM for such a purpose due to its strengths in enhancing understanding of system structure, though their utilisation is primarily qualitative and focuses on visualisation of the system under inspection. Such approaches are relatively common, particularly in mediated modelling contexts (e.g. Rauschmayer and Wittmer, 2006; Stirling, 2006; Antunes et al., 2006; Mendoza and Prabhu, 2005). Santos et al. (2002) suggest that greater insights into functioning and causation can be gained from the use of quantitative SDM. Particularly, when dealing with issues such as non-linear system behaviour, which may not be appreciated through purely visual causal loop diagrams.

Other authors have utilised SDMs to run simulations and predict the outcomes of policy scenarios that feed directly into the MADM. A comprehensive framework, termed the Adaptive Control Methodology (ACM, see **Figure 7.2**) for such an approach was outlined by Brans et al. (1998). Brans et al.'s follow up case study (Kunsch et al., 2001) used the PROMETHEE MCDA tool and the STELLA system dynamics software package to construct, in an iterative manner, a model capable of managing socio-economic processes in a large business group. Despite the strengths the methodology demonstrated in simulating adaptive processes (Kunsch et al. 2001) it does not appear to have been validated in environmental change management contexts as yet. This is perhaps because there are criticisms of the ability of system dynamics models to forecast environmental conditions (Ford, 2010), as discussed in **Chapter 6**. ACM is however, a tool that has gained recognition as an option in a wider emerging field of research on adaptive and robust policy design (Hamarat et al., 2013; Walker et al., 2001).

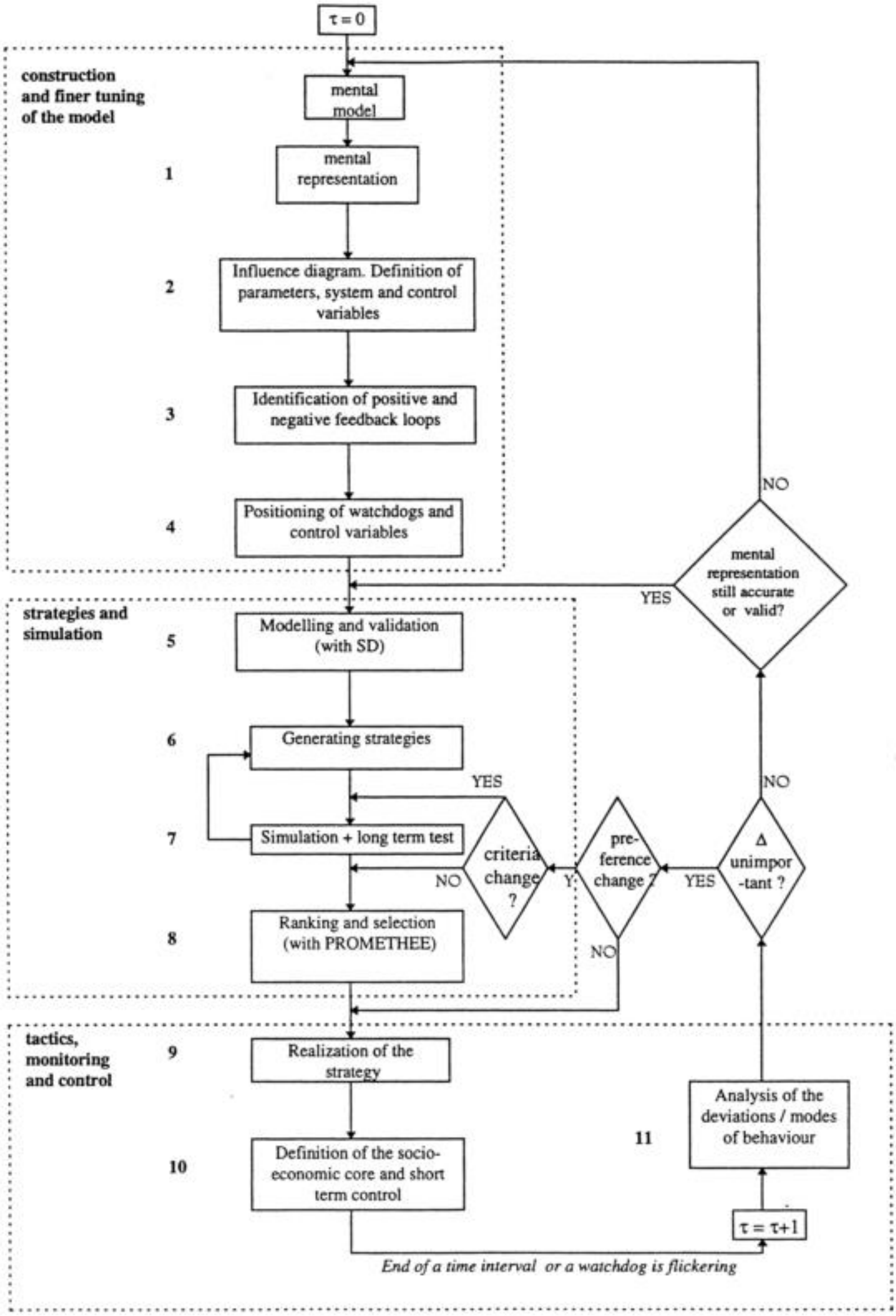


Figure 7.2 A framework for MCDA utilising System Dynamics Modelling to simulate and measure policy performance (Brans et al., 1998).

7.2.4 MCDA and SDM in this thesis

Increasing the role of SDM in MADM, using an adapted version of the ACM framework developed by Brans et al. (1998), would seem to have potential for providing a methodological framework that is novel in the context of the complex dynamics of major delta systems that are being shocked by environmental change. Other researchers have successfully mixed methods with MADM in a context of addressing vulnerability to environmental change, such as Eakin and Bojorquez-Tapia (2008) who combined a livelihoods framework with MCDA to assess household vulnerability to climate change. The challenge posed by further integration of SDM lies in the use of the technique for forecasting.

The justification for SDM usually lies in its ability to uncover internal system behaviours, and not in its ability to forecast. Using SDM to feed outputs into an MADM treats it fundamentally as a forecasting tool and thereby raises questions about its relative performance against other modelling tools in such a task. However, other researchers (e.g. Costa et al., 2011) have successfully navigated this problem in similar (non-MADM) studies by making use of representative outputs, accurate to an order of magnitude or direction of change only, but highly useful for comparative purposes (e.g. **Table 7.1**). Furthermore, the ACM, as can be seen in **Figure 7.2** integrates MADM with SDM while maintaining the circular/iterative element of the SDM process which Ford (2010) regards as essential to learning. As such, this framework prevents the process becoming entirely output focused and retains the many advantages of the SDM approach.

In light of the above considerations modifying the ACM methodology for use in an environmental context was deemed appropriate for this study. It should be noted however, that comprehensive implementation of this method spans beyond the reach of this thesis. Learning and policy impact will rely on iterative work in the VMD, with continual model development taking place collaboratively with stakeholders beyond the analysis presented below as our understanding of the system and the changes and threats it faces develops (see steps 10 and 11 in **Figure 7.2**). In subsequent sections, SDM outputs are utilised entirely comparatively (as in **Table 7.1**) on the assumption that comparative differences will result from different dynamics under different policies (which SDM specialises in identifying) while avoiding reliance on forecasts. Furthermore, the indicators which were chosen to represent system performance on different criteria were, where possible, indicators that reflect temporal dynamics within the model (e.g. number of times income drops to the minimum wage line during a simulation), rather simply a final output.

Table 7.1 An example performance matrix using comparative, representative, measures of scenario performance, rather than predictive (Costa et al., 2011).

Criteria	Scenarios		
	S1 (Increase in subsidies)	S2 (Decrease in subsidies)	S3 (Increase in drought)
Income	++	-	-
Population	+	-	--
Pollution	++	-	+
Water availability	-	+	--
Irrigated land surface	++	+	-
Area of montado	--	--	-

7.3 Executing the MCDA

The applied methods described below follow the established steps of the MADM process outlined in **Section 7.2.2**. The initial steps of problem familiarisation, establishing of governance objectives, model construction, and model evaluation, have previously been conducted in **Chapters 4** and **6**. This section establishes the scenarios and policies which will be tested using the Monte Carlo method (as discussed in **Chapter 6**). In complex systems it is widely accepted that some dynamics may only manifest themselves when the system is subject to variability. At the same time, some dynamics are more easily perceived without variability clouding the model's behaviour, and hence both conditions are tested.

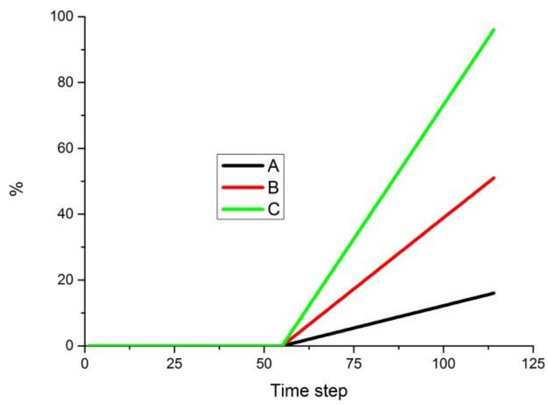


Figure 7.3 The three scenarios of upstream sediment trapping (%) simulated.

7.3.1 Establishing physical scenarios

The model established in **Chapter 6** runs over a 20 year time-frame. This period was regarded as too short a period for prolonged climatic change variables, such as temperature increases, to strongly influence the system's conditions. However, as discussed in **Chapter 2** and **3** large-scale hydropower development is already under way in the Mekong Basin and is likely to have a very strong influence over sediment flows within the 20 year time-frame examined. Two key papers have estimated the likely reduction in suspended sediment concentrations (SSC) caused by dam trapping, Kummu et al. (2010) and Kondolf et al. (2014). These papers represent our current best-estimate of the reductions in SSC that should be expected. However, there is currently a gap in knowledge regarding whether these rates of upstream trapping will, in the short-term, be felt to their fullest extent downstream in the Delta. Some compensatory erosion may take place in the middle reaches of the river. From Kummu et al. (2010) and Kondolf et al. (2014)'s modelling work three scenarios, best, medium, and worst case, of sediment flux decline were developed. Scenario A, best case, runs under the assumption that SSC concentrations will have reduced by 16% by the end of the simulation (Kummu et al.'s bottom line). Scenario B, medium case, assumes a reduction of 51% (Kondolf et al.'s bottom line), and Scenario C, worst case (Kondolf et al.'s upper limit), assumes a reduction of 96% by the end of the simulation (**Figure 7.3**).

7.3.2 Establishing policy scenarios

Within each of the three physical scenarios four policies were tested: triple cropping, double cropping, 3-3-2 rotation, and strategic flooding. Each policy is outlined below. The policies chosen incorporated those that are presently in operation, and those that are considered strong and viable alternatives in the academic and grey literature. Further policies can be hypothesised, and to a lesser extent substantiated as viable options in the literature (e.g. fertiliser subsidies), such policies are discussed in lesser detail after the primary results have been presented. The four primary policies were tested for farmers operating three sizes of farm, as shown in **Table 7.2** (sizes were drawn from the data collected in **Chapter 5**'s survey) in order to test for variations in the impacts of the policies across wealth strata.

Table 7.2 Three farm sizes simulated and the corresponding model conditions.

Quartile	Average farm size (ha)	Average number of workers per farm	Income required for subsistence ('000 VND/season/farmer)	Income required for subsistence ($/day/farmer)
Lower (LQ)	1	1	7,200	3
Median	1.7	1.4	9,700	4
Upper (UQ)	3	2	14,400	6

7.3.2.1 Policy 1: Triple-cropping (business as usual)

Policy 1 is the control simulation. It assumes that, after all farmers switch from the two to three-crop systems (as two thirds have done, Kontgis et al., 2015) they are provided no additional support by the authorities, the farmers take no second-order action, and business continues as usual.

7.3.2.2 Policy 2: Double-cropping

Policy 2 simulates the livelihoods and system dynamics of those farmers, currently approximately one third (Kontgis et al., 2015), who remain double cropping. While this policy can technically be operated within high dykes through sluice gate operation, the vast majority of farmers performing double-cropping are those still enclosed by low dykes, i.e. who might be regarded as living in un-adapted areas. Some suggest, e.g. Hung et al. (2014b) that it is not possible to entirely replicate the traditional double cropping system within high dykes due to the different nature of inundation resulting from sluice gate operation rather than dyke overtopping. This particular issue is poorly understood and requiring further study outside the scope of this thesis. Under policy 2 the farmers supplement their income with non-rice activities during the fallow season. Secondary income generation is not a component explored in detail by the survey or model, representative estimates of each farmers' non-rice income generation potential were garnered from the expert interviews outlined in **Chapter 4** and from Bosma et al. (2005). Through comparison of policies 1 and 2, the original adaptation action, as outlined in **Chapter 4**, is effectively being evaluated.

7.3.2.3 Policy 3: 3-3-2 cropping rotation

The 3-3-2 cropping pattern, explained in **Chapter 5**, is the government's current recommended strategy. This strategy is not enforced and it is infrequently applied by the farmers; it was found in only 2 of the 9 An Giang communes randomly selected for the survey. Once every three years farmers allow their paddy to lie fallow during the monsoon season and for inundation and sediment deposition to take place while they turn to alternative income generating practices. For the purposes of this model, and without data to the contrary, the capabilities of 3-3-2 farmers to generate income from alternative sources are considered to be equal to double cropping farmers.

7.3.2.4 Policy 4: Strategic flooding

Policy 4 closely resembles the proposals in the Mekong Delta Plan (2013), of strategically timed and located facilitation of inundation to maximise sediment deposition and minimise flooding damage. The policy involves either the authorities or farmers identifying years in which the monsoon is bringing a particularly high flood and sediment load to the delta and choosing to allow inundation in those years. Any such action has to be collective as multiple farmers operate within one high dyke ring, farmer cooperatives are the proposed medium. In this policy farmers lose half of the fixed costs of one cropping season as it is assumed that they would not have knowledge of the status of the annual flood until after they had begun planting the third rice crop. For the purposes of this model, and without data to the contrary, the capabilities of these farmers to generate income from alternative sources are considered to be equal to double cropping farmers (though this might be contested). The decision to penalise farmers half their input costs during a fallow season might also be regarded as a penalty on their alternative income generating capabilities. As this policy is hypothetical, no data was available to validate these assumptions.

When farmers do receive inundation, the assumption underlying this policy is that it is particularly sediment-rich.

Perfect operation of such a policy would require utilisation of climate, environmental, and dam operation data collected and disseminated through a mechanism similar to the Mekong River Commission's monitoring and data portal. As an aside, policy 4 is a strategy which was advocated by farmers during informal conversations which took place during the survey in Phú Thành commune (some of the farmers in this commune also happened to be participants in another, related, research project and were particularly open to discussing potential policies for the area). Comparison of policies 3 and 4 with policy 1 might be regarded as evaluation of second-order adaptation action, i.e. action taken in order to better cope under the original adaptation (dyke heightening).

7.3.3 Comparing policies

7.3.3.1 Criteria of success

The different criteria against which the success of policies applied to the social-ecological system controlled by the VMD's dyke network might be measured are many and varied. A suite of broad success criteria (objectives) for the system were distilled from the extensive problem familiarisation and policy background laid out in **Chapter 4**. Particularly, guidance was taken from the discussions, referred to in **Chapter 4**, that were held with local experts from Can Tho University, as well as the different objectives set out for the system by the MDP (2013) and the high ranking provincial officials consulted. In **Table 7.3** the six key criteria of system success (objectives) are outlined.

With the different criteria of success established, model-based indicators of progress towards those objectives were required. **Table 7.3** presents the chosen indicators of measuring progress towards each objective. As is common in time-sensitive policy analysis a discount rate was applied to all of the economic indicators selected (shown in **Table 7.3**) in order to account for a general preference among stakeholders for benefits to be received in the shorter term.

Table 7.3 A summary of the different objectives for the delta, their interested parties, the indicator(s) utilised to measure progress against each objective and the measuring process associated with each indicator of policy performance.

Objective / success criteria	Priority area for stakeholder group?	Indicator/s	Discounted (Yes/No)	Measuring process
Protection from river flooding	(1) International coalition (2) Central government (3) Provincial government (4) Local farmers	Cropping pattern / dyke height	N	The less inundation allowed the higher the score (see **Section 7.3.3.1**) – scoring system X
				The more inundation allowed the higher the score (see **Section 7.3.3.1**) – scoring system Y
Food security	(1) International coalition (2) Central government	Per-hectare rice production	N	The cumulative total rice produced per hectare in bulk weight
Long term delta sustainability	International coalition	Total sediment deposition	N	The cumulative total of the sediment reaching each hectare of floodplain and hence building the height of the delta
Governmental profit	Central government	Government rice tax profits minus policy costs	Y	The cumulative total governmental income (10% of rice sale price) minus policy costs (e.g. fertiliser subsidy costs) per hectare
Local livelihood quality	Local farmers	Average disposable income	Y	The mean cash income per season and per farmer after all costs (including a minimum wage) are subtracted
		Income stability	N	The number of times an individual farmer’s income drops to the minimum wage line (i.e. no disposable income) during a simulation
Local livelihood sustainability	(1) Provincial government (2) Local farmers	Average amount of debt accrued	Y	The cumulative total of the debt accrued by the farming operation
		Prevalence of debt	N	The percentage of farming operations (percentage of runs) which accrue >1,000,000 VND of debt

Choosing a discount rate in environmental management contexts is a notoriously difficult and hotly debated topic (e.g. Kunsch et al., 2008; Markandya and Pearce, 1991). Commentators such as Davidson (2006) have suggested that where the mitigation of climate change impacts is concerned the rates that are commonly applied in policy design of 6-10% are too high, and rates of 0-1% are more appropriate due to the intergenerational impacts. A key benefit of the application of a discount rate is its ability to highlight the temporal dynamics of a policy, i.e. on what time horizon a policy's benefits are received. No official Vietnamese Government discount rate guidance could be found and hence the standard set by the British Government's (2011) Green Book of 3.5% for projects spanning periods of 0-20 years into the future was applied – though it should be noted that World Bank research (Lopez, 2008) suggests 3.5% is at the lower end of common social preferences for discount rates and further, there may be variations in the discount rate desired by different groups. In order to highlight the aforementioned temporal dynamics of the policies tested, the changes in model indicator outputs when moving from a 0% to a 3.5% discount rate were examined and are reported in **Section 7.4.2**.

