UNDERSTANDING COMPLEXITY IN NATURE-BASED AND HUMAN-DOMINATED RIVER DELTA ECOSYSTEMS

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ABSTRACT

Over the past centuries, human influence over nature has risen to the level that we are now considered to live in the Anthropocene. River deltas globally epitomize this increased influence, as places where abundant availability of freshwater and fertile soils has attracted high socio-economic activity and where humans gradually moved to shape the land to their needs. The human quest for control and the relatively stable environment nurtured a paradigm of steady-state thinking. Yet, with human-induced climate change and the severe impacts of that on low-lying, densely populated coastal areas, the steady-state paradigm is being rapidly replaced with a paradigm that sees social-ecological systems as dynamic, and that humans need to adapt. While approaches such as adaptive management and nature-based solutions offer partial solutions to do so, there are deeper questions regarding complexity that need to be addressed. This thesis therefore explores how complex adaptive systems thinking, within adaptive management and nature-based solutions approaches, can be used to improve the adaptive capacity of river delta ecosystems. Using mixed-methods approaches and case studies in the Rhine-Meuse Delta of the Netherlands and the Mekong Delta in Viet Nam, it investigates how local actors use elements of complexity within the realm of freshwater management, and how their interpretations of complexity can be used to inform an integrated, broad approach to understanding complexity. The study finds that interpretation of complexity-related aspects is highly case-specific, but that localized, spatiotemporal analyses of complexity can help in advancing the understanding of complex behaviour. Case studies can help in advancing application and assessment frameworks that are better informed by experience on the ground and the availability of data. An integrated approach across five identified dimensions of dealing with complexity can help in improving adaptive capacity of delta ecosystems in transition.

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Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

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1 INTRODUCTION

1.1 Background

Few themes are as classic as that of the human relationship with nature. It is a theme that has captivated scholars and philosophers throughout scientific history. As humans are now thought to define a whole new geological era through their domination of nature (Steffen et al., 2007) while struggling to deal with the self-inflicted climate change impacts of that same human domination, it is a theme that is as pertinent as ever.

> "Many circumstances conspire to invest with great present interest the questions: how far man can permanently modify and ameliorate those physical conditions of terrestrial surface and climate on which his material welfare depends; how far he can compensate, arrest, or retard the deterioration which many of his agricultural and industrial processes tend to produce; and how far he can restore fertility and salubrity to soils which his follies or his crimes have made barren or pestilential."
>
> George Perkins Marsh (1864) *Man and Nature; or, physical geography as modified by human action.*

Over the past centuries, the ability of humans to control nature has taken flight (Steffen et al., 2007). This ability showed itself in the alteration of landscapes, and most clearly in those places where ecosystem services provided are of great use to humans. River delta ecosystems feature prominently here, given the abundant availability of freshwater and fertile soils. This is one of the main reasons why river deltas are home to 7% of the world population while they only cover 1% of the global land surface (Szabo et al., 2016).

River delta ecosystems are deeply dynamic by nature, and human activity is closely interlinked with those natural dynamics (Morita and Suzuki, 2019). Natural variability in these areas is driven by powerful natural processes, such as river meandering or alternating coastline progression and regression as a result of changes in river flow and sediment load. The changes in the natural ecosystem required continuous adjustments of humans (Bianchi, 2016).

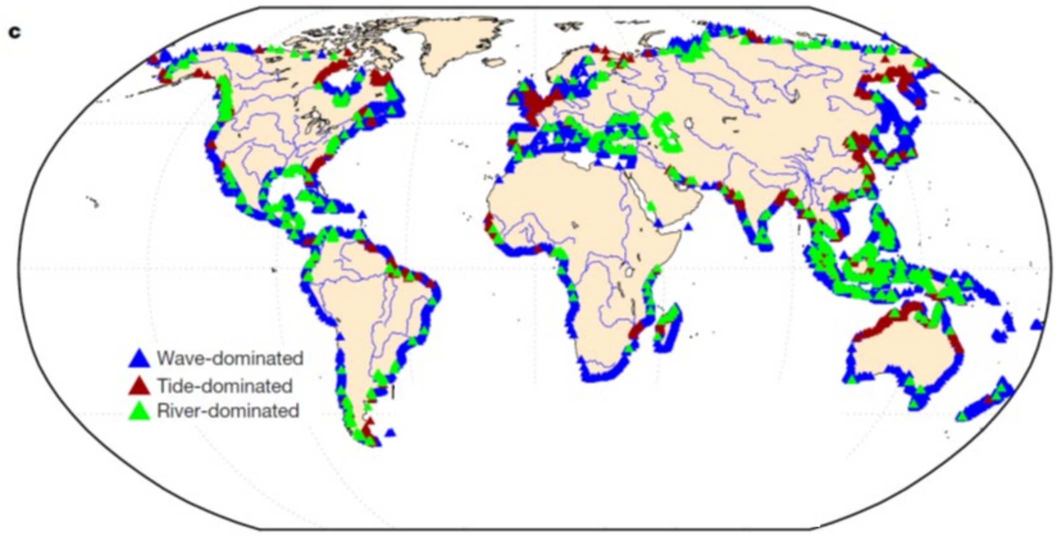

Figure 1 Map showing deltas globally, classified as wave-, tide-, or river-dominated. Adapted from (Nienhuis et al., 2020)

These river delta ecosystems have thereby become a primary display of the human domination of nature. Most modern river deltas were formed when global sea level stabilized within ranges of a few meters, around 6000 years ago (Kuenzer and Renaud, 2012). Over the course of modern history, human interventions started to influence the natural dynamics in these systems more strongly. This started locally, but as resources became more plenty and organizations emerged, human interventions started to affect the system level. Human interventions in river delta ecosystems have succeeded to secure freshwater supply, prevent floods and control water quality (Baldassarre et al., 2013; van de Giesen, 2020).

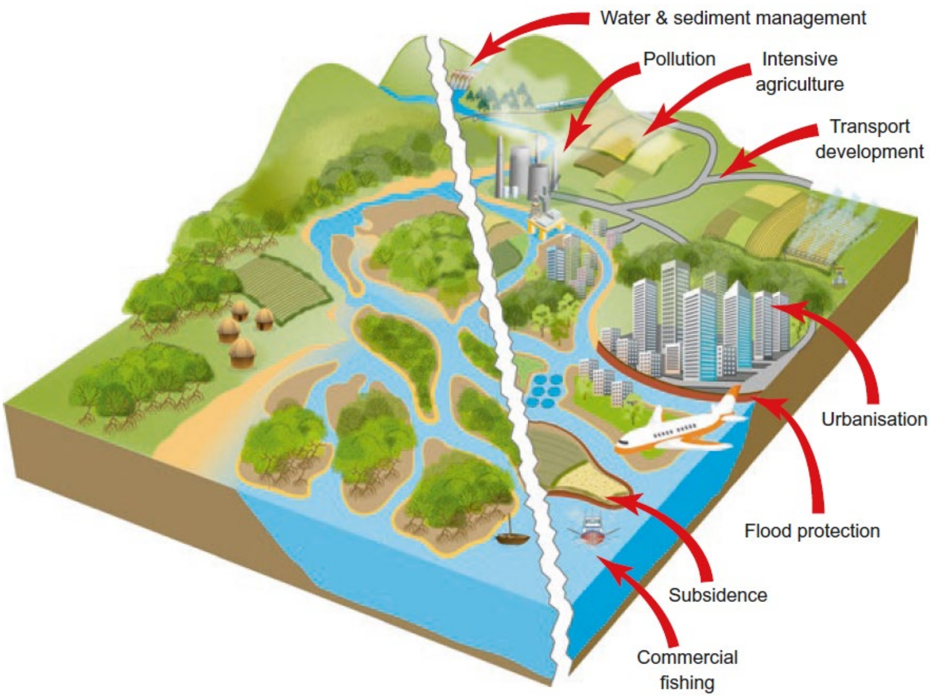

Figure 2 Illustration of nature-dominated or pristine river delta (left) versus a human-dominated river delta (right). Source: (Nicholls et al., 2020)

Many human interventions in river delta ecosystems have, purposefully or unintentionally, attenuated natural dynamics. Rivers and coastlines have been trained to fixed geographic layouts, tidal influences on surface water salinity levels have been removed and vegetation patterns have become more stationary. These effects, combined with the relatively stable state of natural dynamics within the Holocene (Rockström et al., 2009), strengthened the dominant paradigm that management practices of these systems should aim to maintain the equilibrium or stable state .

changing circumstances (Schoeman et al., 2014). This evolution in paradigms can also narrated through the philosophical understanding of the relationship between man and nature, where the dominant image of this relationship is shifting from human as master over nature, to human as partner with nature (Van den Born 2008).