7.3.3.2 Aggregating indicators

The multi-criteria decision aid (MCDA) chosen to perform the aggregation of the different indicator's scores was the linear additive model set out by Dodgson et al. (2009). The linear additive MCDA was selected for its documented ability to produce transparent, balanced, policy recommendations in contexts (such as this) involving independent criteria. Furthermore, the comparative rather than specific nature of its outputs gave it good compatibility with the system dynamics modelling method. Initially each indicator's value under each policy, as derived from the SDM, was given a score out of one hundred (or -100 in the case that the indicator is an undesirable one, i.e. total household debt). Each score is calculated based on its proportional distance from the highest and lowest values across all of the policies. The highest value will score 100, and the lowest 0. Hence, it is an entirely comparative method of scoring. This comparative method takes the emphasis away from the forecasting of future system conditions and hence makes the scoring system appropriate for combination with SDM. For all of the indicators which were numerical outputs of the model this was a simple process, summarised in the "measuring process" column of **Table 7.3**. For the rating of the flood-protection performance of each policy this was less simple and hence it is discussed in **Section 7.3.3.4**.

7.3.3.3 Weighting indicators

The different actors with a stake in the dyke network each hold different priorities for its management and hence will weight the success criteria set out differently. It was hypothesised that all four groups would have at least some interest in promoting all six objectives but, that each group would have different priority areas. For simplification four key stakeholder groups (or sets of priorities) were identified. The four different stakeholder priority sets were labelled: (i) the *international coalition* i.e. those responsible for the MDP, inclusive of two government ministries – MARD and MNRE and other national governments; (ii) the planning and finance oriented departments of the *central government* of Vietnam, e.g. the Ministry of Planning and Investment; (iii) the *provincial governments* of Vietnam, e.g. An Giang Provincial Government, whose priorities are set out in **Table 4.4**; and finally (iv) the *local farmers* of An Giang. The priority areas allocated to each group are shown in **Table 7.3**.

In order to reflect the differing priorities (shown in **Table 7.3**) of the stakeholder groups presented above, a weighting process was required. Weighting is applied by numerically boosting the scores of the indicators corresponding to the criteria/objectives chosen as most important by each stakeholder. Data was available from the interviews with provincial level decision makers (group iii), outlined in **Table 4.4** of **Chapter 4**, to inform the prioritisation of their objectives and allocation of weights. However, this level of detail was not available for the other three stakeholder groups, nor was data collection within the scope of the study. Instead, a crude, representative, weighting system was utilised which was informed by the discussions with local experts from Can Tho University (**Chapter 4**).

In this analysis the weight of the two indicators considered most important by each of the stakeholder groups was doubled. The weights applied are shown in **Table 7.4**. Where two different indicators were used to measure progress towards one objective (as was the case for both livelihood sustainability and quality as shown in **Table 7.4**), the weightings in **Table 7.4** were split across both indicators. This weighting system is not a refined one which places importance on the nuanced differences between stakeholder's priorities. However, it was considered sufficient for exploratory analysis which would provide greater meaning to the policy simulations, particularly, through the presentation of a suite of possible trajectories of change associated with different levels of desirability based in different priority sets. In recognition of the crude approach to weighting utilised herein the sensitivity of the MADM's outputs to alterations in the weightings applied is tested and the results are presented in **Section 7.5.2**.

Table 7.4 A summary of the different weighting combinations tested and how they were applied to the indicators. The weightings boosted according to a stakeholder group preference are shown in bold.

Stakeholder	Indicator weightings							
	Total Rice	Government profit	Sediment deposition	Disposable income	Times income dropped	Accumulated debt	Households in debt	Flood protection
Unweighted	1	1	1	0.5	-0.5	-0.5	-0.5	1
International coalition	**2**	1	**2**	0.5	-0.5	-0.5	-0.5	1
Central government	**2**	**2**	1	0.5	-0.5	-0.5	-0.5	1
Provincial government	1	1	1	0.5	-0.5	**-1**	**-1**	**2**
Local farmers	1	1	1	**1**	**-1**	**-1**	**-1**	1

7.3.3.4 Scoring flood protection performance

Chapter 4 outlined how life and livelihood protection from severe river and coastal flooding was a key driver in the heightening of the dykes which line the channels of the VMD. A systemic multi-criteria analysis should include any such benefits in its analysis. The traditional way of thinking, and the approach already taken by the Vietnamese Government (as stated in the policy documents analysed in **Chapter 4**), is that higher dykes are safer, less inundation of paddies is preferable, and on this basis higher dykes should be given higher scores in the MADM analysis. However, the relative benefits of high dykes for flood protection are contested. Authors such as Birkmann (2011) have extensively analysed the key problem. They argue that this action can exacerbate flooding in regions further downstream from the dyke. An additional hazard, with potential for large-scale loss of life and livelihoods, is the risk of catastrophic dyke failure, similar to that seen in the Mississippi Delta in 2005 (McGray et al., 2007). Furthermore, **Chapter 6** has already substantiated the argument that higher dykes reduce sediment deposition which will ultimately accelerate relative sea-level rise and exacerbate the long term risk of flooding within the delta.

In light of these issues the recent work presented in the Mekong Delta Plan (MDP, 2013) favours the controlled, strategic, flooding which would be associated with policy 4. Indeed, policy 4 might be considered particularly desirable as years of high sediment deposition potential will usually also be years of high flood damage potential, and hence, the controlled flooding in policy 4 would mitigate some of the downstream impacts. This uncertainty around the best strategy for flood protection presents some challenges to its scoring in the MADM analysis. Ultimately two analyses were performed, with two different approaches taken to scoring flood protection. One (X), scores on the traditional view that rising dykes and reducing flooding is preferential, and the other (Y) scores on the assumption that controlled flooding is preferential. Thus, the impact of the different schools of thought on flood protection on the preferentiality of policies could be explored.

7.4 Policy simulations

7.4.1 Simulation outputs

The raw results of the Monte Carlo simulation can be found in **Appendix 9.10** in the form of a set of performance matrices. Each performance matrix is divided into the results obtained from the three physical scenarios of sediment change, four policies, and three farm sizes, all measured against eight indicators of success. For each scenario/policy combination Monte-Carlo simulation was performed (as introduced in **Section 6.4.3**), in the performance matrices the outputs are averaged and accompanied by a standard error. The matrices in the appendix should be approached with caution as they provide highly specific numbers suggesting higher accuracy than the method is intended for or capable of. Rather, the tables should be utilised for comparative purposes, and to spur investigations into unintuitive dynamics. Within the body of this thesis, the results are presented using a representative scoring system of “+” and “-“ as utilised by Costa et al. (2011) and detailed within the tables themselves. However, as it is difficult to perceive the significance of the standard error to the results when presented in this indicative format the standard errors associated with each indicator can be found in **Appendix 9.10**.

7.4.2 The effect of discounting

The fractional change in the three key monetary indicators of success (government income, farmer disposable income, and farmer debt) when the discount rate shifts from 0% to 3.5% per year can be found in **Appendix 9.9**. Significant differences in the fractional changes between policies and indicators would suggest that there are temporal differences in the point when benefits/losses are realised and hence increasing the discount rate has a notable effect. Across all policies discounting substantially reduces (~40%) the accumulated household debt, as a disproportionate amount of households’ debt is gathered towards the end of the simulation when fertiliser prices are especially high. The variations in individual indicators between policies are much more minor. For example, the average total debt accumulated by LQ farmers reduces by around 2-4% more under policy 2 than policies 1, 3, and 4, a factor which appears to be linked to the ongoing decline in sediment flux throughout the simulations (the reduction is also greater under higher trapping scenarios). However, the majority of the differences between policies are negligible and, as a result, the subsequent analysis uses only the data discounted at 3.5% on the assumption that (as discussed in **Section 7.3.3**) this will more closely represent the opinion of stakeholders.

7.4.3 Double vs triple cropping

First examined are the key changes in socioeconomic system dynamics resulting from the main transition or adaptation that has already taken place, i.e. the shift from low to high river dykes associated with the move from double (policy 2) to triple (policy 1) rice-cropping.

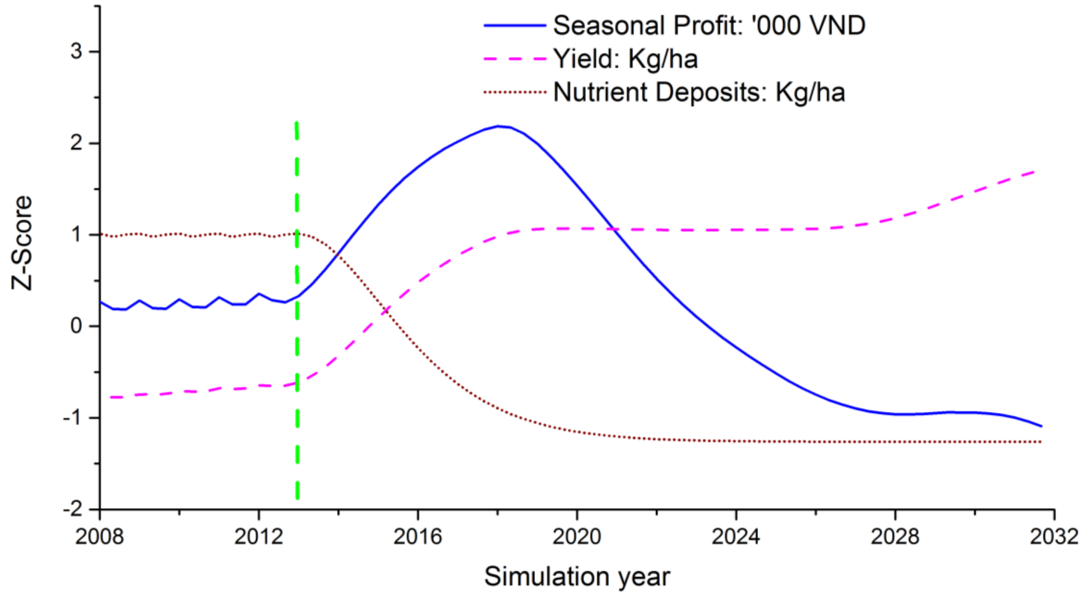


Figure 7.4 An illustrative run of policy 1 for a farm of median size, without random variation applied. Shown: the seasonal profit of the farmer (blue line); the quantity of sediment-bound nutrients available to crops each season (brown line); and the seasonal rice yield (pink line). The vertical green line indicates the point at which farmers adopted triple-cropping. A three year (nine season) smooth is applied to all indicators to improve the visualisation of the double-cropping system, which would otherwise present with one fallow season every three seasons. The chosen indicators have been converted to Z-Scores, i.e. the number of standard deviations each value is from the mean.

First, and as expected, across all farm sizes **Figure 7.4** shows that a clear substitution of sediment (and associated nutrients) for annual rice production (and hence government export profit) takes place when the double-cropping spin-up period ends (at season 53, marked by the dashed vertical green line in **Figure 7.4**) and the triple-cropping (policy 1) begins. In **Table 7.5** the system conditions of the farmers (two thirds of An Giang province) who pursued policy 1 (triple-cropping) are compared with the farmers who remained double-cropping (policy 2). **Table 7.5** indicates that the shift to triple-cropping has negative outcomes on the majority of indicators, barring rice production and government profit, for farms of smallest size (LQ). Results for farms of median size are similar, except that triple-cropping (policy 1) affords greater income stability in this case. However, for farmers with greatest land wealth (i.e. the upper quartile (UQ) of farm sizes), the shift to triple-cropping is predicted to be highly advantageous, comparatively benefitting all indicators bar sediment deposition. The aggregate movements between farm sizes are visualised in **Figure 7.5**. This comparative analysis highlights the presence of system dynamics which differentiate outcomes between farm sizes; below the internal drivers of this process are explored.

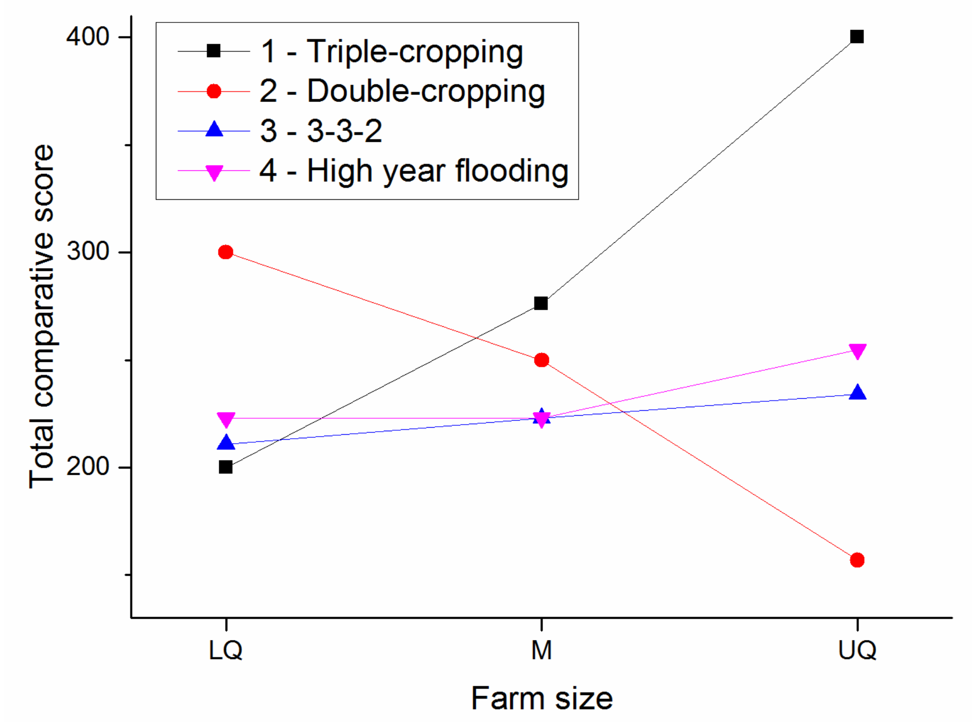


Figure 7.5 The comparative score (out of 100) of each policy in each indicator has been aggregated for each of the policies and for the three farm size classes. Comparisons can be made between the performances of each policy at different farm sizes (lower quartile (LQ), median (M) and upper quartile (UQ) of the 195 farms surveyed. Indicators have not been weighted.

During the model evaluation detailed in **Chapter 6** it was found that the model systematically overestimated the farming efficiency that triple-cropping farmers were able to achieve. Here it is noted that the implications of this inaccuracy for the above findings are simply to strengthen the preferentiality of double-cropping over triple-cropping for lower quartile size farms, and to make the net change for median size farms negligible. There are no ramifications for the comparative conclusions which can be drawn from the model.

The source of the income and debt penalty imposed by the triple-cropping system (policy 1) on poorer (smaller) farmers lies in the increased total and proportional artificial fertiliser application required by the addition of the third crop, and the loss of free sediment-bound fertilisation. The combination of lost free sediment-bound nutrients and the addition of a third rice crop results in an average increase in annual artificial fertilisation of 87% when comparing double (policy 2) to triple (policy 1) cropping. The cost of this increased demand for artificial fertilisation is greater on poorer farmers because the model predicts they operate at a lower level of input efficiency. Averaging across the testing period of the model it can be seen that under the triple-cropping system (policy 1) LQ farmers were at approximately a 9% input efficiency disadvantage against UQ farmers whereas, under double-cropping (policy 2), their disadvantage reduces to 5% - this difference being a result of the farmers' increased economic capacity to invest in efficiency-enhancing technology under policy 2. The dynamic implication of this phenomenon is that, when combined with the finer margins that smaller-scale farmers operate on, triple-cropping (policy 1) farmers are unable to build up a large enough contingency fund to protect themselves against the model's stochastic fertiliser price spikes. In other words, the shift to triple-cropping reduces the economic resilience of poorer farmers in particular. This phenomenon is examined in more detail in **Figure 7.6**. Notably, the debt spikes which can be seen in **Figure 7.6** are found almost exclusively later on (beginning around 6-9 years from policy implementation) in the simulation meaning that evaluations of the (apparent) success of the transition to triple-cropping made in the immediate aftermath of the shift might offer a misleading assessment of its performance over the long term. Moreover, **Figure 7.6** hints that once the farmer's economic resilience is broken, the implications are greater than just a one off loan being taken out, with debt often recurring in subsequent seasons.

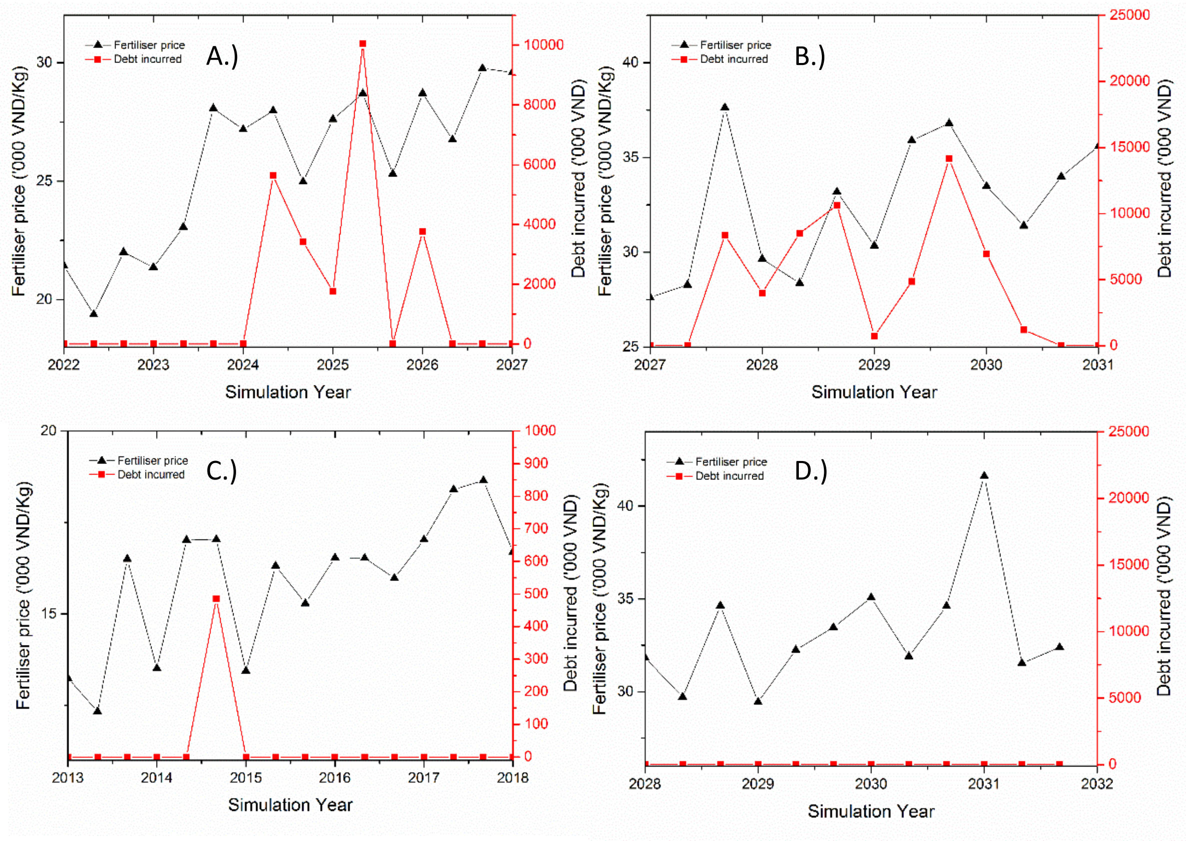


Figure 7.6 Four examples of peaks in fertiliser prices. A, B, and C show LQ simulations, D shows a UQ simulation. In A and B we see peaks in fertiliser prices causing debt spikes. Commonly these spikes occur later in the simulation and the initial spike tends to have a knock-on effect on subsequent seasons. Graph C is a rare example of a small early-simulation debt spike caused by two localised price spikes that does not have a knock-on effect. In graph D we see an example of a UQ size farmer coping with a severe price spike without incurring debt.

Table 7.5 Four policies scored comparatively (unweighted) for three farm sizes: LQ: Lower Quartile, M: Median, UQ: Upper Quartile. Scoring is presented on a simplified comparative scale containing five ratings (--,-,O,+,++) where '--' represents the lowest scoring policy and '++' the highest.

			Total Rice production	Government Profit	Sediment deposition	Disposable income	Income stability	Total debt	Debt prevalence	Flood protection	
										X	Y
LQ	Triple-cropping	1	++	++	--	--	--	--	--	++	--
	Double-cropping	2	--	--	++	++	++	++	++	--	++
	3-3-2	3	+	+	-	--	-	O	--	O	O
	High year opening	4	+	+	-	--	-	-	--	-	+
M	Triple-cropping	1	++	++	--	--	++	--	-	++	--
	Double-cropping	2	--	--	++	++	--	++	++	--	++
	3-3-2	3	+	+	-	--	+	-	-	O	O
	High year opening	4	+	+	-	--	+	--	--	-	+
UQ	Triple-cropping	1	++	++	--	++	++	++	++	++	--
	Double-cropping	2	--	--	++	--	--	+	O	--	++
	3-3-2	3	+	+	-	-	+	-	--	O	O
	High year opening	4	+	+	-	O	+	--	--	-	+

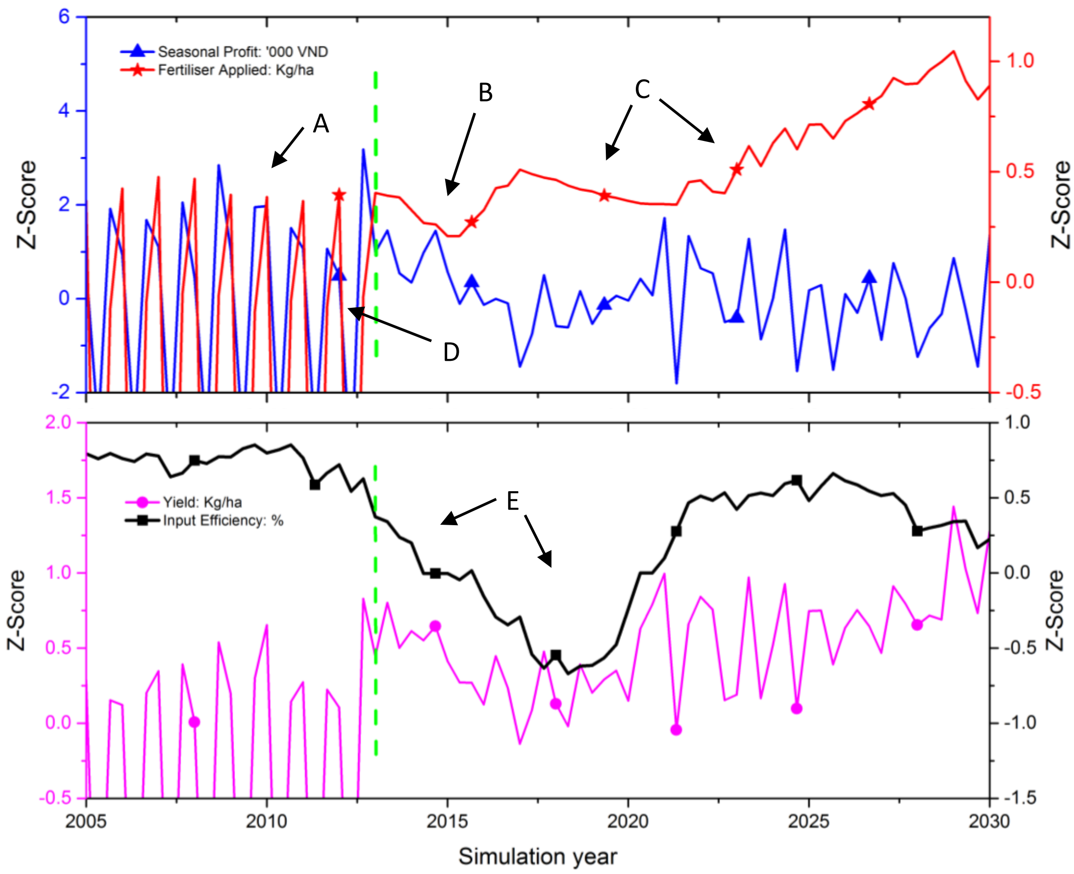


Figure 7.7 Four simulation indicators (seasonal profit, fertiliser applied, yield, and input efficiency) shown for a sample run of a farm of median size operating Policy 1 with random variation on and no smoothing applied. In green, the point at which the switch in cropping pattern took place is highlighted. The chosen indicators have been converted to Z-Scores, i.e. the number of standard deviations each value is from the mean. Some key features are labelled (A-E). A – B: the shift from staggered income to continuous. C: the farmer changing approach to fertilisation. D: a low-profit period immediately prior to the system switch. E: the declining input efficiency which resulted from that low-profit period.

The model also contributes operational insight into the reasons for the 6-9 year lag in the onset of debt. In **Figure 7.4** it can be seen that for the period between 2-4 and 6-9 years after implementation of triple-cropping farmers enjoy a period of substantial financial success. This success is harder to detect when the smooth is removed from the model outputs, as in **Figure 7.7 (A-B)**, as it is sourced from the continuous rather than staggered nature of the farmer's profits. Input costs do not instantly respond to the increased number of rice crops thanks to the buffer of the nutrient rich deltaic soil that is maintained by sediment deposition, as shown in the example simulation in **Figure 7.7 (B)**. However, the model suggests that this boost in profits is inevitably followed by a decline, initially relatively rapidly, then more slowly, through to the simulation end. This decline can be linked to the farmer using up the buffer of natural fertilisation provided by sediment deposition and transitioning to what is sometimes termed an open throughput system (Berg, 2002) that is entirely reliant on artificial fertiliser inputs. This, in turn, has significant economic ramifications. As the sediment buffer declines the burden on artificial fertilisation increases, and the farmer must then identify the optimum level of fertilisation in a context of increasing and variable fertiliser prices (**Figure 7.7 – C**), a process which lasts beyond the point at which sediment-bound nutrients are depleted.

Another key factor controlling farmers' success (or otherwise) lies in their ability to sustain their technological capacity and hence input efficiency. The model simulations identify two mechanisms that control the level of investment in technological advancement. The example simulation in **Figure 7.7** highlights the first mechanism: low profit periods (labelled **D**) reduce a farmer's ability to invest in their technological capacity and lead to an efficiency slump (labelled **E**) which, particularly under triple-cropping, takes some time to recover from. The second factor, which explains why this slump is harder to recover from under policy 1 and contributes to the lower technological capacity seen under policy 1 versus policy 2 (for median and LQ size farms), related to the lower profit margins per rice growing season. Farmers only invest in technology when the seasonal surplus is sufficient for them to feel it worth the risk (the risk being insufficient backup funds resulting in the future accrual of debt). Policy 1 involves continuous cropping of low surplus seasons with a high risk of unexpected input costs; policy 2 involves two high surplus seasons followed by lower risk of unexpected costs, giving farmers greater security to invest.

The simulation's suggestion that An Giang farmers are either currently, or likely soon will be, suffering from an increasing debt burden is one that can be substantiated in the literature and therefore provides an additional validation of the model. The debt issues faced by poorer farmers in particular have been mentioned in previous qualitative research, and attributed to similar causes (e.g. Garschagen et al., 2012), additionally it was reported by the local experts interviewed at Can Tho University (reported in **Chapter 4**). Given the relatively recent conversion of many communes to triple-cropping (while conducting the survey communes were encountered that had converted as recently as 2013), the delay in the onset of debt may mean this issue has not yet been realised or appreciated to its fullest extent.

7.4.4 Dynamics of the 3-3-2 variant

In this section the SDM is used to explore the effectiveness of a variant rice cultivation strategy that has been implemented to alleviate the negative impacts described above. Specifically, the 3-3-2 cropping rotation is the only policy implemented which directly addresses the role of sediment exclusion in the system, albeit as of 2014 it was only found in 2 of the 9 An Giang communes surveyed. From **Tables 7.5** and **Figure 7.5** it can be seen that, comparatively, the 3-3-2 rotation (policy 3) did not excel in any of the key indicators. The 3-3-2 cropping system attempts to find a middle ground between the two extremes of high and low sediment deposition.

Importantly the 3-3-2 rotation involves regular switching between cropping systems, and it is in this regular switching that its poor performance lies.

Every third year, independent of the magnitude of the flood and hence sediment deposition potential experienced in that third year, the farmer sacrifices a crop in order to receive sediment. This means that in the event that the third year coincides with a low flood, sediment deposition potential is reduced relative to a system that switches responsively to maximise sediment deposition potential. The sediment deposited holds both short and medium term value. However, the total short term value the farmer gains from the sediment, combined with income from off-season activities, is often (dependent on the flood level) lower than the income they would gain from a season of rice. Although, when the medium term gain is considered the net gain may be greater. The triple-cropping system requires that the farmer hold sufficient (and significant) short-term savings to cover the increased fertilisation costs. Examining the model simulations it was found that the lower income obtained in the short-term during the double-cropping season reduces the contingency funds available to the farmer for the next year's fertilisation costs. Thus, farmers (operating LQ and median sizes) struggle to fund their input costs in the cropping seasons directly following a fallow season, and their resilience to high fertiliser prices therefore declines. **Figure 7.8**, which shows the probabilities of debt being incurred at different stages, illustrates this issue. As a result, the 3-3-2 system (policy 3) ranks poorly in terms of debt prevalence. Again, this phenomenon only tends to have an impact after the initial income boost the farmer receives from switching to triple-cropping subsides, which the model indicates occurs after 6-9 years. However, it should be noted that the precise length of this lag is primarily influenced by the parameter which determines the time between nutrient deposition and its availability for plant uptake; this parameter was one of five identified as having a notably weaker evidence base in **Chapter 6**. In contrast to policy 1, where triple-cropping performs notably worse for land-poor farmers, the 3-3-2 system's performance is uniformly poor across all farm size categories.

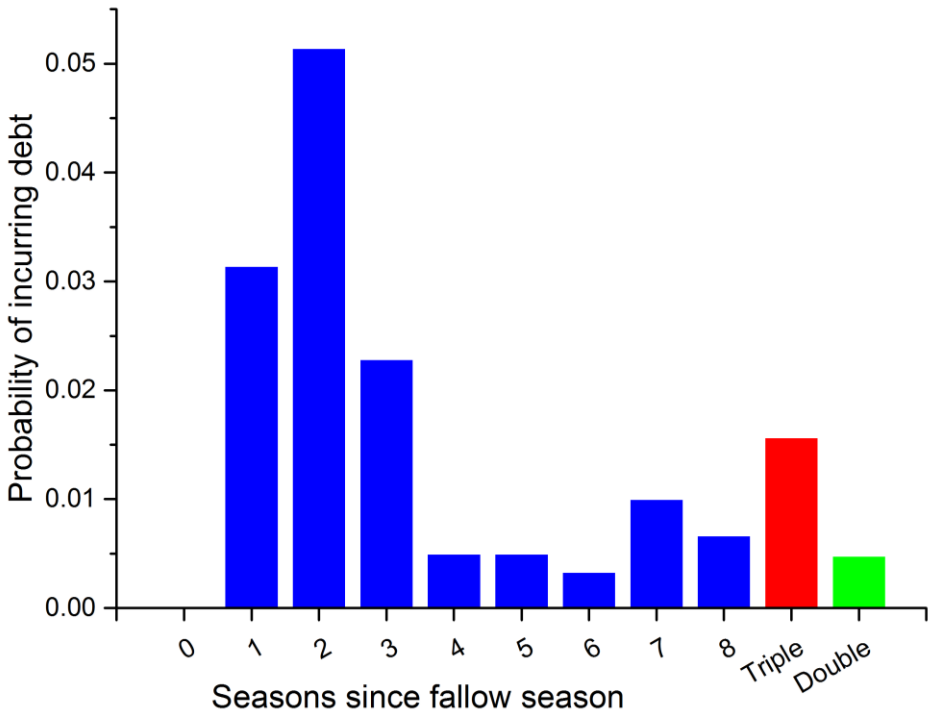


Figure 7.8 The probability of a median size farmer falling into debt during the policy simulation period on a given season under policy 3 (blue bars). For comparison, the average probabilities of farmers operating triple (red bars) and double cropping (green bars) policies falling into debt in any given season are shown.

7.4.5 Dynamics of the MDP variant

Here the question is posed: how do other policies affect the system's dynamics and how do they compare with the status quo? To address this question a model set-up is tested (policy 4) in which the farmer performed double-cropping and allowed inundation and sediment deposition only in years with higher sediment deposition potential. Theoretically this policy would ensure the fallow season was optimised for maximum benefit and it might be hypothesised that this would reduce some of the negative traits of the 3-3-2 rotation (policy 3). Indeed, when all indicators are aggregated policy 4 is seen to offer an improvement relative to policy 3 (**Figure 7.4**). However, policy 4 results in farmers incurring marginally greater debt problems (**Table 7.5**). The phenomenon causing this is now familiar. While fallow seasons are smaller in number under policy 4 versus policy 3, the random nature of when peak flood events occur occasionally means successive years of double-cropping. Such occurrences have a significant impact on farmers' economic reserves and result in debt in the subsequent season in which the farmer returned to triple-cropping. While this phenomenon might be avoided by decision making at the senior level, such decisions might prove contentious due to the downstream flood risk.

Despite the above caveat, when all of the indicators are aggregated, policy 4 performs better than policy 3 across all farm size categories (**Figure 7.5**). This is a direct consequence of the optimisation of sediment-bound nutrient potential, which improves the long term yield to fertiliser ratio. Furthermore, the distribution of impacts would seem more even when comparing with policies 1 and 2. While opinions differ on the best way to protect local livelihoods from intensifying fluvial floods, most agree that controlled inundation during intense flood events is an effective mechanism, particularly for protecting livelihoods downstream of the paddy compartments. This additional benefit would further increase the preferentiality of policy 4 against the alternatives if it were included in the aggregate scores shown in **Figure 7.5** but, it is unclear.

7.4.6 The impact of sediment scenarios

An important factor in terms of the management of the VMD's social-ecological system is whether the level of future sediment flux to the delta, which is highly uncertain but very likely to change, has a noticeable impact on the dynamics of the different policy-scenario combinations.

In all cases policy 1 was unchanged by different sediment flux scenarios due to its total exclusion of sediment. In the case of smaller (LQ) farms the movements in indicators between sediment flux scenarios are less than in the cases of Median and UQ size farms (**Figure 7.9**). This difference points to a dynamic difference within the model, suggesting that in the LQ case the sediment scenario holds less sway over movements in the indicators of success. This is not to say that sediment is not important under policy 2; the dynamics discussed in **Section 7.4.3** suggest very much to the contrary.