At a more mundane level, this evolution in paradigms has led to an updating of practice-oriented frameworks. New frameworks have been developed that are directly or indirectly using complex adaptive systems thinking and seek to help practitioners in increasing the adaptive capacity of ecosystems, including in river delta ecosystems. Notable frameworks are those of adaptive management (Walters, 1986) and nature-based solutions (IUCN, 2016). Adaptive management has steadily gained popularity over the past decades within ecology, and over the last two decades also in the water management space (Schoeman et al., 2014). Nature-based solutions is a more recent collection of approaches including within the engineering and natural resources management space, that seek to better recognize and make use of natural processes for human benefits (Eggermont et al., 2015).

Both adaptive management and nature-based solutions promote a better understanding of natural dynamics, the role of such dynamics and how they can be used in a way that they help achieve human objectives. They embrace elements of uncertainty and temporal variability into updated management strategies for ecosystems. They both link strongly to the popular research field of resilience thinking (Folke, 2006). At the surface, they are therefore synergistic efforts towards implementing the new desired relationship between human and nature.

There are however deeper theoretical and unresolved practical questions, as to how these approaches can ultimately contribute to increased adaptive capacity of river delta ecosystems. From understanding the implications of implementing adaptive management practices and nature-based solutions, to identifying metrics for monitoring attributes of complexity such as resilience, there is a critical role for the people who are directly or indirectly involved in the management of these ecosystems. Their understanding of complexity in human-dominated and nature-based river delta ecosystems is what guides human interventions, and what can help advance the theoretical discussions around complexity and topics such as resilience.

While much progress has been made in furthering the scientific understanding of ecosystems as complex adaptive systems, limited knowledge exists as to how this evolving understanding is applied, let alone how it results in changes in the adaptive capacity of these ecosystems (United Nations Environment Programme, 2021). The strong theoretical advancements need further empirical evidence, studying the interpretation, application and results. A study of these aspects can help close a feedback loop and ensure that the application-oriented frameworks informed by complexity thinking, are grounded in reality.

The diversity in situations of different river delta ecosystems in the world, between fully dominated by nature or dominated by humans (Renaud et al., 2013), offers an opportunity to study how the local context influences the usage of the frameworks and the underlying interpretation of complexity. Such context is thereby not only the current state of the system, but also the historical development of the river delta system and the projected trajectory.

1.2 Focus and research questions

The focus of this dissertation is on the usage of complex adaptive systems theory in the management of river delta ecosystems. It reviews how aspects of complexity are used in two major streams of applied research and management, namely adaptive management and nature-based solutions, investigates how these are applied in case studies and how an integrated approach can help improve the adaptive capacity of these ecosystems. The objective is not to study specific aspects or attributes of complexity, such as resilience or adaptive capacity, per se, but to gain a better understanding of how complex adaptive systems thinking is adopted in general.

The central research question is:

How can complex adaptive systems thinking, within adaptive management and nature-based solutions approaches, be used to improve the adaptive capacity of river delta ecosystems?

This central research question is supported by a four sub questions:

i. How are approaches aimed at improving adaptive capacity of ecosystems, including adaptive management and nature-based solutions, linked in theory and in practice?

ii. How are key attributes of complex adaptive systems understood by ecosystem managers in case studies of river delta ecosystems?

iii. How can an integrated approach based on complex adaptive systems thinking help the transition of ecosystems from nature-dominated to human-dominated river delta ecosystems?

iv. What prospects exist for the use of complex adaptive systems thinking for the management of deltas in transition, and what actions are needed to achieve successful implementation?

1.3 Concepts and frameworks

Table 1 describes the main concepts and frameworks used in this research.

Table 1 Main concepts and frameworks and usage in this thesis

Concept / framework	Description and usage in this research
Complex adaptive systems (CAS)	A theoretical framework for complexity and a means of understanding the spontaneous, self-organizing dynamics of the world. In this research, we use CAS as the main theoretical foundation, study how CAS theory is used in applied frameworks and study how practitioners understand key concept contained in CAS theory.
Adaptive Management (AM)	An applied research field that promotes a structured, iterative process of robust decision-making, thereby positing that human understanding of these ecosystems should be continuously updated, and policies should be seen as hypotheses which are tested through management actions. In this research, we study how AM relates to CAS theory, how it is applied in practice and how it relates to NbS.
Nature-based Solutions (NbS)	A practice-oriented framework used to identify actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits, thereby focusing on using natural processes. In this research, we study how NbS relates to CAS theory, how it is applied in practice and how it relates to AM.

1.4 Research approach and methodology

The research questions span several scientific disciplines, each of which is characterized by different prevailing research methodologies, from qualitative research in the social sciences related to adaptive management, to the more quantitative research in natural sciences such as engineering. To investigate the subject in an interdisciplinary and integrated manner, the thesis is primarily based on mixed-methods research methodology (Creswell and Creswell, 2017; Jick, 1979). Mixed methods research combines quantitative and qualitative research, with the premise that this combination of approaches can provide a better understanding of complex research problems and complex phenomena than one approach alone can achieve.

The thesis specifically uses sequential exploratory research (Creswell and Creswell, 2017) for the case studies and development of a conceptual framework, whereby an investigation starts with a qualitative phase in which information can emerge that can guide a second, more quantitative phase. In this way, the quantitative research can be guided by the findings from literature review and interviews with local stakeholders.

1.5 Structure of the dissertation

This dissertation is structured around individual papers that have been or can be submitted to journals. As a result, the different chapters containing these papers have some extent of repetition.

Chapter 2 is a literature review of the three main frameworks used in this research: complex adaptive systems, adaptive management and nature-based solutions. It reviews how the latter two application frameworks relate to complex adaptive systems theory, how they are connected in theory and in practice.

Chapter 3 is a case study of the Rhine-Meuse Delta in the Netherlands, exploring the understanding of practitioners of complexity-related aspects in the context of freshwater management.

Chapter 4 is a case study of the Mekong Delta in Viet Nam, with the same objective as the case study in the Netherlands.

Chapter 5 is an intermezzo that provides a comparative analysis of the results from the Netherlands and Viet Nam case studies.

Chapter 6 puts forward a conceptual framework describing the dimensions of dealing with complexity in river delta ecosystems, based on the findings of the literature review and case studies.

Chapter 7 contains the conclusions and general discussions, as well as recommendations for further research.

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2 Relationships between complex adaptive systems theory, adaptive management and nature-based solutions: A synthesis

Abstract

The start of the Anthropocene is characterized by human domination over natural dynamics and the subsequent stabilization of social-ecological systems. At the same time, global rates of environmental change are increasing, eroding the old paradigm of equilibrium and advancing the notion that social-ecological systems are complex adaptive systems, thereby accelerating the development of new management approaches. This paper provides a synthesis of how complex adaptive systems theory is related to adaptive management and nature-based solutions when regarding the management of social-ecological systems. We compare how key concepts are linked in theory and applied in practice. We find that adaptive management has a focus on adaptive capacity and learning as means to deal with surprise or novelty whereas nature-based solutions is linked to the complexity aspects of self-organization and emergence through purposeful use of natural processes. We also find that the two fields use only subsets of complex adaptive systems theory and that there are differences in the way aspects of complexity are perused. We conclude that an integrated approach combining adaptive management and nature-based solutions can help to increase adaptive capacity of social-ecological systems, but that further applied research is needed to better understand the effective application of these approaches.

2.1 Introduction

Humankind now dominates many of the ecosystems it lives in, effectively having introduced a transition from the Holocene to the Anthropocene (Crutzen, 2006; Lewis and Maslin, 2015; Steffen et al., 2015, 2007; Waters et al., 2016), where human actions rival or dominate the forces of nature. It has acquired skills to purposefully alter the natural system to improve the provision of those ecosystem services that are most relevant for socio-economic development. Many of these interventions are aimed at stabilizing the social-ecological system, reducing natural variability to minimize risk and damage to human societies and economies (Parrinello et al., 2020). These human interventions coupled with an unusually stable environment for the past 10,000 years (Rockström et al., 2009b) have contributed to a worldview predominant in highly developed countries that, through human interventions, local or regional social-ecological systems can be maintained in a stable or equilibrium state.

At the same time, global environmental rates of change have become exceptionally high as a result of human actions (Gaffney and Steffen, 2017). Human-induced emissions of greenhouse gasses are creating significant changes to the Earth's climate which in turn has an effect on ecosystem services upon which humankind depends (Pachauri et al., 2014) and thereby the boundary conditions of local and regional social-ecological systems. The climate change effects, including sea level rise, changing temperatures and changing rainfall patterns, have adversely impacted terrestrial ecosystems and food security (Shukla et al., 2019). The same effects have also contributed to the erosion of the paradigm of stable system states (Cloern et al., 2016; Milly et al., 2008). While countries globally are implementing adaptation actions, there is however still very limited evidence of resulting reduction in climate risk (United Nations Environment Programme, 2021).