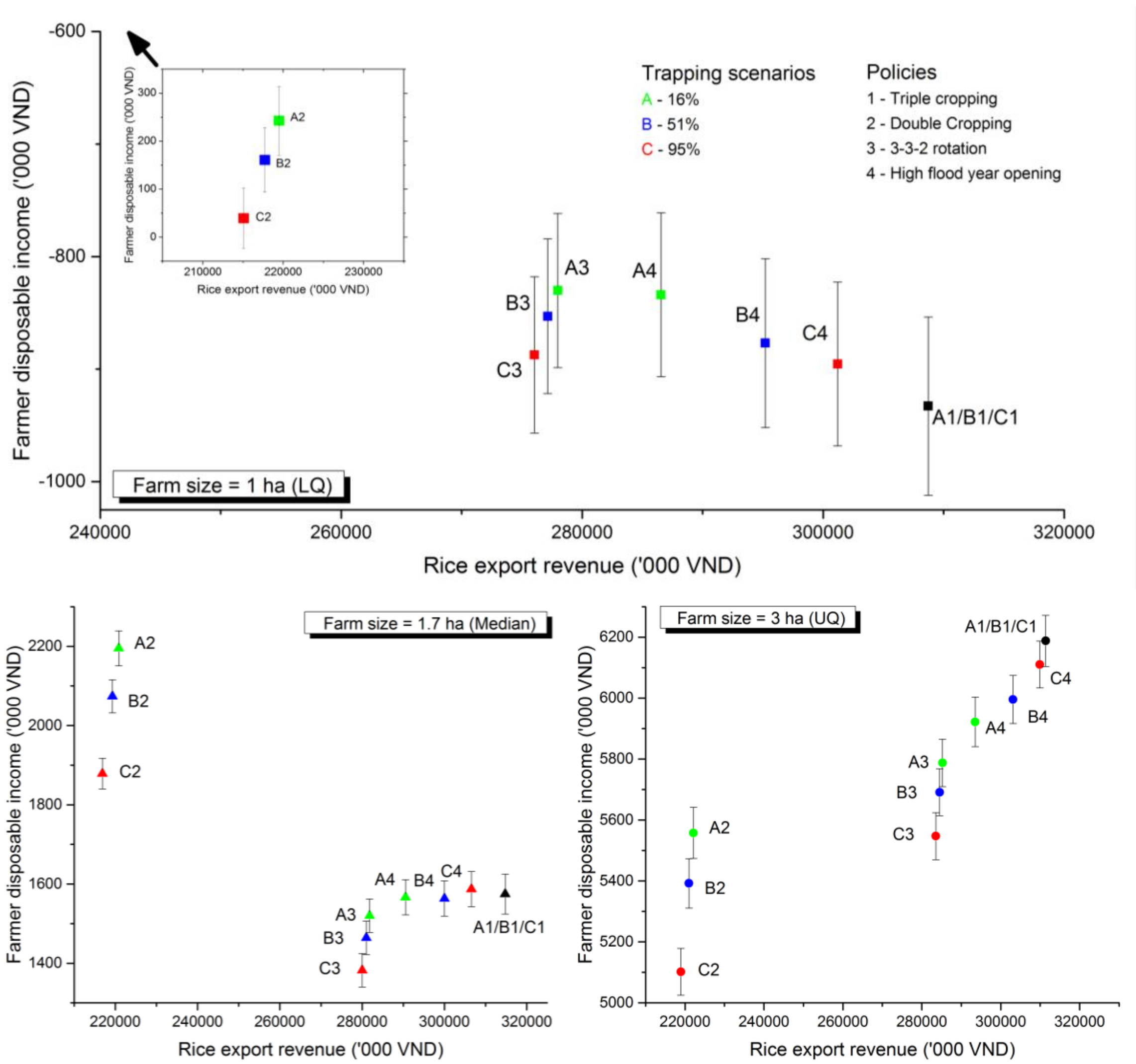


Figure 7.9 Each graph shows a different farm size (LQ, Median, UQ). These graphs show the movements of different policies as the percentage of the sediment flux trapped by dams increases from 16% (Green A) through 51% (Blue B) to 95% (Red C) at the simulation end. It is important to note that the negative disposable income values in the LQ simulation are a product of discounting and not representative of the debt accumulated by the farmer, which is a separate indicator. Standard error (SE) bars are shown in the Y direction, but in the X direction SEs are too small to visualise on these graphs and, as a result, do not undermine the comparability of any of the datapoints.

It can be seen in **Figure 7.10** that even after the larger reduction in sediment flux in scenario C, paddies still receive a considerably larger amount of deposition, and hence economic support to poorer farmers, under policy 2 than the maximum deposition achieved under policies 3 and 4. Poorer farmers receive the additional support of the free fertilisation provided by sediment deposition which, in their case, still more than offsets the benefits of the third rice crop.

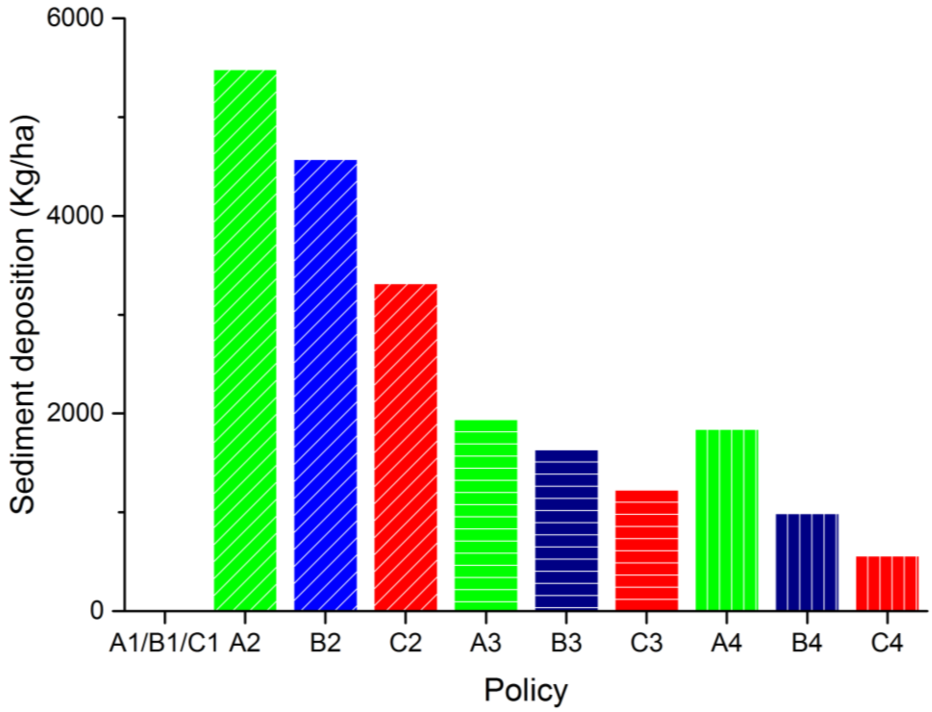


Figure 7.10 The quantities of sediment predicted by the model under the different policies (1-4) and sediment flux scenarios: A (green bars), B (blue bars) and C (red bars).

Policies 2 and 3 were similar to each other in their responses to declining sediment, in both cases and across all farm sizes farmer disposable income dropped as sediment declined, and a minor decline in government income also resulted (**Figure 7.9**). In the case of Policy 4, an interesting dynamic unfolded. For farms of Median and UQ size, policy 4 (sporadic and irregular floodplain inundation), actually improved in performance as dam trapping increased. The reason for this was that, as sediment flux declined, the number of instances in which fallow seasons were enforced, and hence rice cropping was not possible, also declined. As a result, farmers had greater stability in their operation, and only very occasionally received (higher than average) influxes of sediment. This dynamic did not present for LQ size farmers. Their incomes declined as sediment trapping increased under policy 4, because sediment plays a more important role in the financial success of their operation. Interestingly, however, in all cases the income farmers received under the combination of scenario C (high trapping) and policy 4 could not be statistically distinguished from policy 1 (as highlighted by the error bars in **Figure 7.9**). The implication is that there is little cost to the small amount of sediment gained from the sporadic floodplain inundation. However, greater insight into the comparability of policies 1 and 4 is provided by the MADM analysis in **section 7.7**.

A question which can be asked of the data is whether the additional income the government receives under triple-cropping (assuming a 10% export tax rate) is sufficient for them to entirely compensate for the losses to income made (by LQ and Median farmers) when switching away from double-cropping; and further, whether their ability to do so interacts with sediment. The line which would demarcate the theoretical indifference curve could not be shown on **Figure 7.9** due to scaling issues. However, it would be located at a point at which (across all LQ scenario-policy combinations) the losses of LQ farmers when moving away from policy 2 *cannot* be compensated for by the gains made by the government. Conversely, the losses of median farmers *can* be compensated for, but at an average cost of around 60% of the government's additional income. No income losses are incurred by UQ farmers. These conclusions remain the same regardless of which sediment scenario is simulated and regardless of which triple-cropping policy is operated.

7.5 Multi-criteria analysis results

7.5.1 Weighted and aggregated policy performance

Each indicator's scores were subsequently weighted according to a selection of different priorities for the system (outlined in **7.3.3**) using the crude method of doubling the weight of the indicators considered a priority area by each stakeholder group. The scores across all indicators were then aggregated to give indicative overall policy scores, shown in **Tables 7.6** and **7.7**. Highlighted, are the highest (and joint highest) scoring policies according to each stakeholder's preferences. In **Table 7.8** the number of times each policy-scenario combination was selected as preferential (or joint most preferred) by a stakeholder group is shown.

Perhaps the most clear-cut insight provided by the outputs of the MADM process is that the 3-3-2 cropping rotation (policy 3) performs poorly across all weightings of the model's outputs. Policy 3 aside, all of the policies are shown to be preferential under different circumstances. The drivers of which policy emerges as preferential can be divided into three sets. Policy 1's preferentiality is primarily driven by the adoption of the old or traditional (X) interpretation of flood protection benefits (**Table 7.8**). Particularly for median and large size farms, policy 1 completely dominates.

Table 7.6 A matrix of stakeholder groups (sets of weights) and their comparative preferences for different policies under different scenarios of sediment change. This matrix assumes that flood protection benefits are scored under the traditional assumption that less flooding is better (X). The stakeholder groups are coded as follows: **U** = unweighted, **I** = international coalition, **C** = central government, **P** = provincial government, **F** = local farmers. In each case the top policy is highlighted in green; where two or more policies are tied for the lead they are highlighted in light green. Rows are separated into the different policies (1-4) and the different scenarios of sediment flux decline (A-C).

		LQ					**Median**					**UQ**				
	No.	**U**	**I**	**C**	**P**	**F**	**U**	**I**	**C**	**P**	**F**	**U**	**I**	**C**	**P**	**F**
Triple	A1	++	++	++	++	--	++	++	++	++	++	++	++	++	++	++
Double	A2	++	++	--	++	++	--	--	--	--	+	--	--	--	--	--
332	A3	--	--	O	--	--	--	--	O	--	--	-	-	O	-	-
Highyear	A4	-	O	+	--	--	--	-	O	--	--	O	O	O	-	-
Triple	B1	++	++	++	++	--	++	++	++	++	++	++	++	++	++	++
Double	B2	++	++	--	++	++	--	--	--	--	--	--	--	--	--	--
332	B3	--	--	O	--	--	-	-	O	-	--	-	-	O	-	-
Highyear	B4	-	O	+	--	--	O	+	+	O	O	+	+	+	O	+
Triple	C1	++	++	++	++	--	++	++	++	++	++	++	++	++	++	++
Double	C2	++	++	--	++	++	--	--	--	-	+	--	--	--	--	--
332	C3	--	--	-	--	--	--	--	-	--	--	-	-	O	-	-
Highyear	C4	O	+	+	-	--	+	++	++	+	++	++	++	++	++	++

Table 7.7 A matrix of stakeholder groups (sets of weights) and their comparative preferences for different policies under different scenarios of sediment change. In this matrix flood protection benefits are scored such that the controlled flooding of compartments is preferable (Y). The stakeholder groups are coded as follows: **U** = unweighted, **I** = international coalition, **C** = central government, **P** = provincial government, **F** = local farmers. In each case the top policy is highlighted in green, where two or more policies are tied for the lead they are highlighted in light green. Rows are separated into the different policies (1-4) and the different scenarios of sediment flux decline (A-C).

		LQ					**Median**					**UQ**				
	No.	**U**	**I**	**C**	**P**	**F**	**U**	**I**	**C**	**P**	**F**	**U**	**I**	**C**	**P**	**F**
Triple	A1	--	--	-	--	--	--	--	++	--	--	++	++	++	++	++
Double	A2	++	++	-	++	++	++	++	--	++	++	--	--	--	O	--
332	A3	-	-	--	-	-	--	--	O	--	--	--	--	O	--	--
Highyear	A4	-	O	++	-	-	--	--	O	--	--	-	-	O	--	-
Triple	B1	--	--	-	--	--	O	O	++	--	O	++	++	++	++	++
Double	B2	++	++	-	++	++	++	++	--	++	++	--	--	--	O	--
332	B3	-	-	--	-	-	--	--	O	--	--	--	--	O	--	--
Highyear	B4	-	-	++	-	-	++	++	++	O	O	++	++	++	++	+
Triple	C1	--	--	-	--	--	-	-	+	--	-	+	+	++	+	++
Double	C2	++	++	-	++	++	++	++	--	++	++	--	--	--	-	--
332	C3	--	--	--	-	--	--	--	--	--	--	--	--	-	--	--
Highyear	C4	-	O	++	-	-	++	++	++	O	+	++	++	++	++	++

Table 7.8 The total number of times each policy is found preferential (or joint preferential according to the scoring system) under each sediment scenario and according to the two different systems of scoring flood protection benefits outlined in **Section 7.3.3.4**. Rows are separated into the different policies (1-4) and the different scenarios of sediment flux decline (A-C).

	No.	**Flood protection scoring X**	**Flood protection scoring Y**
Triple	A1	11	5
Double	A2	3	6
332	A3	0	0
Highyear	A4	0	1
Triple	B1	11	5
Double	B2	3	6
332	B3	0	0
Highyear	B4	0	6
Triple	C1	11	2
Double	C2	3	6
332	C3	0	0
Highyear	C4	7	7

Policy 2 is primarily advocated by the farmer stakeholder group and in the simulations of the smaller (LQ) farmers. While the long-term sustainability of the delta body was treated as important to all stakeholders, in the MADM analysis the deposition of sediment was given particular weight in the preferences of the group referred to as the international coalition. Despite this, it would appear to be the economic role of sediment in supporting small scale farming livelihoods that proved to be the primary driver of preference for policy 2 – the most sediment-friendly policy (see the LQ sections of **Tables 7.6** and **7.7** where policy 2 is highly preferential). Policy 4 is primarily advocated in the scenarios involving higher sediment trapping. As previously mentioned, in such scenarios less frequent floodplain inundation of the paddy compartment was allowed but, when it was allowed, it provided optimal sediment deposition benefits.

7.5.2 Sensitivity of the MADM

As identified in **Section 7.3.3.1** the method used to set the weighting associated with each stakeholder group in the MADM was not nuanced. As such, sensitivity analysis, a common component of MADM (Dodgson et al., 2009), was especially important. In order to explore the significance of the specific values chosen to weight the areas preferred by each stakeholder group, the MADM was run two further times with the weight applied to the preference areas of each group first halved, then doubled. **Table 7.9** shows the number of times, for each farm size, this change resulted in a change to the policy which was ranked most preferential. In general, there were few changes, especially considering the relatively large modification made to the weightings; this highlighted a relatively robust set of conclusions. The most noticeable shift took place in the simulations of LQ size farms when scored under flood protection scoring system Y - that floodplain inundation should be encouraged- introduced in **Section 7.3.3.4**. In this case, three preferences changed, all from the perspective of the group called *Central Government*, whose preferences in all cases, shifted from policy 4, to policy 2. The implication of this shift is only to bring the *Central Government*'s preferential policy in line with that of all other stakeholder groups for the LQ farm size, providing a unanimous verdict.

Table 7.9 This table highlights the sensitivity of the MADM to changes in the weights assigned to stakeholder preferences. The number of times the most preferential policy changed as a result of the change in weighting is shown for the different categories of farm size and the different flood protection scoring systems. Highlighted is a stand-out change.

Farm size	Flood protection scoring system	Halved weights	Doubled weights
LQ	X	0/12	0/12
	Y	3/12	1/12
Med	X	0/12	2/12
	Y	1/12	0/12
UQ	X	0/12	0/12
	Y	0/12	0/12

7.6 Discussion on the MCDA results

7.6.1 Plausibility and reliability

A key issue to emerge from the modelling is that farmers, particularly small-scale, face a battle against the burden of debt. This finding has been documented by qualitative evidence since the early 2000's (see Taylor, 2004). One case study performed in 2006 found that as much as 87% of a commune may already have been dependent on moneylenders in some form (Swain et al., 2008). However, Swain et al.'s study was conducted in a region where rice is less intensively cultivated. The quantitative model constructed here allows a more detailed operational investigation into the drivers of debt under triple-cropping. The model suggests there are multiple contributing factors, including lost sediment-bound nutrients, a lack of movement in rice prices against the increasing expense of agricultural inputs, and lower input efficiency among some groups. The rice and input price issues will be present under both the double and triple cropping systems (with and without sediment). But, the evidence presented above suggesting a shift to a more input-intensive three-crop farming system greatly exacerbates the problem from the perspective of poorer farmers, supports findings of earlier qualitative research (Garschagen et al. 2012).

The corroboration of secondary sources such as Garschagen et al. (2012) and Swain et al. (2008) with the insights provided by the model is a good initial indicator that the model's results provide a plausible representation of reality. The model developed spanned a number of sectors of a complex system, in the process, decisions had to be made about which variables to leave out, and how to cope with variables of a highly uncertain nature. Examples of factors that were left out due to being deemed negligible included:

- By reporting cash income the study ignores any nutritional requirement farmers meet with their own produce.
- Flooding which takes place via sluice gate operation will have different, but largely unknown, sediment properties from flooding via dyke overtopping.
- A small number of farmers reported in the field that they have access to manure or straw (organic amendments) that can provide additional, low cost, fertilisation (a poorly understood area, Dawe et al., 2003).

Examples of variables with highly uncertain values were presented in **Chapter 6**, but most proved to have low influence over the model in sensitivity testing.

7.6.2 Implications

The differing fortunes of the richer versus poorer farmers under the new system threatens to exaggerate a segregation of the populace which has been taking place since the de-collectivisation of Vietnam's agricultural sector (Akram-Lodhi, 2005). With no single policy preferential across all land wealth strata in this analysis it is difficult to guide decision makers on which stakeholder groups' needs to prioritise. At present, the government enforces no policies, but does recommend policy 3, the 3-3-2 system. One of the most clear-cut findings of the combined survey, model, and MCDA process is that the 3-3-2 strategy is not effective across all of the criteria considered herein. The survey findings (**Chapter 5**) suggested the 3-3-2 strategy made little difference to the post-adaptation trends. The MCDA suggests that policy 3 is not preferential under any scenario/stakeholder combination.

Examination of the model's dynamics suggests policy 3's poor performance is linked to the economic damage which results when fallow seasons are followed by seasons with high fertiliser prices. Farmers are forced into debt, with only minor sediment benefit. Policy 4, involving the irregular opening of sluice gates to allow sediment deposition when deposition conditions are optimal, performs better. Indeed, policy 4 was rated most preferential in a number of cases, and when the raw scores of the MCDA are examined it can be seen that policy 4 never rated least preferential. There is, therefore, an argument that policy 4 is most palatable policy across all scenarios and stakeholders. However, policy 4 still makes poorer farmers considerably worse off than they would be had they continued with double-cropping (policy 2), and the model suggests there is still potential for policy 4 to exacerbate the aforementioned segregation of the wealth classes. The above issues indicate that futher exploration of the impact of input subsidies is additionally worthwhile.

As discussed in **Chapter 4** criticisms have been made against the Vietnamese central government's enforcement of rice targets which effectively impose triple-cropping on the provinces (Giesecke et al., 2013; World Bank, 2011). An interesting insight provided by the division of the MADM analysis into two flood protection scoring systems is that under the old interpretation of flood protection the triple-cropping system is preferable for the majority (72%) of stakeholder and scenario combinations. As such, their course of action might at very least be regarded as understandable if not correct under previous knowledge. However, as the academic and grey literature consensus appears to be moving away from this interpretation of flood protection, the current consensus may be losing its validity. Unfortunately, the system may now be too path-dependent to accommodate a widespread policy change. Under a new interpretation of flood protection the most commonly preferential policy was policy 2. But, a complete conversion back to policy 2 may not be physically, politically, or economically viable in those regions already triple-cropping (2/3 of An Giang Province). Policy 4, which was second most preferential, therefore requires serious consideration.

7.7 Conclusions from the MCDA process

This chapter has explored the dynamics and performances of various policies of first and second order adaptation under three scenarios of physical (sediment supply) change. The policy-scenario combinations tested were explored with a particular focus on their comparative performance for different wealth strata in the VMD's society. First the initial adaptation of increasing dyke height and switching to triple-cropping cropping (business usual) was compared with the situation had the action not been implemented. It was found that overall the policy currently being pursued is most desirable to wealthier farmers and government objectives of rice production and export. Dynamics were revealed which indicated that over the short term the business-as-usual policy may also appear advantageous to other wealth classes. However, due to an inherent threshold, across the 20 year simulation there was a net loss in most indicators. The losses incurred by median-low wealth farmers under triple-cropping, and indeed the 3-3-2 cropping cycle, were primarily linked to the new system reducing their resilience to fertiliser price shocks and causing debt spikes.

The advantages of policies involving double cropping and hence sediment deposition, which provides free nutrients to agriculture, were illustrated, especially from the perspective of poorer farmers. As the magnitude of the change experienced in the physical scenarios of sediment flux decline increases the effectiveness of double-cropping policies reduces. In the worst case scenario, i.e. a 94% decline in sediment flux by the simulation end, there is a growth in the comparative desirability of policy 4, in which sluice gates are opened in intense years of flooding and sediment deposition potential. In terms of the overall preferentiality of the four policies, when the different priority sets were considered, the policy which came out as optimal depended particularly on the approach towards flood protection. A strong argument is produced that under traditional, total-exclusion, ideas on flood protection (scenario X), the status quo of triple-cropping may be the correct course of action. But, with a growing consensus that strategic flooding is in fact a more sustainable and systemic approach, the optimal strategy would seem to shift towards either policies 2 or 4.

Chapter 8: Discussion and Conclusions

8.1 Summary of key findings

This project attempted an ambitious evaluation of the Vietnamese Mekong Delta dyke network as an adaptation in the strategically important rice-agriculture sector. Particularly, it focused on the role of sediment in the local socioeconomic system. Initially this thesis tracked the dyke network's evolution as an adaptation in policy; it then performed a correlational investigation into the changing trends which can be observed between the pre and post-adaptation environments; built a model of the system within which the adaptation acts, capable of revealing the causation of the undesirable trends identified; and finally, it evaluated policy options aimed at alleviating the adaptation action's negative impacts from the perspective of different delta stakeholder groups, and comparatively analysed the performance of different courses of action under different scenarios of sediment flux change.

In **Chapter 4** some key features were identified in the dyke network's policy background which had implications for the network's performance as an adaptation. Firstly, the action was adopted as an adaptation in the context of high path dependency of local actors, which had emerged due to past motivations of agricultural intensification. Due, in part, to this path dependency, it would seem the adoption of the dyke network as an adaptation took place without any form of systemic evaluation of the consequences. However, the absence of systemic evaluation might also be attributable to the national political context. During the period examined rapid decentralisation of power was taking place, leaving the implementation of adaptation policy to smaller regional departments that many argue, and indeed they themselves admitted in interview, do not currently have the technical capacity for such an evaluation. A particular oversight that was identified herein was the lack of consideration of the role of sediment within the local social-ecological system. Furthermore, while the role of sediment has been recognised in more recent national level policy documents (e.g. MDP, 2013), those documents flagged a lack of understanding of the socioeconomic trade-offs implicit in management decisions (now stated to be adaptation choices) affecting sediment deposition.

Through its examination of the impacts of the adaptation **Chapter 5** built understanding of the role of sediment in the northern VMD system. The survey detected the contribution made by sediment to the physical and economic productivity of the pre-adaptation (low dyke) agricultural system. Furthermore, it identified unsustainable trends in the yield/fertiliser ratio under the triple-cropping system which is associated with the adaptation. The fertilisation value of sediment deposition was valued at USD $170 per year (2014 prices) to the average farmer and USD $11 million to all farmers presently double-cropping in An Giang Province. At the same time, the survey results suggested around USD $15 million of potential value is being lost annually through high dykes' exclusion of sediment deposition. An additional trend identified by the survey was the reversal in the comparative efficiency advantage of operating smaller over larger farms - which may link to the sacrificing of sediment. In the pre-adaptation environment no measurable efficiency gain was found in having a larger farm, whereas in the post-adaptation environment a noticeable efficiency benefit was present for larger-scale farmers. It was hypothesised, but not causally proven, that this shift related to the large proportional and total increase in inputs required under the new system, which would increase the value of the efficiency enhancing practices and technologies available to wealthier farmers.

Having identified the above trends **Chapter 6** looked at building a model capable of understanding the dynamics which cause them. Despite some weaknesses in the secondary data available to build the model, a functional model was constructed. The model's ability to simulate the dynamics of the reference behaviour identified in **Chapter 5** was strong in terms of the relative errors produced. Furthermore, confidence was instilled through the comparison of those errors against errors produced by (loosely) comparable system dynamics modelling studies. The model's ability to forecast specific values however, was not its strength. Five relationships within the model were identified as being particularly poorly substantiated by secondary evidence. However, the model's sensitivity to the majority of the key parameters in those relationships proved to be low, especially when compared with other similar studies. One exception was identified; the farmers' cash profit was found to be highly sensitive to the rate of increase in fertiliser prices. As fertiliser prices are highly variable and difficult to predict no further accuracy in this parameter was attainable. Instead, the farmers' sensitivity to fertiliser prices was regarded as the first finding of the model. This finding sat well with the evidence presented by both secondary literature, and the primary qualitative data reported in **Chapter 4** and hence, the strong ability of the model to provide operational mechanisms for complex phenomena reported in the field was attested to.

With a functional model established, **Chapter 7** utilised it to evaluate various scenarios of physical change and second-order policy responses. For the business-as-usual policy (uninterrupted triple-cropping), a key finding of the model simulation is that poorer farmers were driven into spiralling debt by the interaction of the increased dependence on fertiliser inputs with their lower levels of technical efficiency, the lost sediment-bound nutrients, fluctuating fertiliser prices, and finer profit margins (as was hypothesised in **Chapter 5**). In general it was found that the transition from double to triple-cropping represented an exchange of sediment for additional rice and rice export profit. This exchange came at a small cost to the income of median-size farmers, and a major cost to the income, debt, and economic stability of poorer farmers. But, land-wealthier farmers benefitted on all economic indicators. Importantly, the survey's indication that the shift to triple-cropping exacerbates economic inequality was substantiated by the model.

Looking into the future, four rice cultivation policies were tested for their ability to meet the objectives of the various stakeholder groups considered over the next 20 years.

- If sediment deposition is to be abandoned altogether (policy 1), as the status quo broadly suggests, it was found that support, such as through a government subsidy, would likely be required to lessen the impact of fertiliser price increases and variability on farmers. For larger farms the additional income gained by the government from export taxes generated by the third crop could pay for this. For lower quartile size farms the government would likely incur a loss to do so but with out it, debt issues may be widespread. These issues, in combination with the ongoing decline of agricultural productivity and exacerbation of net subsidence rates due to nutrient and sediment exclusion, question the long-term sustainability of policy 1.
- Without subsidies, median and lower quartile size farmers would, in financial terms over the full simulation period of 20 years and under almost all different indicator weightings, have been better off had they remained double-cropping (policy 2). By ensuring free sediment-bound nutrients reach the floodplain policy 2 most effectively minimises income inequality between farm size classes over the course of the simulation. However, in the scenarios of higher sediment flux decline due to dam trapping, the performance of policy 2 rapidly declines over the course of the simulation.
- The 3-3-2 cropping rotation (policy 3), an effort to mitigate the impacts of the shift to triple-cropping, performed poorly. It was shown that interrupting the triple-cropping regime with regularity to allow sediment deposition was damaging to local farmers. The requirement imposed by triple-cropping on the farmer to maintain high season-to-season contingency funds meant the off-season often presented high debt problems, especially when the triennial opening of sluice gates coincided with years of low sediment deposition potential.
- Under the scenario of greatest sediment flux decline, the policy proposal which involved allowing inundation and sediment deposition erratically in years of high flood and deposition potential (policy 4) became more preferential from the perspective of most stakeholder weightings. In this scenario, a small amount of sediment deposition could be facilitated at relatively low detriment to other indicators. This finding sits well with recent international policy documents such as the Mekong Delta Plan (2013) which advocates a *room for river* policy which also involves strategic inundation and sediment deposition.

8.2 Policy Implications

In interview, those responsible for decision making on the management of the VMD dyke network reported that a key reason they are unable to enforce floodplain inundation and sediment deposition during the monsoon season (which would be in the interests of long-term delta sustainability), is that the farmers are economically dependent on the income drawn from wet-season rice. To a degree this claim was substantiated by the model, which suggested that both regular and sporadic breaks in the triple-cropping had a very high probability of driving farmers into debt (with the exception of large scale farmers). However, what the model also shows is that the farmers affected by this phenomenon would likely be better off (at least on a 10-20 year time scale) if they had never been forced into the shift to triple-cropping by the heightening of the dyke network. It must be recognised here, however, that the provincial government argued in interview that even if this were the case, their decision was justified by the lives the high dykes save from flooding disasters – others would argue that high dykes exacerbate flood risks further downstream, in dyke breach events, and in the long-term due to accelerating the threat of submersion due to sea-level rise. When the MADM was weighted to reflect these disadvantages of high dykes, the provincial decision makers' claim about the benefits of triple-cropping seems to be largely invalidated.

Local policy makers are now faced with a difficult decision. Practically, a full shift back to double cropping would be difficult for those farmers presently triple-cropping due to the path dependency many have established over recent years (having dispensed of their non-rice income generation activities) and the central government's operation of rice production targets. Furthermore, **Chapter 7** has shown that the impending loss of sediment in the Mekong River due to dam trapping, and the reduction in suspended sediment caused by the passing of water through sluice gates (rather than flooding by dyke overflow) may remove any benefits of facilitated flooding. However, for the one third of farmers who remain double-cropping there are significant economic benefits to be gained from not enforcing high dykes and the triple-cropping regime, at least in the short to medium term. There may also be cause for further research into the implications of the upstream dam developments on the potential for future serious flood surges in the VMD as any notable reductions in future extreme-event flooding intensity may reduce the mandate for high dykes, even under traditional flood-protection schools of thought.

Arguably the most equitable way forward is instead of pursuing either continuous triple-cropping or the 3-3-2 rotation to enforce sporadic high flood-year inundations. But, in the process consideration would also need to be put into the potential debt impact of fertiliser price spikes, particularly in the seasons following the fallow (inundation) seasons; subsidies or other support may be necessary. A further caveat of the high-year flooding policy (policy 4), not explored in any depth in this thesis, is that it requires environmental knowledge i.e. information systems capable of informing the relevant decision makers that a high flood year is impending in time for the farmers to make the necessary preparations and avoid losses.

The Vietnamese Mekong Delta faces a real threat to its long term integrity. None of the policies tested here have the potential to remedy that situation. Even under the least severe of dam development scenarios, dangerous sea-level rise is likely, at least over the next half a century, to be unavoidable. Nevertheless, this thesis supports the proposals in the Mekong Delta Plan that inflexible adherence to a policy of maximising rice production in the northern province of An Giang is worsening the situation in terms of both the longevity of the delta and the welfare of the most vulnerable in society. The policy explored here of opening sluice gates to allow flooding during severe monsoon seasons shows itself worthy of exploration, potentially providing multiple varied benefits. However, the precise nature of its implementation requires considerable further research, and potentially capacity building on the part of the responsible authorities.

8.3 Theoretical implications

This thesis has tracked the evolution, implementation and consequences of an adaptation. While vulnerability assessments and predictive climate change impact assessments are being produced in significant and increasing numbers, case studies, such as this, which report the full process of adaptation implementation and evaluation were shown in the **Chapter 2** literature review to be rare. Some key lessons have emerged from this case study which are addressed briefly below.

8.3.1 Adaptation in practice

Recent work reviewing adaptation policy in deltas highlights an explosion in the use of adaptation terminology, often in reference to policies which have been in place since long before climate change adaptation was a policy making driver (Dey et al. 2016; Haq et al., 2016; Hazra et al., 2016; Mensah et al., 2016). This trend is likely to continue as international climate agreements and organisations increasingly influence the policy making sphere. As discussed in **Chapter 2** the process of assimilating climate change adaptation into broader development policy, often called *mainstreaming*, can be beneficial as overlapping objectives (co-benefits) are most efficiently met (Suckall et al., 2014a). However, this thesis has highlighted that such policies may not be evaluated as adaptations, and when evaluated, may not perform well against common indicators in the academic literature (i.e. indicators of maladaptation). In the Mekong context this was in large part due to the implementation of adaptation in a path-dependent system (linked to agricultural intensification and specialisation). In a path-dependent context however, simply highlighting the presence of maladaptive traits proved to be of little value. Instead, a practical and comparative approach which first tests the performance of realistic options when implemented in the wider system, and then tests possible second-order adaptations (Birkmann, 2011) which can mitigate any negative impacts which are shown to be unavoidable, proved effective herein. Adaptation in complex systems subject to multiple drivers of change, such as deltas, is likely to be imperfect and second-order adaptation may be necessary. In light of this thesis I propose that further study, with reference to case studies, into the role, framing, and occurrence of second-order adaptation would be valuable. It may be that indicator based frameworks for adaptation evaluation, such as the maladaptation approach, can be improved by including reference to the feasibility and efficacy of second-order action. In broader terms, this simply means taking a more holistic approach appreciative of the full lifecyle and feedbacks of the adaptation process, as is encouraged in the resilience approach to decision making, rather than assessing the performance of success indicators at a static point in time.

8.3.2 Operationalising the resilience approach

In **Chapter 2**'s literature review the resilience approach was discussed and presented as an emerging and potentially effective approach to adaptation evaluation, but one that suffers from similar issues of real-world impracticality to those mentioned in relation to maladaptation above. Indeed, operationalising the resilience approach to adaptation decision making has thus far proved particularly challenging for researchers. Issues were highlighted such as (i) over-reliance on certain indicators to measure resilience (a problem shared with vulnerability approaches to policy targeting), (ii) reconciling the traditional static baseline of ecological resilience with the moving baseline conditions under climate change, and (iii) reconciling the desires of different stakeholders with different interpretations of what features a resilient system might preserve. Herein an methodology was executed akin to the resilience approach in its focus on feedback loops, thresholds, and the general ability of the system to buffer exogenous pressure (sediment supply decline). While this thesis still utilised a limited set of indicators, it addressed the first of the challenges facing the resilience approach (i) by concurrently exploring the system in question more broadly and seeking out the features that were driving undersirable trends in the indicators chosen. Notably, this identified dynamics linked to fertiliser price changes and their relationship with other componenets of the model (technicaly efficiency, debt, sediment deposition). In doing so I identified fertiliser price spikes and growth as key issues threatening to breach the resilience of the system (subject to a threshold) in the context of sediment exclusion, despite that fertiliser prices were not an indicator in the initial indicator set explored. The second issue mentioned above, (ii) of reconciling resilience with a moving baseline set of conditions, was ultimately overshadowed by the fact that in the Mekong context all pathways ultimately lead to an undesirable future of delta drowning (albeit with potential policies proposed to slow the onset). What was shown however, was the undesirability of a policy (policy 1 – triple cropping) that attempts to maintain the status quo (continuous rice cropping inside high protective dykes) despite growing exogenous pressures (baseline conditions). In essence, this highlights the dangers of measuring resilience in the traditional ecological manner, i.e. against a static baseline of system conditions. The final challenge of the resilience approach (iii) related to balancing different stakeholder interpretations of a desirable, resilient, system was addressed through multi-criteria analysis. The four policies looked at herein were evaluated from multiple perspectives, and their overall desirability across multiple objectives for the system was evaluated. This process highlighted what is likely to be a challenge common to all adaptation evaluation approaches – that the overall optimal policy (policy 4) is not the policy which is optimal for some of the different groups within society (land-wealthy vs land-poor). Usefully however, the unstable pillars in the system which threaten the resilience of the status quo (policy 1) were identified, pointing to the value of the (loosely) resilience-based methodology that was applied. An accurate prediction of the values associated with the threshold found in relation to fertiliser prices, sediment loss, and technical efficiency under the high-dyke adaptation was not made herein; this was to avoid stretching the forecasting power of the model further than the methodology allowed. An estimate might be possible with further research. A practical method for identifying the thresholds at which a system's resilience might break before, during, and after adaptation, may prove important in society's attempt to cope under intensifying climate change.