Within this paradox of stability and change in and around social-ecological systems, the proposition that we need to regard and manage social-ecological systems as inherently dynamic has become widely supported. The traditional stability and equilibrium-oriented paradigms for management of social-ecological systems are being replaced by paradigms that have their roots in complex adaptive systems (CAS) theory, which in its essence is a "theoretical framework for complexity and a means of understanding the spontaneous, self-organizing dynamics of the world" (Dodder and Dare, 2000), viewing system behaviour as an emergent result of interaction between the agents that comprise the system who continuously adapt to changing circumstances.

Scholars studying social-ecological systems (SES) are using CAS concepts to better understand system behaviour. CAS concepts help to understand relations and feedback that shape dynamics in SES, explaining the complex nature and associated patterns (Preiser et al., 2018). One of the most prominent research fields in continuation of this quest for better understanding is that of resilience thinking (Folke, 2006). CAS theory and resilience thinking are strongly linked to ecology, that has long focused on nature-dominated systems and excluded human influence (Alberti et al., 2003).

The paradigm shift towards understanding the behaviour of SES as non-stationary and as CAS instead, is yet to be fully translated into practice. Several application frameworks have been developed aimed at improving adaptive capacity in human-dominated SES to deal with environmental changes, including adaptive management (AM) and nature-based solutions (NbS), see Figure 3 for an indicative timeline and visualisation. These approaches have a link to CAS theory, but it is not evident how they are linked within the framework of CAS theory and to which extent and how they peruse CAS theory and concepts.

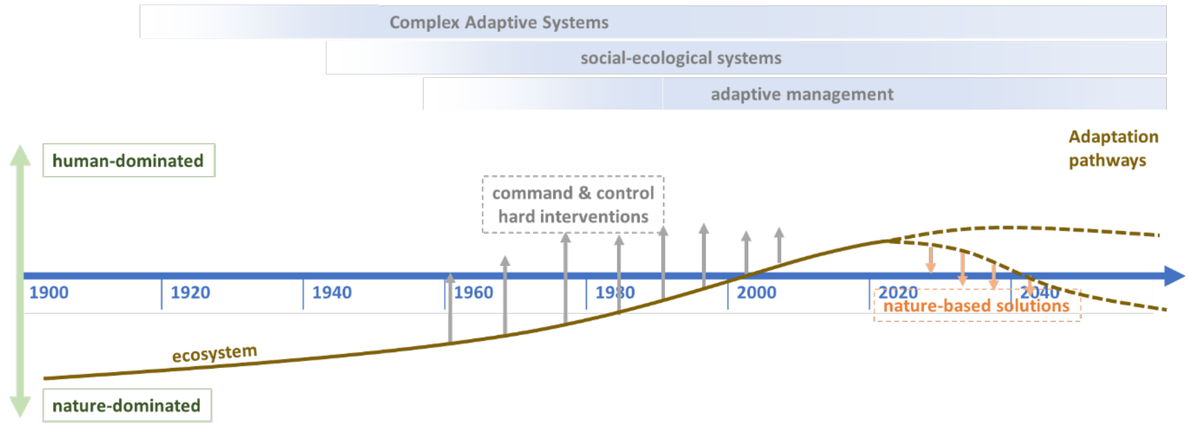

Figure 3 Schematic timeline overview of paradigms and trends presented in this study, linked to an illustrative ecosystem undergoing a transition from nature-dominated to human-dominated

Water is a particularly relevant entry point to further the understanding of CAS behaviour in SES. More than half of all accessible surface water being put to use by humanity (Vitousek et al., 1997). Water demand is predicted to increase rapidly over the coming decades (WWAP (United Nations World Water Assessment Programme), 2017) and growth of human population and economies in flood-prone coastal areas is high (Hinkel et al., 2014), while in many regions climate change will result in decreased streamflow in low flow season and increases in flood magnitude and frequency (Pachauri et al., 2014). Yet, water management systems around the world have been designed for reliability on the assumption of (climate) stationarity, which is no longer valid (Brown, 2010; Milly et al., 2008), and these systems may thus not be able to deal with future changes. Hinkel et al.,(2014) for example estimate that, without adaptation, coastal flooding will affect 0.2 – 4.6% of the global population and result in 0.3 – 9.3 % annual losses in GDP.

In this study, we review the advances made in the application of CAS theory to practice in SES, through AM and NbS. The two research fields emanate from and have been popularized within different disciplines (AM in social sciences, NbS in natural sciences and engineering) but share a purpose of making human-dominated social-ecological systems more adaptive.

We examine the different ways in which both fields peruse CAS theory and how this has been applied in practice. Such an integrated study helps to reveal new insights on commonalities and differences, as well on those aspects of CAS theory that are not addressed by these applied research fields.

2.2 Methods

2.2.1 Identification and selection of literature

As this this synthesis comprises several areas of research, we use a semi-systematic approach that is applicable when addressing a topic that has been conceptualized differently within diverse disciplines (Snyder, 2019).

We use different literature selection methodologies for each area of research. For the underlying theory on CAS, seminal works have been reviewed (Berkes et al., 2008, 2000; Gunderson, 2001; Holland, 1992; Walker et al., 2004; Walters, 1986). For the area of AM, a large body of scientific research is available. The review has focused on the most frequently cited, peer-reviewed papers in Web of Science (WoS, core collection) and Google Scholar for AM. The longlist of results was screened for relevance to the topic (excluding papers not related to the management of SES) and reduced to a list of 30 most frequently cited papers. Furthermore, a specific search in the longlist for review articles and reviews of AM in practice was carried out.

For the research field of NbS, a structured snowballing procedure was followed (Wohlin, 2014) starting from key articles in the field, including those most frequently cited articles but also non peer-reviewed literature. In selecting these key articles, we included “ecological engineering” articles as a strongly linked field of research. For each of the key articles, the reference list was studied and abstracts reviewed for inclusion in the literature review (*backward snowballing*), and the same was done for papers citing these key articles found through a Google Scholar search (*forward snowballing*).

2.2.2 Analysis of interlinkages and trends

To analyse the interlinkages between the different fields of research, we carried out an analysis of trend in the number of studies in the Web of Science core collection. We used article title search terms “adaptive management”, “adaptive governance” and “complex adaptive system”, each in combination with “water” or “natural resources” or “social-ecological system” or “ecosystem”, and we used search terms “nature-based solutions” and “ecological engineering” to construct a bibliography (n = 469). We investigated these studies for temporal patterns using

Microsoft Excel, and for bibliographic coupling using VOSviewer (Van Eck and Waltman, 2010).

2.2.3 Analysis of application of CAS theory

The study is subsequently structured as an investigation into the application of CAS theory in the realm of SES, through the selected applied research fields of adaptive management and nature-based solutions. We present an overview of CAS, relevant CAS attributes, the use of CAS theory in SES literature and identify two critical arguments. We subsequently provide a synthesis of the fields of AM and NbS, investigate how CAS attributes are reflected in these fields and how they correspond to the two critical arguments identified.

2.3 Results

2.3.1 Trends in research

The analysis of research trends in Web of Science (Figure 4) shows a consistent scientific interest in the field of ecological engineering since the late 1980s and in CAS since the 1990s, while the field of AM gradually emerges in the 1990s to peak in the late 2000s. The analysis clearly shows that NbS is a relatively new field of research, emerging rapidly after 2015.

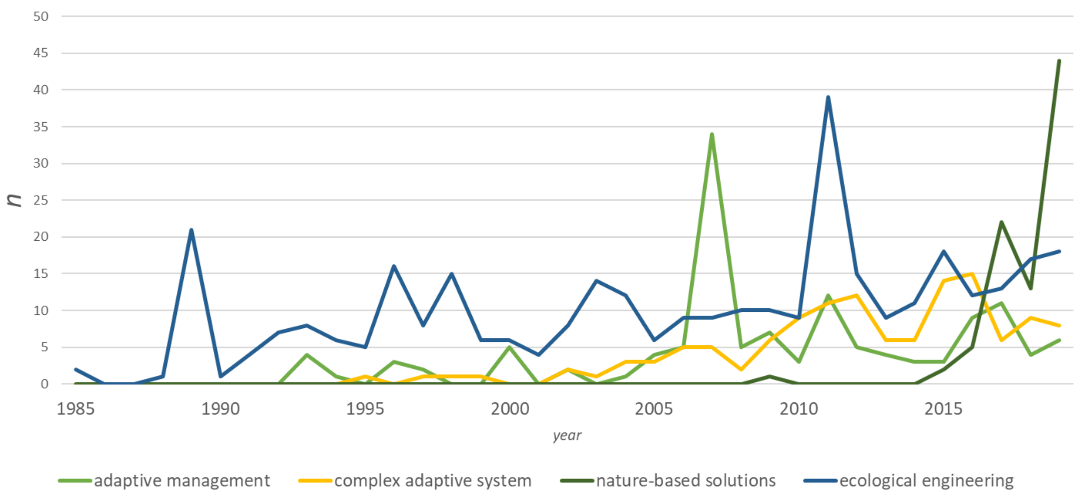

Figure 4 Analysis of number of publications (n) for selected fields of research. Note that given the different techniques used for literature review, the trendlines can only be analyzed individually and in terms of trends, not in terms of absolute number of publications.