8.4 Methodological contribution

The broad components of this study's methodology (in system dynamics terminology) included: problem familiarisation (qualitative research); problem definition (survey execution); model construction (mixed qualitative and quantitative parameterisation); policy testing (model simulation); and results analysis and evaluation (multi-criteria analysis). A key feature of the study design utilised herein was that the system dynamics model was not constructed from the time-series data reported in the survey. The survey data (**Appendix 9.6**) was correlational and hence did not provide information about system functioning. Instead the survey data was used to validate the model, and the model's structure and functions were built from a comprehensive review (including primary data collected through expert and stakeholder consultation) of our existing knowledge of the system under observation. This approach means asking the question 'can the phenomenon observed be deduced by synthesising and exploring our current understanding of the system's functioning?'. The advantage of this approach is that it avoids the model becoming a self-fulfilling prophecy, simply able to replicate the trends it was built on. Learning about the system is facilitated on the basis that the whole (the model) is greater than the sum of its parts. In general, the disadvantage of this approach is that our existing knowledge might be incomplete or inaccurate (albeit that our knowledge will likely always be incomplete). In this study, validation of the model outputs against the survey data identified that our system knowledge was sufficient to answer the questions posed of the model. As explained in **Chapter 3** Ford (2010) sees this as the ultimate test of any model's worth. The model construction and simulation process then revealed dynamics within the system which were not previously appreciated (particularly the relationship between sediment and farmer debt). The strengths of the methodology were therein apparent. However, as expected, the model did not perform strongly as a forecasting tool. This fact, and indeed other facets of the methodology more broadly, do mean its outputs should be treated with a degree of caution. The unorthodox use of farmers estimates of sediment and time-series data, for example, and the use of disparate data sources (including personal intuition) in the model may have reduced the accuracy of the data being interpreted.

Chapter 3 highlighted the system dynamics modelling approach to adaptation evaluation as one growing in popularity. I would argue that the study I have outlined here only strengthens the case for expanding this research body, and indeed mainstreaming the integration of multi-criteria analysis into the system dynamics methodology in order to provide most practical decision-support. Climate change adaptation must contend with challenging dynamic problems and must do so rapidly with little room for error and often a low resource base to work with. This approach can sit complementary (answering different questions) to studies with a stronger predictive/forecasting objective to ensure robust decisions are prioritised and particularly that the distributional elements of climate change impacts and adaptations on society are fully considered.

8.5 Epilogue

Inevitably there were elements of this thesis which could have been improved upon with further research. I also took some risks; the utilisation of farmer observations of sediment deposition was somewhat unorthodox and as such I was unable to follow any established procedural framework. I contend however, that with this thesis I have opened up a new (yet muddy!) dimension to the evaluation of adaptation in the Mekong Delta, which ultimately may contribute to a more equitable and sustainable future within Vietnam and, potentially, in other deltas around the world facing similar problems. Driven by that belief, I am pursuing policy impact for the findings presented herein, in the short-term by feeding-back to the various decision makers I met while working in Vietnam. In the long term, I will be developing further iterations of the model, aiming to improve its simulation of the system, broaden its scope and increase its impact through collaboration with other projects.

Chapter 9: Appendices

9.1 Regional time-series data

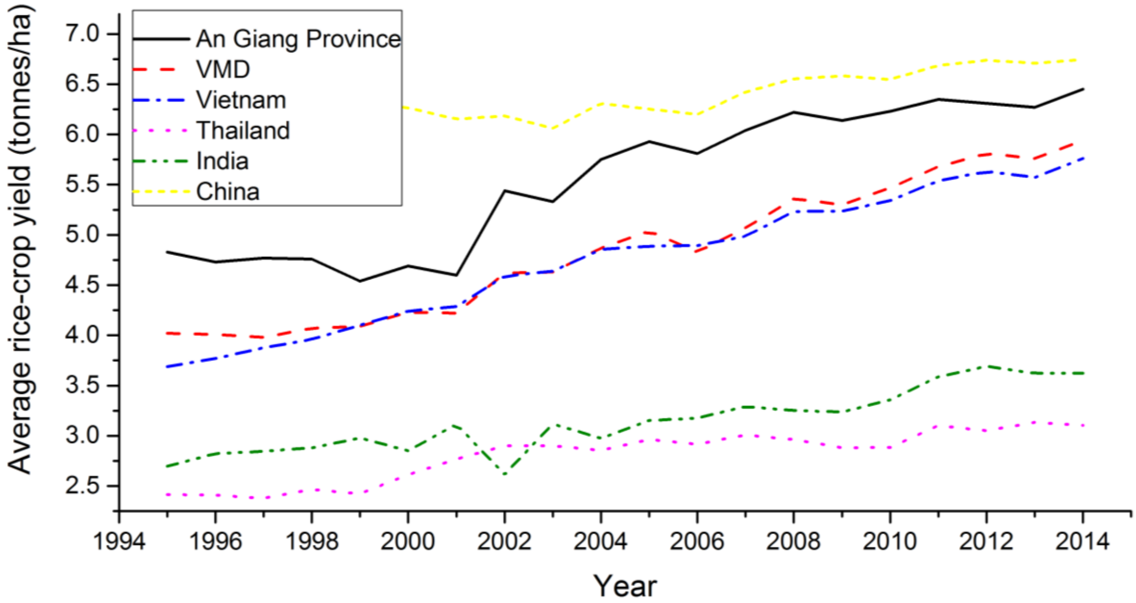


Figure 9.1 Rice-crop yield (tonnes/ha) time series data from four countries 1995-2014 (GSO, 2014 and World Bank, 2014)

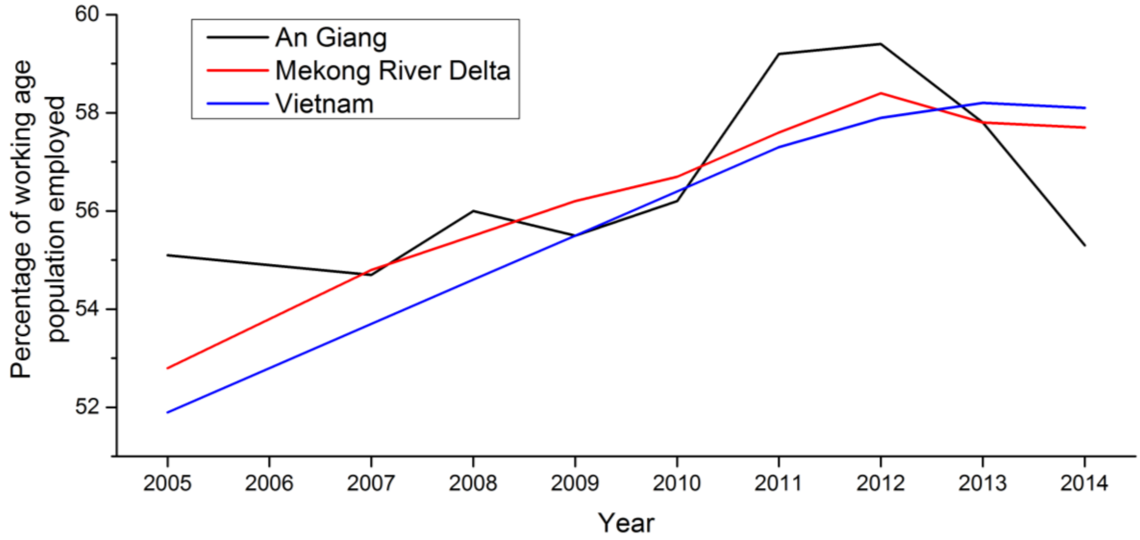


Figure 9.2 Time series data (2005-2014) on the percentage of the working age population in employment in Vietnam (GSO, 2014)

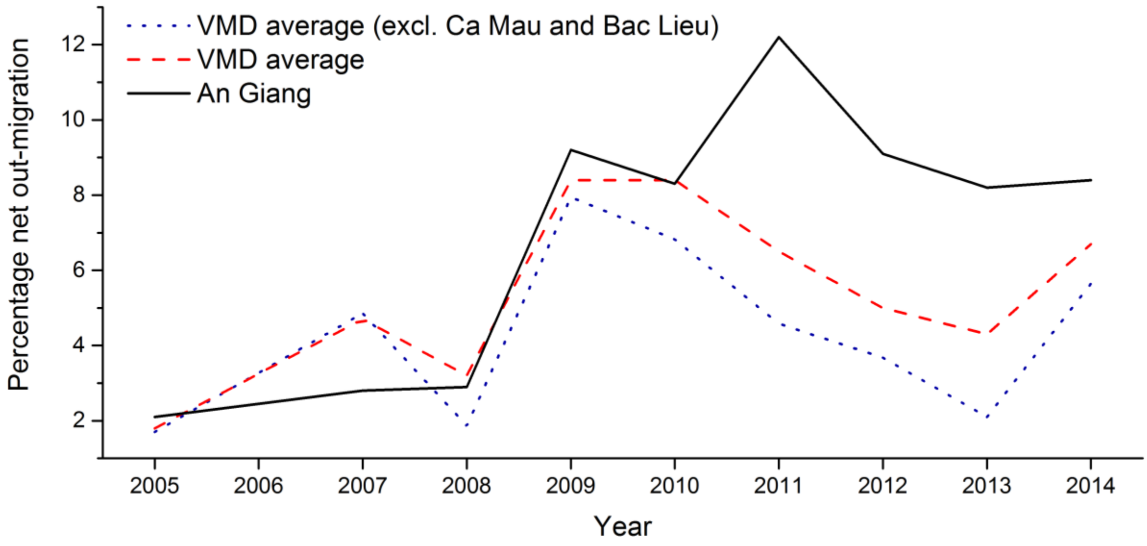


Figure 9.3 Time series data (2005-2014) on the net percentage of the population migrating out of the Vietnamese Mekong Delta provinces (GSO, 2014). The red dashed line represents the average net outmigration across all 13 VMD provinces. The blue dotted line shows the average across all delta provinces except for Ca Mau and Bac Lieu, two provinces with notably high rates of outmigration due to coastal erosion and land subsidence. In black, is An Giang province

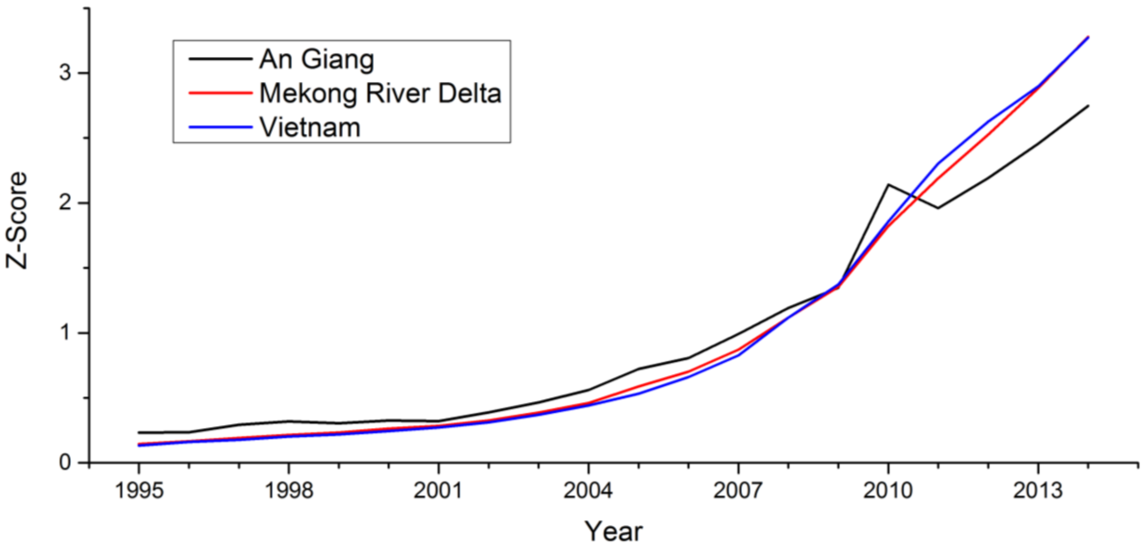


Figure 9.4 A comparative time-series of the total sales of goods and services in three regions of Vietnam, Z-scores are used to standardise the vales reported by GSO (2014) and highlight the relative rates of change

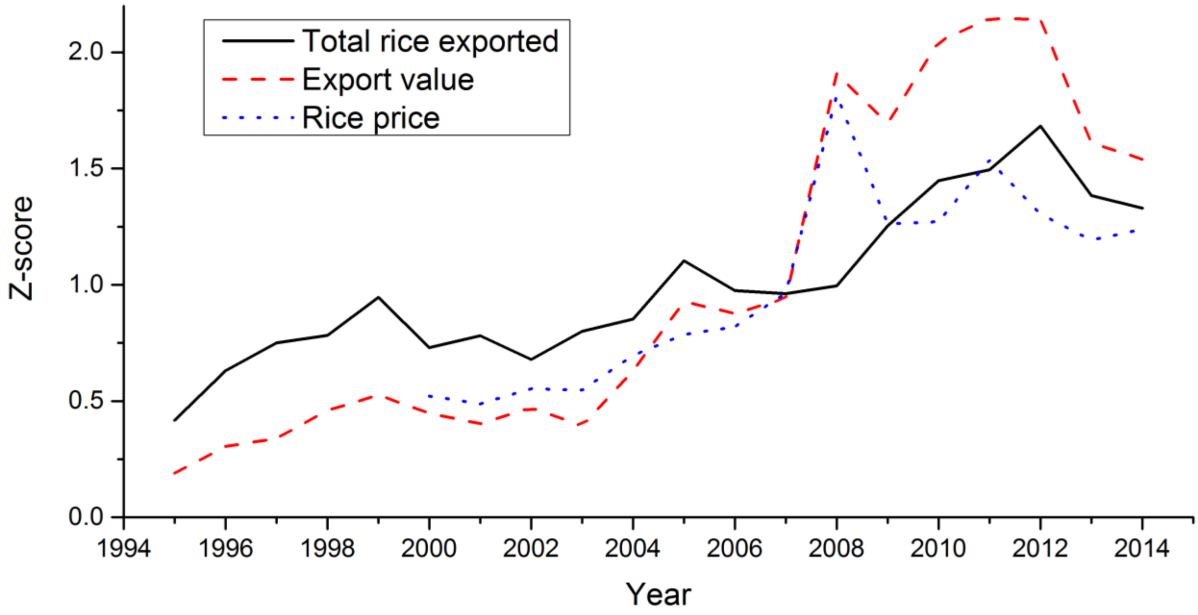


Figure 9.5 A time series (1995-2014) of rice exports and price in Vietnam. Z-scores are used to standardise the values and highlight rates of change in the three indicators of, rice price, total rice exported, and total export value (GSO, 2014)

9.2 Commune leader survey

1.) Can you estimate the population of your commune?

2.) Please can you describe the crops that are grown in your commune

Crop	Percentage of total
(e.g. rice)	(e.g. 80%)

3.) What variety of rice is used? And does everybody in the commune use the same variety?

4.) What percentage of farmers used machines in the commune?

5.) Can you describe what kind of dikes this commune has? How high are they?

6.) Can you describe any major problems this commune has had with pests and diseases on their crops

7.) Have you or members of your commune noticed a relationship between the sediment left by the flood on your fields and the yield of your agriculture?

9.3 Household survey

**Note to reader: This represents the pre-translation version of the survey. Some minor modifications to its language were made during translation in order to make it appropriate to the local context.*

1.) Which commune is your land in?

2.) Are you directly involved in managing that land?

Yes ☐ No ☐ Declined ☐

(end of qualifying questions)

3.) Do you own your land?

Yes ☐ No ☐ Declined ☐

4.) What crops do you grow on your land?

Decl. ☐

5.) What size is your crop land?

Units: Decl. ☐

6.) Has your land changed size or location since 2000?

Yes ☐ No ☐ Decl. ☐

7.) If yes, which year did it change?

Decl. ☐

8.) Can you estimate the shortest distance from your land to the closest river or canal?

Units: Decl. ☐

9.) How many people work on your land throughout the whole year? (not including harvest labourers)

Decl. ☐

10.) What kind of dike protection does your paddy have from the river?

High (2m+) ☐ Low (0-2m) ☐ None (0m) ☐ Decl. ☐

11.) Have the dikes around your land changed since 2000?

Got higher ☐ Got lower ☐ No change ☐ Decl. ☐

When did the dikes change in height?

Year: N/A ☐

12.) Can you estimate how long your land was flooded for in these years?

Years	Length of time	Units (days/weeks/months)	Decl.
2013			
2012			
2011			
2010			
2009			
2008			

13.) How many crops did you grow in each of these years (1, 2, or 3)?

2013: ☐ 2012: ☐ 2011: ☐ 2010: ☐ 2009: ☐ 2008: ☐

14.) What was your total yield from crops in 2013?

Units: Decl. ☐

15.) Can you estimate your yield in these years in comparison to 2013?

Much higher (double); Higher (50%); About the same; Less (around half); Much less (less than half) Decl. ☐

Years	Difference from 2013	Precise value (if possible)
2012		
2011		
2010		

2009		
2008		

16.) Can you estimate how much fertiliser you used in 2013?

Units: Decl. ☐

17.) Can you estimate your fertiliser use in these years in comparison to 2013?

Much higher (double or more); Higher (50%); About the same; Less (around half); Much less (less than half) Decl. ☐

Years	Difference from 2013	Precise value (if possible)
2012		
2011		
2010		
2009		
2008		

18.) Can you show me the area of your paddy which was covered with mud after the flood in 2013 (**See separate sheet**)?

Which one did the participant choose? Decl. ☐

19.) Can you describe how deep the mud was in 2013?