A visualization of the same set of studies for bibliographic coupling using VOSviewer (see Figure 5) shows the clustering of studies around the papers of (Pahl-Wostl, 2007) on AM, (Keesstra et al., 2018) on NbS and (Lewis III, 2005; Mitsch and Jørgensen, 2003) on ecological engineering. It reveals a strong connection between the cluster around ecological engineering and that around NbS, and a much weaker connection between the clusters around NbS and AM. This visualization is a useful tool to identify studies that integrate different perspective (situated between clusters).

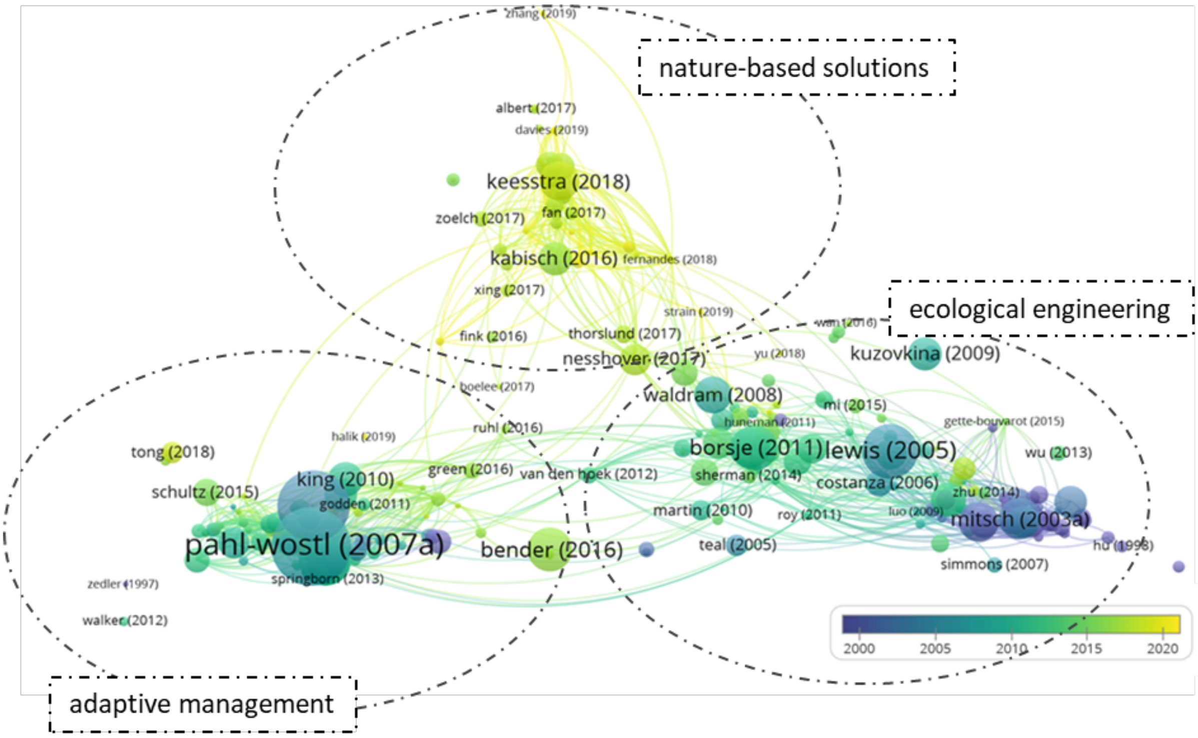

Figure 5 Visualization of bibliographic coupling in selected studies using VOSviewer. Each bubble is one study, the diameter of the bubble corresponds to the number of citations, the color of the bubble to the year of publication (see legend). Dashed contours indicate the key thematic grouping.

2.3.2 Overview of Complex Adaptive Systems

The theory of CAS, strongly linked to complexity theory and complex systems theory (see Preiser (2019) for a detailed comparison), developed over the second half of the 20th century. Its origins have been attributed to three major scientific developments in the 20th century (Holden, 2005): the development of quantum mechanics in physics, positing that particles need to be understood as the dynamics resulting from interaction between molecules; chaos theory in mathematics as proposed by Poincaré and later advanced by Lorenz, exploring the concept of non-linearity; and Prigogine's theory on self-organization and the emergence of order from chaos (Prigogine and Stengers, 1984). It is however argued that ideas of self-organization and emergence have been around for much longer (Miller and Page, 2009).

A further impetus towards the modern CAS theory came from Holling (1973) who noted that, as opposed to the at that time prevailing view of stable equilibrium, both natural undisturbed as well as human-influenced systems are likely to be continually in a transient state. Holling pointed out that also resilient systems may fluctuate greatly and noted the implications of his theory on the management of natural resources to shift from systems with precise capacity to predict the future to systems that can absorb and accommodate unexpected events.

The term Complex Adaptive Systems was coined by researchers at the Santa Fe Institute (Holland, 1992). Holland (ibid) sees three shared characteristics in these systems: evolution, (emergent) aggregate behaviour and anticipation. CAS are not aggregations of individual static entities, but rather composed of multiple interacting agents which mutate and evolve. Many systems are regarded as CAS, from the human immune system to the financial stock markets as well as ecosystems. Elements of an adaptive system are continuously evolving to respond to their changing behaviour. The notion of complexity adds that the behaviour of the system cannot be understood by perfectly understanding the behaviour of each component of the system only, but rather emerges from the interaction between components.

Self-organization and emergent behavior are important features of complex adaptive systems and are related to the non-linear generation of the higher-scale emergent patterns by lower-scale evolutionary processes (Levin, 2005) or in other words, the appearance of un-planned order. Self-organization seems to cause uncertainty to grow over time (Folke et al., 2005) but is at the same time viewed as a key contributor to a system's resilience. Self-organization and emergent behavior in turn lead to *surprise* or *novelty* in a system.

Resilience is most commonly defined as the ability to maintain a system's functionality and basic structure while it undergoes changes. In practice, most people conceive of resilience as the speed of bouncing back after stress (or shocks), the ability to endure greater stress or the disturbance given by a certain amount of stress. This is what C.S. Holling named *engineering resilience*, and what has also been termed *common-sense resilience* (Martin-Breen and Anderies, 2011). Apart from engineering resilience, Quinlan et al. (2016) identify another seven predominant definitions of resilience with different emphases.

The definition and assessment of resilience is topic of a long-term debate in science and practice. Carpenter et al., (2001) note that resilience has multiple levels of meaning: as a theoretical construct or metaphor linked to sustainability, as property of dynamic models and as an operational, measurable indicator. Carpenter et al. state that to be able to use resilience as a measurable indicator, it needs to be defined as resilience *of* what *to* what. Paradoxically when using the last definition, if systems are highly optimized to deliver a certain service regardless of the influence of a particular variable (e.g. resilience of something to something), vulnerability to other variables may increase and overall system resilience as metaphorical system property may be reduced (Carlson and Doyle, 2000; Carpenter et al., 2001; Cifdaloz et al., 2010). This paradox points to the sometimes fuzzy boundary between resilience and robustness.

The term *adaptive capacity* is closely related to a number of other concepts including adaptability and coping ability (Smit and Wandel, 2006), and may be defined as the capacity to undertake adaptations in response to external disturbances and / or surprise in the system. Similar to resilience, the term adaptive capacity is context-specific. It can be analyzed in terms of thresholds or coping ranges but is not static. Like resilience, adaptive capacity is a nested concept whereby local adaptive capacity is reflective of broader conditions, and needs to be assessed for a specific timescale (Brooks et al., 2005).

2.3.3 CAS theory in the realm of social-ecological systems

An important use of CAS theory is in the field of SES (Berkes et al., 2000), in its most rudimentary form a “system of people and nature”. The SES field of study emphasizes the artificial and arbitrary delineation between social and ecological systems. The theoretical framework of SES was developed in response to the observation that equilibrium-based thinking in ecosystem management, with an implicit assumption that ecosystem responses to human intervention are linear, predictable and controllable, was an inadequate conceptual basis to deal with real-world issues (Berkes et al., 2008; Folke et al., 2005). SES is a steadily growing research field that comprises an original framework (Berkes et al., 2000) with more recent diagnostic-oriented frameworks (Colding and Barthel, 2019). Many scholars see SES as CAS (Preiser et al., 2018), with an underlying objective that “managers must understand the properties that enable an ecosystem, as a complex adaptive system, to maintain its integrity in the face of changing environmental conditions and human impacts” (Levin, 2005).

To analyse the relationship between CAS theory and the frameworks of AM and NbS, we use the six organizing principles that bring about CAS features and the related concepts and attributes proposed by Preiser (2019), see Table 2.

Table 2 CAS organizing principles and related CAS concepts. Source: Preiser (2019)

CAS organizing principle	Related concepts and attributes
1. CAS are constituted relationally	Netlike structure, hierarchies, holarchic, diverse components, built-in redundancy, heterogeneity.
2. CAS have adaptive capacities	Self-generation, self-organization, decentralized control, memory, evolutionary and concurrent persistence and change (resilience), anticipatory capacities.
3. Dynamic processes generate CAS behaviour	Far-from-equilibrium, multiple-trajectories possible, periods of fast and slow change (punctuated equilibria), nonlinear interactions, attractors, thresholds, tipping points, regime shifts, feedback loops (enabling and constraining), cross-scale interactions.
4. CAS are radically open	Porous boundaries, embeddedness, nestedness, exchange of matter, information, energy, teleconnections.
5. CAS are contextually determined	Function changes as system changes, components with multiple context dependent identities.
6. Novel qualities emerge through complex causality	Circular/recursive causality, large webs of causality, multiple pathways of causality, high levels of stochasticity, same starting conditions that produce different outcomes, emergent properties.

From the reviewed literature applying the CAS theory to the management of SES, we distill two arguments that we identify as critical dilemmas relevant to adaptive management and nature-based solutions.

The first critical dilemma is centered around the argument that “natural resource management should strive to retain critical types and ranges of natural variation in ecosystems” (Holling and

Meffe, 1996) facilitating existing natural processes (through self-organization) rather than changing or reducing these processes. This argument has been further expanded to include the need for failures as a result of natural processes, to increase resilience at higher levels, as proposed by Janssen and Anderies (2007) in their work on robustness and resilience tradeoffs. Folke et al. (2010) subsequently observe that crises at certain scales may provide windows of opportunity for novelty and innovation that can transform SES into more resilient states. The argument points to a need to determine what these critical types and ranges of natural variation are and for methods to do so.

In a logical continuation, the second critical dilemma is centered around the need to “recognize both the designed and self-organizing components of a SES and to study how they interact” (Anderies et al., 2004), or in other words to understand to which extent system behavior is governed by environmental conditions, and to which extent by self-organization (Levin, 2005). This is a particularly relevant question in human-dominated SES which have a high degree of designed components.

The third critical dilemma concerns the speed of change and the ability of humans to recognize and respond to changes in environmental conditions. (Walker et al., 2012) describe *fast and slow variables* in a complex adaptive system. “Fast” variables are typically those of primary interest to users, such as freshwater availability or production. These fast variables are shaped by other, “slow” system variables which typically are considered to change much more gradually, such as biodiversity or the extent of arctic ice sheets.

2.3.4 Adaptive Management and relation to CAS

2.3.4.1 Adaptive management in theory

Adaptive management theory states that as complex ecosystems have self-organizing properties that cause uncertainty to grow over time, understanding should be continuously updated, and policies should be seen as hypotheses which are tested through management actions (Walters, 1986; Williams, 2011).

Since its emergence in literature in the mid-1970s, adaptive management quickly gained popularity in scholarly, policy and management circles. Adaptive management has even become a something of a mantra among conservation ecologists and natural resource managers (Karkkainen, 2002). But with its popularity, the concept of adaptive management has become increasingly simplified or misrepresented (Rist et al (2013). .

Table 3 lists 7 elements of adaptive management comprises as proposed by Rist et al. (2013) and their relationship to CAS.

Table 3 Elements of Adaptive Management and their relation to CAS concepts and attributes. R = responding to; I = improving; C = contradicting; - = Unclassified

Element of Adaptive Management	Most relevant CAS concept or attribute (relation)
Participation of those outside the management institution in order to manage conflict and increase the pool of contributions to potential management solutions	Heterogeneity (*I*)
Defining and bounding of the management problem, including the setting of management objectives	Decentralized control (*C or I*)
Representing existing understanding through system models that include assumptions and predictions as a basis for further learning	Multiple-trajectories possible (*R*)
Identifying uncertainty and alternate hypotheses based on experience;	Memory (*R*)
Implementation of actions/policies to allow continued resource management or production while learning (reducing uncertainty);	Evolutionary and concurrent persistence and change (resilience) (*I*)
Monitoring of the effect of implementing new policies	(-)
Reflection on, and learning from, monitoring results, comparison with original expectation in order to revise	Feedback loops (enabling and constraining) (*I*)

Various evolutions of and variations to adaptive management have emerged. Adaptive *co*-management places more emphasis on the institutional set-up of natural resources management, combining the feedback loop characteristics of adaptive management with elements from cooperative management and collaborative management (Olsson et al., 2004). Adaptive governance (Dietz et al., 2003; Folke et al., 2005) is a field that expands focus from adaptive management to include broader social contexts, creating the conditions for order and providing a vision and direction for sustainability, whereby management is the operationalization of that vision. Adaptive governance is generally characterized by polycentric institutional arrangements, loosely structured with entities that spontaneously emerge or self-organize (Folke et al., 2005). Rist et al. (2013) describe the difference between *active* and *passive* adaptive management, where active adaptive management is most often used to describe management practices where different management strategies are tested and learning is an explicit objective, while passive adaptive management uses a single preferred course of action based on the best available knowledge, which is then modified as experience grows.

Adaptive management has become particularly popular in the field of water management. Geldof (1995) developed an early idea of adaptive water management as a strategy to better deal with three common problems in water management: (i) the problem of scale: water management processes operate at different spatial and temporal scales, making it difficult to approach them mathematically; (ii) the problem of level: integrated water management includes processes that are non-physical and non-chemical such as social processes, increasing the contribution of positive feedbacks; and (iii) the problem of assessment: due to this complexity, it is no longer possible to deduce unequivocal standards for assessment of the situation. Adaptive water management and related concepts of Integrated Water Resources Management (Savenije and Van der Zaag, 2008) and Ecosystem-Based Approaches form a new paradigm for water management against the previously predominant "prediction and control" regime (Pahl-Wostl et al., 2011; Schoeman et al., 2014).

2.3.4.2 Adaptive management in practice

Early reviews of adaptive management practices (McLain and Lee, 1996; Walters, 1997) showed that existing traditional approaches were difficult to replace. In planning adaptive management approaches, modelling exercises often revealed insufficient knowledge on key processes. Including experimental options in management strategies was often ultimately found to be increasing costs and risks, and also monitoring costs were found to be inhibitive. Attempts to introduce adaptive management approaches are hampered by vested interests and institutional beliefs that pretense of certainty is necessary to maintain credibility (Walters, 1997).

McLain and Lee (1996) found that the use of system models to test hypotheses led to overly technical framing of social-ecological issues, thereby excluding stakeholders from the decision process. The cases they reviewed used highly science-oriented adaptive management approaches, which failed to create shared understanding among stakeholders. Recognizing that social interactions required more prominence in the adaptive management approach (Tompkins and Adger, 2004) and that non-scientific, indigenous knowledge also needs to be included in the process (Berkes et al., 2000), the concept of adaptive co-management was formed (Olsson et al., 2004; Plummer et al., 2012). Armitage et al. (2008) found further weaknesses in the learning mechanisms supporting these approaches, and further expanded the concept of adaptive co-management to include a learning framework that incentivizes stakeholders to acquire new understandings. The temporal and spatial scales relevant to case studies furthermore make it difficult to ascertain whether adaptive management has failed or succeeded, related to short monitoring timescales which may not be adequate to cover rarer but significant "black swan" environmental events (Schreiber et al., 2004). Furthermore, learning outcomes of adaptive management are not necessarily recognized as indicators of success, and may be too dispersed across actors to be registered for external observers (Allan and Watts, 2018). Allen and Gunderson (2011) identified additional reasons for common failures of adaptive management: suppression of surprises, where surprises are effectively eliminated from the system, and the domination of process over action.

Rist et al., (2013) found that for the selected review year of 2009, the majority of studies on implementation of adaptive management concerned water, wildlife / biodiversity and forests; in North America, Australia and Europe. Keith et al. (2011) reviewed the implementation of adaptive approaches to wildlife conservation and found that for those few cases where adaptive management was actually implemented, institutional barriers similar to those identified by Walters (1997) continue to persist. Furthermore, they find that scientists need to shift their attention from the discovery phase to implementation, as a means to provide further scientific evidence and learning. Walters (2007) found that out of 100 case studies on adaptive management of fish resources, the majority have been failures related to the same barriers.

As the adaptive management paradigm matured into a well-developed framework that helps to better understand and handle uncertainty in natural resources management, the larger changes in climate, landscape and biodiversity require the framework to be adjusted and expanded (Williams and Brown, 2016).