Where did they indicate on the scale? Decl. ☐

20.) How much mud was left by the flood in these years, compared to 2013 (**See last page**)? Decl. ☐

Much more (more than double); More; About the same; Less; Much less (less than half); None

Years	Difference from 2013	Which image did they choose?	How deep on the scale?
2012			
2011			
2010			
2009			
2008			

21.) Please provide any comments you have on the role of sediment in your rice production: Decl. ☐

9.4 Participant information sheet

Study Title: Developing a method of evaluating adaptation options to the impacts of altered hydrology and sediment loads in the Mekong Delta

Researcher: Alexander Chapman Ethics number: 8855

Please read this information carefully before deciding to take part in this research. If you are happy to participate you will be asked to sign a consent form. Xin vui lòng đọc kỹ thông tin này trước khi quyết định tham gia vào nghiên cứu này. Nếu bạn đồng ý tham gia, xin vui long kí tên vào giấy đồng ý

What is the research about, Nghiên cứu về vấn đề gì?

I am Alex Chapman, a PhD student studying climate change adaptation at the University of Southampton, UK. This study is part of my PhD research project. This study focuses on developing a method for evaluating adaptation options to altered hydrology and sediment loads. Tôi tên là Alex Chapman, nghiên cứu sinh về thích nghi với biến đổi khí hậu tại trường đại học Southampton, Anh. Nghiên cứu này là một phần của dự án tiến sĩ. Nghiên cứu này tập trung vào việc phát triển một phương pháp để đánh giá các lựa chọn thích ứng về việc thay đổi chế độ thủy văn và tải trầm tích

Why have I been chosen? Tại sao tôi được chọn?

You have been approached for this survey because you live and work in the Mekong Delta and are directly affected by the impacts of environmental change. Your voluntary participation and advice in this questionnaire will be highly valuable as it will help in terms of collecting the appropriate and needed data for this study. Therefore, your voluntary participation in this study is greatly appreciated. Ông/bà đã được tiếp cận cho khảo sát này bởi vì Ông/bà sống và làm việc ở ĐBSCL và biết về những ảnh hưởng trực tiếp do sự tác động của sự thay đổi môi trường. Sự nhiệt tình Ông/Bà về việc tham gia và tư vấn trong câu hỏi này sẽ được đánh giá cao cũng như nó sẽ giúp cho việc lựa thu thập các số liệu thích hợp và cần thiết cho nghiên cứu này. Do đó, sự tham gia nhiệt tình của Ông/bà trong nghiên cứu này được đánh giá cao.

What will happen to me if I take part? Điều gì sẽ xảy ra với tôi nếu tôi tham gia?

This study uses open closed questionnaire questions to which you provide responses to the best of your ability, however you do not have to if you do not want to. Your responses will be completely anonymous. Once the questionnaire is complete, your answers will be given an anonymised number and there will be no means for the researcher to identify who you are. It should take no longer than 30 minutes. Nghiên cứu này sử dụng câu hỏi đóng mở mở để Ông/bà cung cấp câu trở lời tốt nhất khả năng có thể của Ông/bà. Tuy nhiên, Ong/bà có thể không trả lời nếu như không muốn và những trả lời của Ông/bà sẽ được giữ bí mật. Sau khi hoàn tất bản câu hỏi, câu trả lời của Ông/bà sẽ được ẩn danh và sẽ không có phương tiện nào để các nhà nghiên cứu để xác định bạn là ai. Nó phải mất không quá 30 phút

Are there any benefits in my taking part? Có những thuận lợi gì trong việc tham gia của tôi?

You might not get any direct benefit for participating in this study personally but it is hoped that the findings of this study will benefit our understanding of the impact of altered hydrology and sediment loads on climate adaptation in the Mekong. In the long run this may inform and help the decisions you and the local government make on land management in your area. This study could be used as a medium for you to express your opinions regarding the topic. Ông/bà có thể không nhận được bất kỳ lợi ích trực tiếp của việc tham gia trong nghiên cứu này nhưng hy vọng rằng những phát hiện của nghiên cứu này sẽ có lợi cho sự hiểu biết của chúng ta về tác động của thay đổi thủy văn và phù sa bồi lắng thích ứng với khí hậu ở sông Mekong. Về lâu dài điều này có thể thông báo và giúp Ông/bà quyết định và chính quyền địa phương thực hiện quản lý đất đai trong khu vực của Ông/bà. Nghiên cứu này có thể được sử dụng như một phương tiện để bạn có thể bày tỏ ý kiến của bạn về chủ đề này

Are there any risks involved? Có những rủi ro liên quan gì không?

There are no significant risks involved in your participation in this study beyond those you would encounter in everyday life. You may leave or choose not to answer any questions if you would prefer. Không có những rủi ro đáng kể liên quan đến việc tham gia vào nghiên cứu này ngoài những người bạn sẽ gặp phải trong cuộc sống hàng ngày. Ông/bà có thể bỏ hoặc chọn không trả lời bất kỳ câu hỏi nếu Ông/bà muốn.

The data that will be collected will only be used for academic purposes. The responses will be completely anonymous as participants' names will not be recorded; instead they will be allocated pseudonyms such as 'expert on hydrology' or 'policy maker A' or 'local famer A'. All information will be treated as confidential and participants will not be identified through their responses. Các dữ liệu sẽ được thu thập sẽ chỉ được sử dụng cho mục đích học tập. Các câu trả lời sẽ là hoàn toàn bí mật như tên người tham gia sẽ không được ghi lại; thay vào đó họ sẽ được phân bổ bút danh như "chuyên gia về thủy văn" hay "Người làm chính sách A" hoặc "người dân địa phương A". Mọi thông tin sẽ được giữ bí mật và những người tham gia sẽ không được xác định thông qua những trả lời của họ.

The notes taken will be stored in a locked suitcase and all data will be kept secure on a laptop which will be protected by a password in order to be accessed. No one will be able to access the interview notes except for the researcher. Interview notes will be destroyed/ shredded and files deleted after the analysis. The data obtained from this study will not be passed to the third party. The data will be saved using code names and only the researcher has the sole access to these. Các ghi chú sẽ được lưu trữ cẩn thận và tất cả các dữ liệu sẽ được lưu giữ an toàn trên một máy tính xách tay sẽ được bảo vệ bởi một mật khẩu để truy cập. Không ai có thể truy cập các kết quả phỏng vấn, ngoại trừ các nhà nghiên cứu. Kết quả phỏng vấn sẽ bị hủy/ cắt nhỏ và các tập tin sẽ bị bị xóa sau khi phân tích. Các dữ liệu thu được từ nghiên cứu này sẽ không được thông qua bên thứ ba. Các dữ liệu sẽ được lưu lại sử dụng tên mã và chỉ các nhà nghiên cứu có quyền truy cập duy nhất để các.

Will my participation be confidential? Sự tham gia của tôi sẽ được bảo mật không?

Your participation in this study is anonymous. All data are treated as confidential. Sự tham gia Ông bà vào nghiên cứu này là vô danh. Tất cả các dữ liệu được coi là bí mật.

The data that will be collected will only be used for academic purposes. The responses will be completely anonymous as participants will not be asked for their names. All information will be treated as confidential and participants will not be identified through their responses. The researcher will not be able to trace you through your responses. Các dữ liệu sẽ được thu thập sẽ chỉ được sử dụng cho mục đích học tập. Các câu trả lời sẽ là hoàn toàn vô danh cũng như những người tham gia sẽ không được yêu cầu biết tên của họ. Mọi thông tin sẽ được giữ bí mật và những người tham gia sẽ không được xác định thông qua trả lời của họ. Các nhà nghiên cứu sẽ không có thể theo dõi Ông/bà thông qua trả lời của Ông/bà.

What happens if I change my mind? Điều gì xảy ra nếu tôi thay đổi suy nghĩ?

Participation in this study is completely voluntary. Participants may withdraw from this study at anytime. Sự tham gia trong nghiên cứu này là hoàn toàn tự nguyện. Người tham gia có thể rút khỏi nghiên cứu này bất cứ lúc nào.

What happens if something goes wrong? Điều gì xảy ra nếu có điều gì sai?

If the participant have any concern or complaint about this study, they may contact Head of Research Governance, Dr Martina Prude via email at mad4@soton.ac.uk or call via this number: 02380 595058. Nếu người tham gia có bất kỳ mối quan tâm hoặc khiếu nại về nghiên cứu này, họ có thể liên hệ với Trưởng Quản trị nghiên cứu, Tiến sĩ Martina Prude thông qua email mad4@soton.ac.ukhoặc gọi qua số này: 02380 595058

Where can I get more information? Tôi có thể lấy thêm thông tin ở đâu?

If the participants have any questions about this study, they may contact the researcher via email at adc1g12@soton.ac.uk. Nếu những người tham gia có thắc mắc về nghiên cứu này, họ có thể liên hệ với các nhà nghiên cứu thông qua email tại adc1g12@soton.ac.uk.

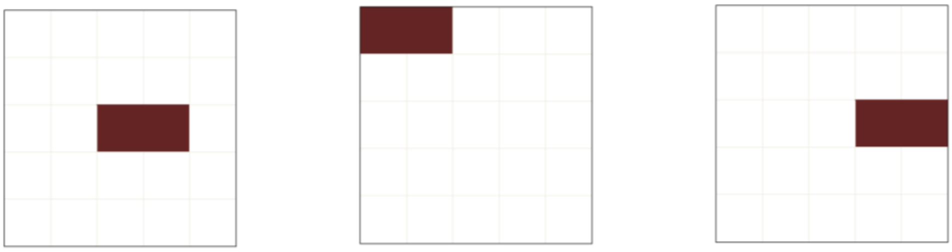
9.5 Visual aid

A. Không có phù sa bồi lắng trên ruộng hoặc không có lũ

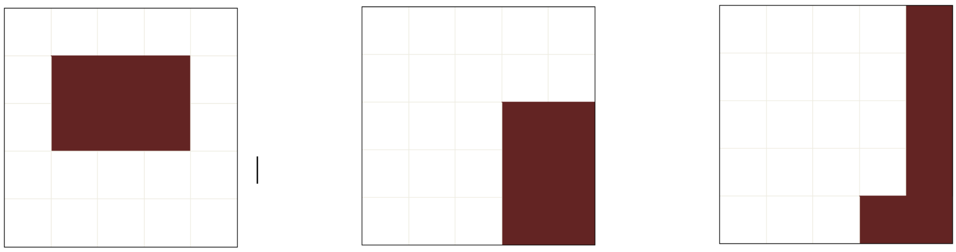
B. Hầu hết đất canh tác được bao phủ bởi phù sa bồi lắng (80-100%)

C. Lượng phù xa bồi lắng khoảng (60-80%)

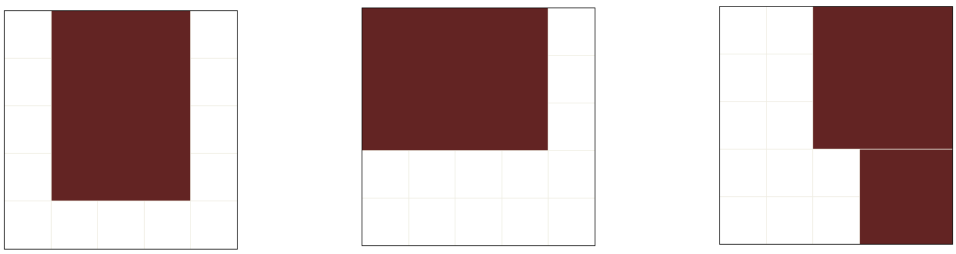
D. Chỉ có một phần diện tích (0-20%) được phù sa bồi lắng



E. Một phần diện tích (20-40%) được bao phủ sa bồi lắng



F. Khoảng (40-60%) diện tích đất canh tác được phù sa bồi lắng



9.6 Full survey results

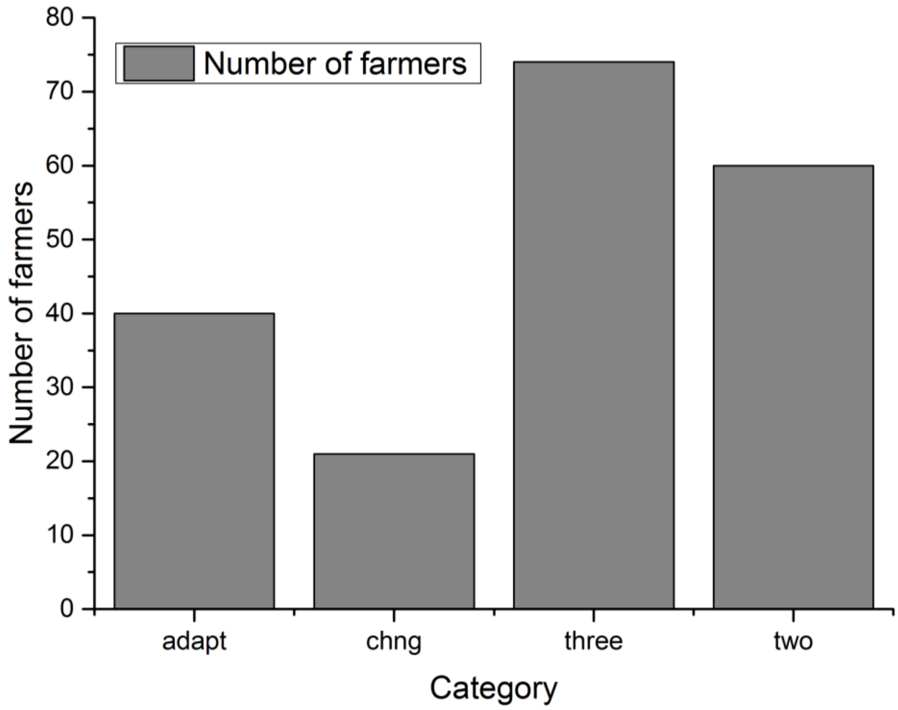


Figure 9.6 The number of farmers interviewed in each sub-category in An Giang Province (all Soc Trang farmer data utilised herein (n=118) came from triple-cropping farmers)

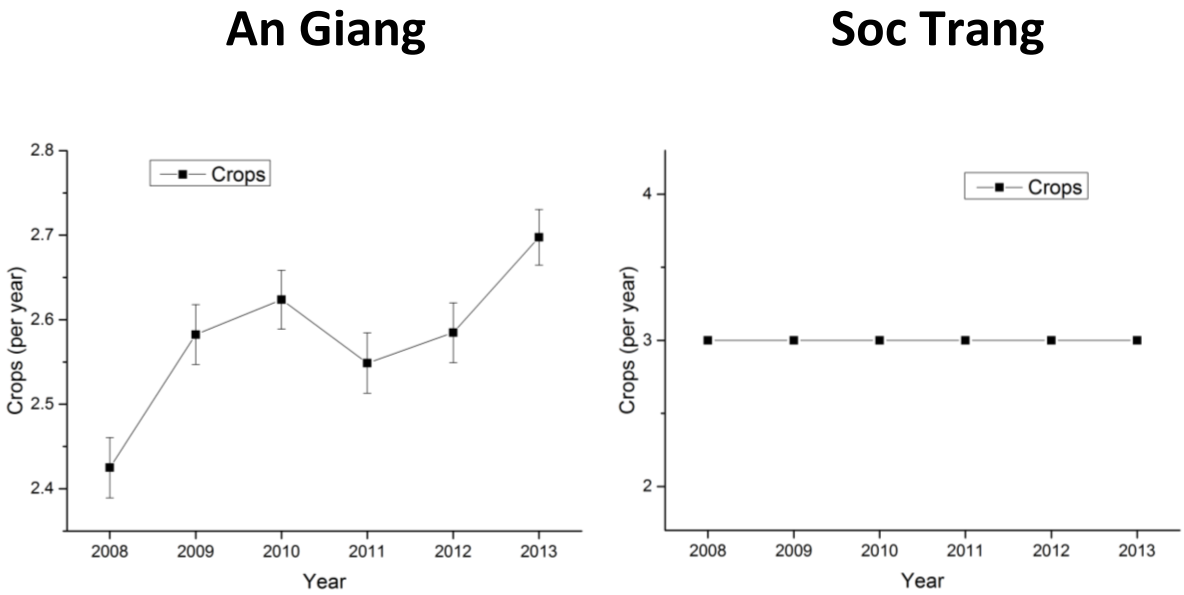


Figure 9.7 The average number of rice-crops being grown per year (with standard error bars) in two VMD provinces, as reported by farmers in the survey (note y-axis are scaled differently)

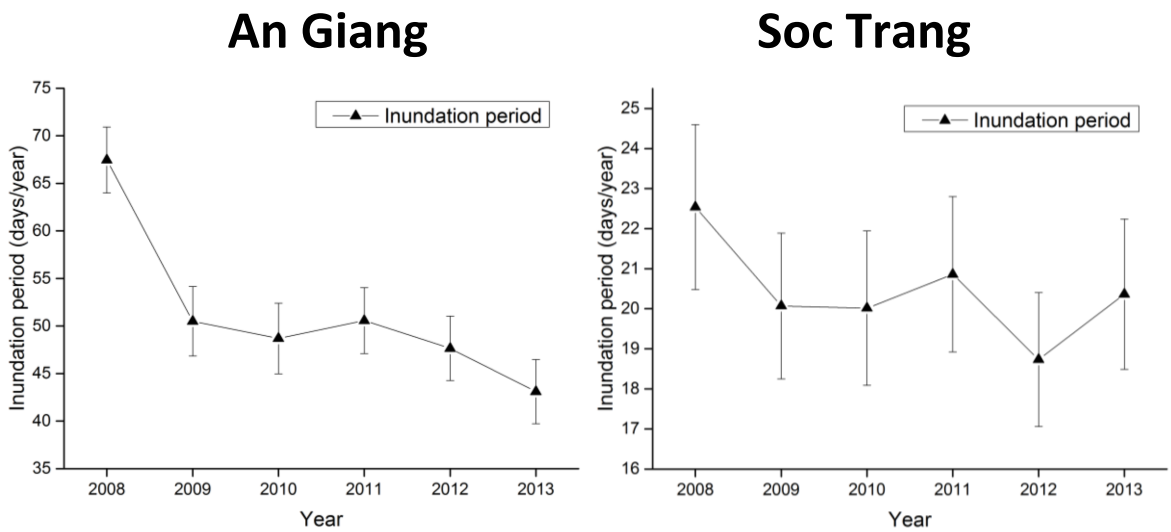


Figure 9.8 The average number of days per year (with standard error bars) that paddy floodplains were inundated in two VMD provinces, as reported by farmers in the survey (note y-axis are scaled differently)