Adaptive water management has become a particularly active subfield of research and reasonably integrated into mainstream water management thinking (e.g. Rockström et al., 2014). Pahl-Wostl, (2007) proposed a framework for the introduction of adaptive water management, recognizing the challenges such a transition process brings along. While other scholars have made efforts to integrated adaptive management into the older concept of IWRM (e.g. Halbe et al., 2013; Medema et al., 2008), Engle et al., (2011) find that for their case study of water reform in Brazil, the mechanisms of IWRM may be at odds with the flexible and self-organizing nature of adaptive management. Peat et al. (2017) reviewed practitioners' perceptions of adaptive water management in two case studies and found that informal institutional arrangements tended to constrain adaptive management.

2.3.5 Nature-based solutions and relation to CAS

2.3.5.1 Nature-based solutions in theory

NbS is a relatively young field of research introduced in the early 2010s (IUCN, 2016) that promotes the use of nature as a solution to environmental challenges, particularly those related to climate change mitigation and adaptation. While there is no consensus on a precise definition for NbS, two predominant definitions can be distinguished, proposed by IUCN and the European Commission (Bauduceau et al., 2015; Maes and Jacobs, 2017) (see Table 4).

Table 4 Two definitions of Nature-based Solutions

IUCN	European Commission (EC)
Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits.	Living solutions inspired by, continuously supported by and using nature designed to address various societal challenges in a resource efficient and adaptable manner and to provide simultaneously economic, social and environmental benefits

NbS is an "umbrella concept" that is regarded to cover a range of related approaches that pre-date NbS and have emerged in different disciplines, listed by Nesshöver et al. (2017) as (i) ecological engineering; (ii) green / blue infrastructure; (iii) ecosystem approach; (iv) ecosystem-based adaptation / mitigation; (v) ecosystem services approach; and (vi) natural capital.

Eggermont et al. (2015) provide a typology of NbS applications (Figure 6) that is based on two major parameters: the required level of engineering of social-ecological systems and the level of enhancement of ecosystem services that can be achieved through NbS. Three major types are identified: (i) solutions that involve making better use of existing natural or protected ecosystems; (ii) solutions based on developing sustainable management protocols and procedures for managed or restored ecosystems; and (iii) solutions that involve creating new ecosystems. IUCN (2016) developed eight core principles of NbS, which are listed in Table 5 and reviewed for their relation to CAS concepts and attributes.

Table 5 Elements of Nature-based Solutions and their relation to CAS concepts and attributes. R = responding to; I = improving; C = contradicting; - = Unclassified

Principle of Nature-Based Solutions	Most relevant CAS concept or attribute (relation)
embrace nature conservation norms and principles	(-)
can be implemented alone or in an integrated manner with other solutions to societal challenges	diverse components (*I*)
are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge	embeddedness, nestedness (*R*)
produce societal benefits in a fair and equitable way, in a manner that promotes transparency and broad participation	Heterogeneity (*I*)
maintain biological and cultural diversity and the ability of ecosystems to evolve over time	Evolutionary and concurrent persistence and change (resilience) (*I*)
are applied at a landscape scale	(-)
recognise and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystems services	Circular/recursive causality (*R*)

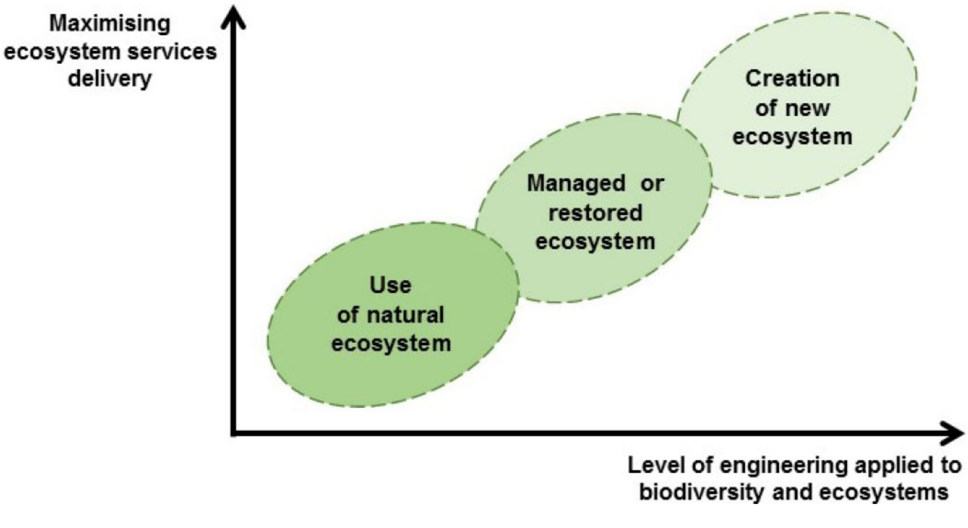

Figure 6 Typology of NbS. IUCN (2016) adapted from Eggermont et al. (2015)

The most long-standing and well-developed field of research contributing to the NbS space is ecological engineering (Mitsch and Jørgensen, 2003; Odum, 1989; Parrott, 2002). Ecological engineering has evolved from the field of ecological restoration, which aims to restore ecosystems to their original state prior to human disturbance. Parrott, (2002) states that ecological engineering differs from traditional engineering in two ways: (i) it is founded on an underlying ethic that acknowledges the key importance of preserving the ecosystem; and (ii) it has ecology as its fundamental science base. As such, ecological engineering is primarily aimed at using nature's self-organizing properties to fulfil human needs, rather than creating artificial systems focused on efficient short-term delivery of certain services, but which can have unexpected detrimental effects on the overall ecosystem.

In water management, various other terms have been put forward that form part of nature-based solutions. Temmerman et al. (2013) use the term *ecosystem-based flood defence* to describe an emerging approach in coastal engineering to minimize interventions with "hard" structures such as dykes and groins, instead relying on natural processes such as those occurring in wetlands and mangroves. This approach is named after the concept of ecosystem-based adaptation (Colls et al., 2009) which aims to integrate the use of ecosystem services and biodiversity into adaptive ecosystem management and has also been termed "Building with nature" (Van Slobbe et al., 2013).

The collection of research fields within the NbS space have seen little integration over the years, with ecological engineering being predominant in literature but, perhaps due to its strong roots in ecology, not finding its way as a concept to mainstream engineering. A common ground between the various fields of research is the desire to increase the use of nature's self-organizing capacity and reduce human intervention. Moreover, they start from an observation that in the past, human interventions in the ecosystem may have been too far-reaching or have had unexpected negative impact, that may have been prevented if more use had been made of nature's self-organizing capacity. Cohen-Shacham et al., (2019) reviewed strengths and weaknesses of the eight core principles of NbS as adopted by IUCN (IUCN, 2016) and found that these do not adequately capture aspects of adaptive management, multi-stakeholder participation and temporal scale.

The Adaptation Gap Report 2020 (United Nations Environment Programme, 2021) found that NbS are often not connected to climate risks, and that system-scale approaches are needed to achieve the full potential of NbS for climate change adaptation. In line with that diagnosis, the most recent NbS studies focus on the conditions needed to introduce NbS or to ensure their effectiveness (e.g. Kabisch et al. (2016) and the challenges related to this (Seddon et al., 2020).

2.3.5.2 Nature-based solutions in practice

Given the recent nature of the NbS research field, evidence of the effectiveness of nature-based solutions in practice is still limited. A review of the application of NbS in cities Frantzeskaki (2019) points to the gap in the NbS framework on governance and collaboration aspects as earlier identified by Cohen-Shacham et al. (2019), as well as to gaps regarding the experimental aspects of NbS and the need to devise a strategy for learning and replication at scale. Similar to the development trajectory of the adaptive management research space, scholars have now developed assessment frameworks for analysing the adoption of NbS (Calliari et al., 2019; Raymond et al., 2017) and strategies to aid the transition into the adoption of NbS (Davies and Lafortezza, 2019).

When reviewing the underlying frameworks of NbS, more research evaluating implementation is available. (Mitsch, 1998) described the challenges of introducing ecological engineering in the early days, which were mostly focused on the use of wetlands for wastewater treatment. He saw that ecologists need to get more involved in problem solving rather than describing them, and that engineers needed to better understand the importance of biological and ecological sciences to their job. In order to achieve these goals, Mitsch proposed a dedicated and formalized education and accreditation system for ecological engineering. (Mitsch, 2012) reviewed progress 14 years later and found that ecological engineering was being practiced globally and covering a wide spectrum of approaches. He found that the principles and practices of ecological engineering had been well established, and that further progress was limited by regulations and lack of acceptance by more traditional disciplines.

Borsje et al. (2011) reviewed the implementation of ecological engineering approaches for coastal protection using *ecosystem engineering species*, organisms capable of controlling availability of resources to other organisms (Jones et al., 1994). Such approaches include the use of mussel beds for erosion protection and the planting of willow trees to reduce the impact of waves on river dikes. They find that, for specific spatial and temporal scales linked to the purpose identified, ecological engineering approaches can be effective for coastal protection. They however also note that responses of ecological engineering features to extreme events is difficult to model and predict, and that for those cases more emphasis needs to be put on monitoring.