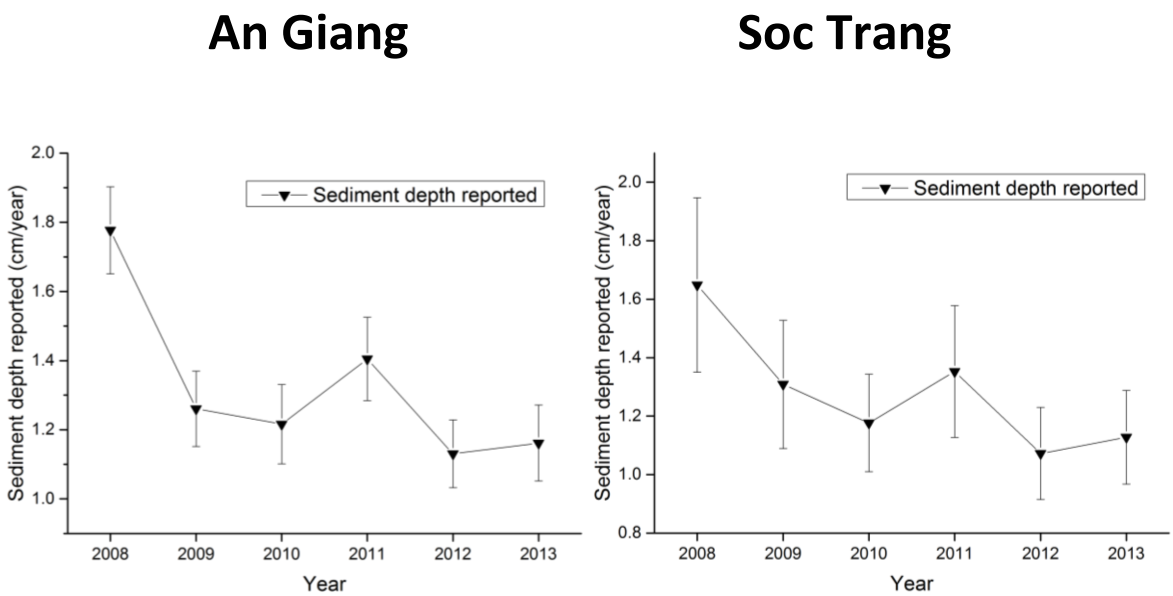


Figure 9.9 The average depth of sediment (with standard error bars) that farmers reported being deposited on paddy floodplains each year (note y-axis are scaled differently)

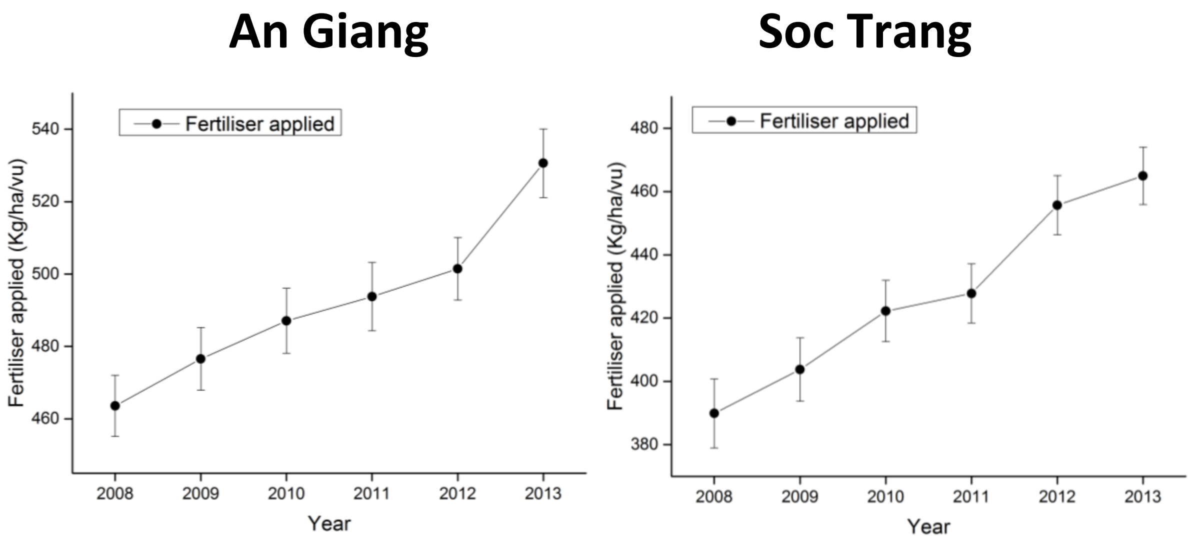


Figure 9.10 The average amount of fertiliser applied per season per hectare (with standard error bars) in two VMD provinces, as reported by farmers in the survey (note y-axis are scaled differently)

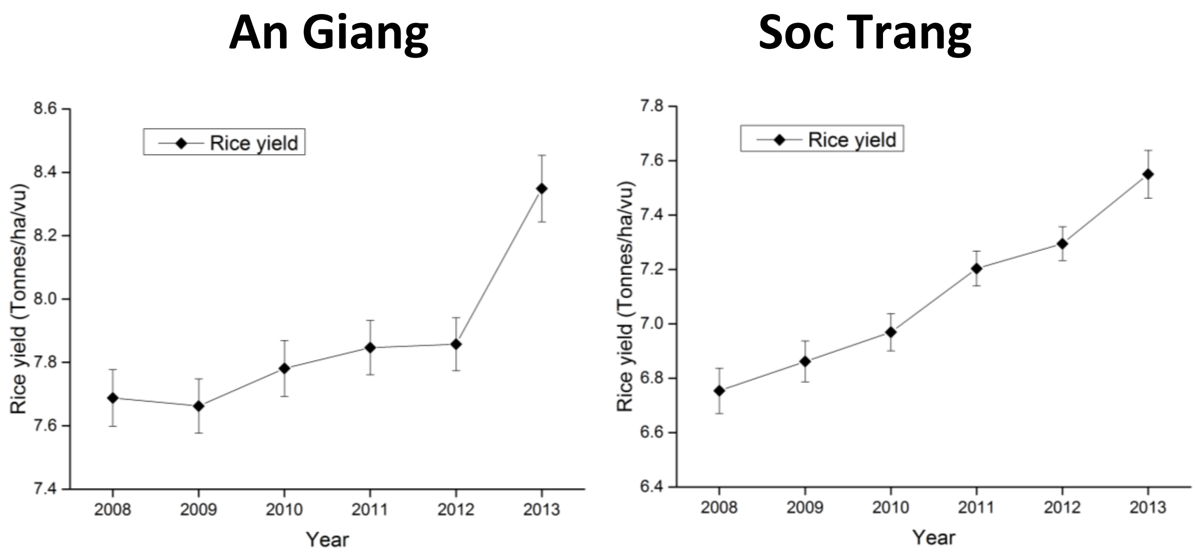


Figure 9.11 The average yield achieved per season per hectare (with standard error bars) in two VMD provinces, as reported by famers in the survey (note y-axis are scaled differently)

9.7 Model secondary data validation

Table 9.1: The categories of surveyed farmers and the code corresponding to the equivalent model set-up

Survey sub-group	Model simulation code
Three	Model3
Two	Model2
Chng	Modelc

Table 9.2: ANOVA results comparing the absolute values of all modelled and field datasets. Highlighted are the relevant results.

Comparison	Difference	Lower bound	Upper bound	P-value
model2-chng	1.505	0.5149	2.496	0.0002
model3-chng	0.07855	-0.9118	1.069	0.9999
modelc-chng	1.139	0.1494	2.130	0.0133
three-chng	1.439	0.3261	2.553	0.0032
two-chng	0.5571	-0.4879	1.602	0.6511
model3-model2	-1.426	-1.901	-0.9517	0.0001
modelc-model2	-0.3654	-0.8405	0.1096	0.2408
three-model2	-0.06565	-0.7619	0.6306	0.9998
two-model2	-0.9481	-1.528	-0.3676	0.0001
modelc-model3	1.061	0.5861	1.536	0.0001
three-model3	1.361	0.6647	2.057	0.0001
two-model3	0.4785	-0.1019	1.059	0.1743
three-modelc	0.2998	-0.3964	0.9961	0.8232
two-modelc	-0.5826	-1.163	-0.00214	0.0485
two-three	-0.8824	-1.654	-0.1103	0.0144

Table 9.3: ANOVA results comparing the rates of change of all modelled and field datasets. Highlighted are the relevant results.

Comparison	Difference	Lower bound	Upper bound	P-value
model2-chng	0.06740	0.02773	0.1071	0.0001
model3-chng	0.04581	0.006128	0.08549	0.0129
modelc-chng	0.03893	-0.00075	0.07861	0.0581
three-chng	0.02641	-0.01824	0.07106	0.5404
two-chng	0.06872	0.02684	0.11061	0.0001
model3-model2	-0.0216	-0.04063	-0.00256	0.0156
modelc-model2	-0.02848	-0.04751	-0.00944	0.0003
three-model2	-0.041	-0.06894	-0.01305	0.0004
two-model2	0.001317	-0.02196	0.02460	0.9999
modelc-model3	-0.00688	-0.02592	0.01215	0.9075
three-model3	-0.0194	-0.04735	0.008545	0.3540
two-model3	0.02291	-0.00037	0.04620	0.0567
three-modelc	-0.01252	-0.04047	0.01543	0.7972
two-modelc	0.02980	0.006514	0.05308	0.0036
two-three	0.04232	0.01132	0.07331	0.0014

9.8 Model sensitivity

Table 9.4: Full list of the different indicators' sensitivities to different levels of variation in different model parameters. Indicators: desired level of fertilisation (DF); rice yield (RY); cash profit (CP; and technical efficiency (TE). Values greater than 0.1 are highlighted in red.

Parameter	Level of variation (+/-)	Indicator			
		DF	RY	CP	TE
Fertiliser price rate of change	10	0.123	0.0486	0.7477	0.0570
	20	0.004	0.0040	0.6737	0.0545
	30	0.152	0.0086	0.6206	0.0423
	40	0.0591	0.0110	0.5487	0.0390
Farmer's desire to invest	10	0.0463	0.0107	0.1509	0.0335
	20	0.0376	0.0047	0.1255	0.0341
	30	0.0382	0.0046	0.1075	0.0340
	40	0.0159	0.0064	0.0751	0.0358
Farmer's backup fund fraction	10	0.0077	0.0012	0.0155	0.0076
	20	0.0092	0.0021	0.0162	0.0075
	30	0.0093	0.0029	0.0116	0.0065
	40	0.0065	0.0038	0.0403	0.0026
Time to nutrient availability	10	0.0077	0.0031	0.0202	0.0036
	20	0.0152	0.0001	0.0170	0.0028
	30	0.0187	0.0015	0.0159	0.0025
	40	0.0185	0.0013	0.0164	0.0023
Technological depreciation rate	10	0.0224	0.0107	0.0106	0.0487
	20	0.0588	0.0129	0.0030	0.0468
	30	0.0608	0.0141	0.0053	0.0408
	40	0.0633	0.0148	0.0037	0.0401

9.9 Effect of discounting

Table 9.5: The fractional change in each of the monetary indicators which occurred when discounting was applied. Values are calculated from the raw, mean, outputs of the 100 Monte Carlo runs performed for each policy/scenario combination.

		LQ			Median			UQ		
Policy	Code	Government income	Household income	Household debt	Government income	Household income	Household debt	Government income	Household income	Household debt
Triple	A1/B1/C1	0.74	0.75	0.60	0.74	0.75	0.56	0.72	0.75	0.59
Double	A2	0.74	0.74	0.57	0.74	0.74	0.57	0.74	0.74	0.58
332	A3	0.74	0.75	0.59	0.74	0.75	0.55	0.74	0.75	0.55
Highyear	A4	0.74	0.75	0.60	0.74	0.75	0.59	0.74	0.75	0.58
Double	B2	0.74	0.75	0.57	0.74	0.75	0.57	0.74	0.75	0.58
332	B3	0.74	0.75	0.59	0.74	0.75	0.55	0.74	0.75	0.55
Highyear	B4	0.73	0.75	0.59	0.73	0.75	0.58	0.73	0.75	0.58
Double	C2	0.74	0.75	0.56	0.74	0.75	0.57	0.74	0.75	0.58
332	C3	0.74	0.75	0.59	0.74	0.75	0.55	0.74	0.75	0.55
Highyear	C4	0.73	0.75	0.59	0.73	0.75	0.57	0.73	0.75	0.57

9.10 Model outputs

Table 9.6: The model outputs **for a farm of LQ size** (averaged over 100 Monte-Carlo simulations) are shown for eight indicators of model performance: RY – total Rice Yield (Kg/ha), GP – total Government Profit ('000 VND/ha), S – total Sediment deposition (Kg/ha), HI – average Household disposable Income ('000 VND/season), IS – average household Income Stability (frequency), HD – total Household Debt ('000 VND), DP – Debt Prevalence (% households), FP – Flood protection (unitless). GP, HI, and HD, have been discounted at 3.5% per year and the indicators are unweighted.

Policy	Code	RY	SE(RY)	GP	SE(GP)	S	SE(S)	HI	SE(HI)	IS	SE(IS)	HD	SE(HD)	DP	FP
Triple	A1/B1/C1	520263	2355	154361	649	0	0	-933	79	29	1	19854	1523	97	3
Double	A2	362880	682	109740	368	5486	27	243	72	22	0	167	58	9	1
332	A3	466926	1549	138988	467	1943	16	-830	68	27	0	10023	909	93	2
Highyear	A4	480512	2181	143270	620	1844	49	-834	73	27	1	12442	1020	95	3
Double	B2	359857	789	108856	375	4577	23	161	67	22	0	201	57	12	1
332	B3	465550	1605	138568	476	1638	14	-853	69	28	0	11660	983	94	2
Highyear	B4	498673	2138	147602	571	989	37	-877	75	28	1	15169	1143	95	3
Double	C2	355363	959	107542	392	3321	19	40	63	23	0	314	74	18	1
332	C3	463806	1657	138020	491	1231	11	-887	69	29	0	14175	1078	98	2
Highyear	C4	510358	2121	150601	597	561	34	-895	73	29	1	16244	1113	98	3

Table 9.7: The model outputs **for a farm of LQ size** (averaged over 100 Monte-Carlo simulations) are shown for eight indicators of model performance: RY – total Rice Yield (Kg/ha), GP – total Government Profit (‘000 VND/ha), S – total Sediment deposition (Kg/ha), HI – average Household disposable Income (‘000 VND/season), IS – average household Income Stability (frequency), HD – total Household Debt (‘000 VND), DP – Debt Prevalence (% households), FP – Flood protection (unitless). GP, HI, and HD, have been discounted at 3.5% per year and the indicators are unweighted.

Policy	Code	RY	SE(RY)	GP	SE(GP)	S	SE(S)	HI	SE(HI)	IS	SE(IS)	HD	SE(HD)	DP	FP
Triple	A1/B1/C1	527451	2044	157382	555	0	0	1575	50	8	0.33	1683	321	39	3
Double	A2	364306	736	110417	367	5486	27	2195	44	21	0.08	303	93	12	1
332	A3	470992	1418	140912	430	1943	16	1520	42	12	0.27	1563	313	40	2
Highyear	A4	484821	2080	145269	575	1844	49	1566	45	11	0.31	1978	317	49	3
Double	B2	361614	848	109650	377	4577	23	2074	42	21	0.09	289	86	11	1
332	B3	469675	1439	140517	434	1638	14	1464	42	13	0.27	1802	340	44	2
Highyear	B4	504294	1941	150011	518	989	37	1563	44	10	0.32	1675	279	44	3
Double	C2	357332	966	108432	386	3321	19	1879	39	21	0.11	309	85	12	1
332	C3	468030	1490	140016	444	1231	11	1382	42	13	0.28	1936	360	42	2
Highyear	C4	516878	1932	153280	548	561	34	1587	44	9	0.32	1383	269	34	3

Table 9.8: The model outputs **for a farm of LQ size** (averaged over 100 Monte-Carlo simulations) are shown for eight indicators of model performance: RY – total Rice Yield (Kg/ha), GP – total Government Profit (‘000 VND/ha), S – total Sediment deposition (Kg/ha), HI – average Household disposable Income (‘000 VND/season), IS – average household Income Stability (frequency), HD – total Household Debt (‘000 VND), DP – Debt Prevalence (% households), FP – Flood protection (unitless). GP, HI, and HD, have been discounted at 3.5% per year and the indicators are unweighted.

Policy	Code	RY	SE(RY)	GP	SE(GP)	S	SE(S)	HI	SE(HI)	IS	SE(IS)	HD	SE(HD)	DP	FP
Triple	A1/B1/C1	532011	1896	155698	506	0	0	6188	84	3	0	601	141	19	3
Double	A2	366017	699	111066	367	5486	27	5558	84	20	0	1034	210	32	1
332	A3	474972	1366	142624	428	1943	16	5787	78	9	0	1505	310	46	2
Highyear	A4	487802	2014	146770	563	1844	49	5922	81	7	0	1762	266	45	3
Double	B2	363964	830	110502	375	4577	23	5392	81	20	0	937	194	33	1
332	B3	473791	1402	142268	432	1638	14	5691	77	9	0	1524	308	45	2
Highyear	B4	507195	1956	151558	527	989	37	5995	79	5	0	1092	193	31	3
Double	C2	360259	1000	109480	397	3321	19	5102	77	20	0	811	177	27	1
332	C3	472185	1428	141786	436	1231	11	5547	77	9	0	1235	269	39	2
Highyear	C4	520229	1920	154957	537	561	34	6110	77	4	0	564	141	19	3

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