2.4 Discussion

This study reviewed and compared literature in the theoretical field of Complex Adaptive Systems and the applied research fields of adaptive management and nature-based solutions. There are significant differences between these areas of applied research that partly impede comparison. Adaptive management research is well-developed and comprises a large body of scientific research, not all of which could be reviewed in this study. Nature-based solutions comprises rather scattered subfields with limited interconnections between the bodies of research, although this may change rapidly with the recent increase in scientific and societal interest in the subject.

The results show that the various research fields reviewed share features of complex adaptive systems theory, with adaptive management having been explicitly built on the theory while nature-based solutions originate more from practice. Adaptive management has a focus on adaptive capacity and learning as means to deal with surprise or novelty. NbS, on the other hand is primarily linked to the aspect of self-organization and emergence, as closely linked to the purposeful use of natural processes.

There are various interpretations and usages of key aspects of complex adaptive systems theory within the discussed applied frameworks, which prompts the question of the need for consistency. While there is a rapidly increasing body of 'intermediate' literature focusing on specific aspects of CAS, such as on resilience and ways to measure it (e.g. Douxchamps et al., 2017; Jones et al., 2021), such processes may not address the broad range of CAS-related aspects nor be effective in influencing other research fields. The notion of *adaptive capacity* is one example of the potential need for consistency, where in most case studies this notion is reduced to the capacity to deal with one or more known potential (expected) disturbances, not including surprise. Similarly, the term self-organization is used in engineering realms to describe natural processes at smaller scales, not necessarily the process responsible for the emergence of higher-level system properties.

The transition from a traditional equilibrium-based management approach to an adaptive management approach is discouraged by significant barriers, including institutional inertia, risk aversion, pretence of certainty for credibility and limited leadership. Transition frameworks such as the one developed by Pahl-Wostl (2007) may provide implementers with tools to overcome some of these barriers, but more research on the transition and implementation phase is needed to better understand the underlying causes of resistance to change and potential mitigation measures.

The economic and financial aspects of the transition and implementation phase remain poorly explored. While the costs of planning and implementing an innovative approach to the management organisation are an obvious hurdle, there is no analysis of financial impact on other stakeholders nor of effects the economy as a whole. It is however likely that the transition will have significant economic impact, threatening vested interests while creating new economic opportunities, which in turn will influence the likelihood of success of introducing a new management regime.

Case studies show that the often suggested dichotomy of command-and-control versus adaptive management may not adequately reflect reality nor be realistic. Both from a management as well as an engineering perspective, there will rarely be unlimited freedom in terms of allowable system behaviour. In this regard, Heinimann, (2010) proposes a pragmatic concept in adaptive management based on a backbone of control theory, in order to keep system dynamics within an acceptable range. Such an approach will be essential when trying to introduce adaptive management to deal with the provision of ecosystem services that directly affect human security, such as flood management.

It is often argued that adaptive management and nature-based solutions existed well before their formalization in literature. Indeed, Berkes et al. (2000) note that some traditional knowledge and management systems that used ecological knowledge to interpret and respond to feedback from the environment, had certain similarities to adaptive management as it is advocated currently. Similarly, in the nature-based solutions space, many ancient practices were based on using natural processes to achieve the same objectives for which we now put in place infrastructure. From farmers in the Mekong Delta in Viet Nam using natural flooding to increase fertility of their soils (Käkönen, 2008), to farmers in Africa making "fanya juu" terraces using natural erosion and sedimentation processes (Thomas and Biamah, 1991). Some may even argue that to develop real adaptive social-ecological systems, we should simply reverse some of the human interventions made in recent decades.

These two observations point to the fundamental question on what a good balance would be between natural processes and human intervention. Ecosystems may be engineered and managed to maximize their function-delivery in the short term, but this could be a short-sighted strategy. It may however be possible to use the insights developed in the scientific and policy debate around planetary boundaries (Rockström et al., 2009a), to determine safe ranges of variability, and in this sense maintain or increase control, without strong human interventions in the ecosystem.

Finally, there is a question whether adaptive management and adaptive engineering should in the future become the norm for any type of ecosystem management. Currently presented as distinct fields of research and ways of doing things, there has been limited research into how much of these ideas are already integrated in the mainstream thinking and practice.

2.5 Conclusions

Progress is being made in translating scientific insights on CAS into practice in the management of SES, through the applied research fields of adaptive management and nature-based solutions.

While efforts in both spheres are oriented towards the same goal of creating managed adaptive ecosystems, they take a different entry point focusing on adaptive capacity on the one hand and self-organization on the other hand.

Further exchanges between the two fields will allow for the development of an integrated approach towards managed adaptive SES. The lessons learned in adaptive management spheres on stakeholder engagement, monitoring and learning will help engineers in achieving stronger support by policymakers, project developers and financiers for introducing innovative, adaptive engineering practices, and enable them to document evidence of success as a key to further replication. Vice versa, experiments with adaptive engineering practices can provide a testing ground for those specializing in adaptive management and to further adapt theoretical management approaches to reality.

Future research on integrated approaches to managed adaptive ecosystems, combining adaptive management and nature-based solutions, needs to be more oriented towards the transition and implementation phase, to understand barriers to implementation and identify potential ways to overcome these. A better understanding of the economic aspects of adaptive management, and the balance between control and self-organization will also be beneficial to develop more realistic and pragmatic tools for practitioners to lead the change towards increasing adaptive capacity of ecosystems.

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3 Understanding complexity in freshwater management: Practitioners' perspectives in the Netherlands

Abstract

Ecosystems have been stabilized by human interventions to optimize delivery of certain ecosystem services, while at the same time awareness has grown that these systems are inherently dynamic rather than steady-state. Applied research fields have emerged that try to increase adaptive capacity in these ecosystems, using concepts deriving from the theory of Complex Adaptive Systems. How are these concepts of complexity interpreted and applied by practitioners? This study applies a mixed-methods approach to analyse the case of freshwater management in the Netherlands, where a management paradigm promoting nature-fixating interventions is recently being replaced with a new paradigm of nature-based solutions. We find that practitioners have widely varying interpretations of concepts and of how the ecosystems they work in, have evolved over time, when described with complex systems attributes. The study allows for the emergence of key complexity- related considerations among practitioners that are not often discussed in literature: (i) the need for physical and institutional space for self-organization of nature; (ii) the importance of dependency and demand management; and (iii) trade-offs between robustness and flexibility. The study furthermore stresses the importance of using practitioners' views to guide applied research and practice in this field.

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3.1 Introduction

We live in an anthropogenic era where humans are more than ever interconnected with global and local ecosystem services. Ecosystems have been engineered to stabilize and optimize the delivery of those services they provide that are most directly important to humans and their economic development in the short term, traditionally in a command-and-control fashion (Holling and Meffe, 1996). Ever since the seminal 1987 Brundtland report (Brundtland, 1987) brought environmental sustainability into mainstream thinking, ecosystem management approaches have still most often been based on the assumption of a steady-state or stationary system (Chapin et al., 2010).

Accelerated by the progress in understanding climate change, the exceptionally high rates of global environmental change (Gaffney and Steffen, 2017) and the potentially long-term irreversible changes in ecosystems resulting from these (Lenton et al., 2019), current day research has moved from steady-state to resilience thinking. Scholars have transitioned to understanding these systems as social-ecological systems (Berkes et al., 2000), where natural and human influences need to be analyzed jointly, and as examples as of Complex Adaptive Systems (Holland, 1992; Preiser et al., 2018), which are characterized by the analysis of systems as composed of multiple interacting agents which mutate and evolve, and exhibiting emerging behavior that cannot be understood by perfectly understanding the behavior of each component of the system. This has subsequently led to the understanding that changes in ecosystems need to be accommodated rather than solely counteracted (Walker et al., 2004), while ensuring that critical biophysical thresholds are not crossed (Rockström et al., 2009). Furthermore over recent years, the need for nature-based solutions, as opposed to purely artificial interventions in ecosystems, has become broadly accepted (IUCN, 2016) and is now becoming a priority for policy makers and investment funds.

There is thus general support emerging in both policymaking and practice, for a new two-sided paradigm for management of ecosystems that posits on the one hand that human-dominated ecosystems need to allow for some level of change, through an intrinsic adaptive capacity, and on the other hand need to make use of natural processes instead of engineered solutions, where possible. Applied research fields have developed, attempting to facilitate a transition towards effective implementation of this paradigm. Among these, the fields of adaptive management (Williams, 2011) and adaptive governance (Folke et al., 2005) focus on increasing the intrinsic adaptive capacity of ecosystems by building in feedback and learning loops. In recent years, the theme of nature-based solutions has emerged (Nesshöver et al., 2017) which encompasses several applied research fields from engineering and ecological sciences, including ecological engineering (Mitsch and Jørgensen, 2003; Odum, 1989) and ecosystem-based engineering (Temmerman et al., 2013). These applied research fields share a foundation on the theory of complex adaptive systems (Rutten, n.d.).

While the thinking on ecosystem management has evolved steadily in the past decades, there is little evidence on whether this has allowed human-dominated ecosystems to effectively become more adaptive. Do the various approaches, frameworks and tools developed related to ecosystem management and engineering, and the increased awareness of the fact that ecosystems are in principle dynamic, lead to a higher adaptive capacity at system level? Are the systems able to better deal with shocks and surprise events, resulting in less damage or quick changes in the structure of the system? Most reviews thus far (e.g. Huntjens et al., 2011;

Peat et al., 2017) focus on the adoption of the adaptive approach itself, rather than the effect on the adaptive capacity of the system. While there is a rapidly increasing body of literature on ecosystem resilience and ways to measure it (e.g. Douxchamps et al., 2017; Quinlan et al., 2016), there have been very few attempts to assess the development of resilience over time.

Water has been a primary target for human domination with more than half of all accessible surface water being put to use by humanity (Jaramillo and Destouni, 2015; Rockström et al., 2014), and water demand is predicted to increase rapidly over the coming decades (WWAP (United Nations World Water Assessment Programme), 2017). With water also being a principal conduit of climate change impact, through sea level rise and changing rainfall patterns, the water management sphere has especially seen considerable activity on resilience thinking (e.g. Boltz et al., 2019; Pahl-Wostl, 2007; Rockström et al., 2014). Water has a direct linkage to human wellbeing, is typically situated between a high number of different users and sectors and is often subject to multiple spatial and temporal scales of management. Local human interventions in water systems, from flood protection to freshwater supply to changes in water abstraction, have complex interlinkages and causalities. Water management needs to deal with the emerging patterns from interactions between those interventions across scales, making it a good example of a complex adaptive system (Bohensky and Lynam, 2005).

Complexity thinking is far from an academic exercise only. People professionally engaged in water management frequently need to use complexity aspects, thereby providing an opportunity for research into the application of complexity thinking in management of human-dominated ecosystems.

This research thus aims to understand the perspective and opinions of actors involved in human dominated ecosystems, with regards to the key features and concepts of complex adaptive systems theory, and the applied research fields building on it. It looks at ways in which actors use common system attributes in their own framing of these theories.

The focus of this paper is on the Netherlands, selected as a case study area because of its leading status in the field of water management, and the influence of the Dutch water management model on the global water management dialogue. The Netherlands ecosystem has gone through a long transition from nature-dominated to human-dominated which culminated in the 20th century (Van der Brugge et al., 2005), while currently being dominated by a policy context of reintroducing natural variability, albeit partially.

The objective of this research is to analyze how complex adaptive systems aspects in ecosystem management, such as water management under changing climatic conditions, is understood by its managers in practice. This case study looks at freshwater management provision in the Netherlands as an example of a complex adaptive system, and the efforts made to make this system (more) adaptive to meet unknown and unpredictable water resources changes.

The approach of this study is to use the perspectives of people professionally engaged in ecosystem management, as a basis to understand at system level the complex adaptive system aspects of the case study. The study therefore uses a multi-phased approach. In phase 1, it analyses the way in which the actors use concepts (such as adaptive management, ecosystem-based engineering) and attributes (such as resilience, flexibility, robustness, adaptive capacity) linked to complex adaptive systems theory. In phase 2, an analysis of these results leads to emerging patterns and hypotheses held by ecosystem managers. These are further analyzed in phase 3, using existing biophysical and socio-economic data to, where possible given data availability, validate those hypotheses.

While some of the concepts in this study are relatively recent, this study purposefully applies a lens of modern concepts to not only analyze the present and the future, but also the past. While most resilience and climate change studies are forward-looking, evaluations of how systems have developed in the past using modern-day theory, are scarce. Such historic evaluations can however provide a grounding or calibration opportunity for assessments of expected future developments.

3.2 Materials and methods

A mixed-methods has been applied using the logic of exploratory sequential mixed methods design (Creswell, 2014). Mixed-methods research gained traction in the 1980s (Jick, 1979) as a way to combine the qualitative approach of exploring and understanding viewpoints of individuals and groups (Hay, 2000), whilst letting information emerge from the research, with a quantitative approach that is principally aimed at testing hypotheses through variables that can be measured. Integrating these two methods, through mixed-methods research, is a way to provide a more complete understanding of a problem under study and is therefore particularly suitable for studying complex adaptive systems. Exploratory sequential mixed-methods research starts with an investigative, qualitative phase. The analysis of the results of the first phase is then used to guide the second, quantitative phase.

This study begins with a literature review (qualitative) and an analysis of the application of adaptive management and nature-based solutions. This is followed by semi-structured interviews with key actors who are part of the complex adaptive system to gain an understanding of their individual perspective (qualitative). From the interviews and exercises carried out during these interviews, patterns are identified and analysed in the different viewpoints of actors. The emerging viewpoints are then triangulated with independent data where possible (quantitative), which was collected from existing literature and data sources.

The population group of interest to this research comprises actors who are professionally engaged in the governance and management of freshwater in the Netherlands as well as representatives of water users. The study sample participants were identified based on a mapping of relevant actors and institutes, using published reports and participants lists from stakeholder meetings held on the subject. This was followed by a criteria-based sampling strategy, identifying potential candidates based on the type of organization they belong to and their primary area of interest as defined by their mandate in their respective organization (see Table 6). A total of 17 participants were interviewed during March –April 2017, in their respective offices. The interviews were undertaken in Dutch and participants were informed about anonymized use of the data collected, prior to their consent to start the interview. Interviews were audio-recorded and transcribed, after which they were analysed using qualitative data analysis software (Nvivo) for word frequency analysis and source clustering.

Table 6 Categorization of participants, by organization and by primary area of interest.

Organization	Number	Primary area of interest	Number
Water boards and provincial government	5	Water management	9
Scientific	4	Environment and climate	3
Central government	3	Economy, laws and regulation	3
Water user representatives and civil society organizations	3	Agriculture	2
Independent consultant	2		
Total	**17**	**Total**	**17**

At the start of the semi-structured interview, participants were provided with a graph showing a horizontal timeline axis (from 1900 to 2080) and a vertical index scale (from 0 to 200, with a 100 mark at the year 2017). As an experimental qualitative-quantitative method, the participants were asked to sketch the development of two complex adaptive system attributes, 'robustness' and 'flexibility' of freshwater provision in the Netherlands, over time. Participants had not been informed in advance of this exercise.

The two attributes, robustness and flexibility, were chosen because of their frequent use in most of policy and strategic documents on freshwater provision in the Netherlands as identified in the literature review, as well as in international literature (e.g. Smith et al., 2019). Amongst others, a reference document for the Delta Programme 2017 Deltacommissaris (2016) states that "solidarity, flexibility and sustainability are the basic values" (Slob and Bloemen, 2014) to achieve sustainable and robust water security and freshwater provision. This common use of 'robustness' and 'flexibility' in documents, suggests a certain familiarity with and shared understanding of the attributes, which was considered preferred as compared to using system attributes or terms that are less frequently used and/or with which participants are likely to be less familiar (such as resilience and adaptive capacity). 'Robustness' and 'flexibility' can furthermore from a theoretical point of view be regarded as attributes with considerable distance between them in terms of common interpretation, the former more often linked to reliability and continued functioning of a system, even under stress. Whereas 'flexibility' is more often linked to capacity to adapt to changes.

During the interview, participants were not provided with any definition or explanation of these attributes, but instead asked to use their own definitions of the two attributes, to obtain their personal perspective and individual framing instead of imposing a particular definition. This qualitative, constructivist method is most fit to establish the meaning of a phenomenon from the view of the participant.

After sketching the historic trend in the two system attributes *robustness* and *flexibility*, using the year 2017 as an index benchmark (2017 = 100), participants were asked to explain the trend they observed. From there, participants were requested to sketch their expectation in terms of future trends for both attributes, while indicating the events or trends they consider as influencing the two attributes. The graphs drawn by participants were later analyzed using Microsoft Excel, combined with analysis of narratives, aiming to determine patterns in the responses, both with and without taking into account the categorization of participants in terms of organization and primary area of interest. The remainder of the semi-structured interview was carried out using an interview guide, with the drawn graphs used as a reference point.

Q-methodology is a method originally developed in the 1930s by William Stephenson (Stephenson, 1953). Q methodology combines qualitative and quantitative elements to investigate the subjective views held by those people directly involved in a topic (Herrington and Coogan, 2011). Q studies aim to identify patterns in individuals' responses to statements without imposing a priori meanings, in order to understand the range of viewpoints regarding a particular topic.

Participants are presented with a set of statements and asked to rank these. In order to be able to understand the viewpoints of participants, it is important that the set of statements reflects the full range of sentiments likely to be held on the topic of interest. For this case study, a set of 34 statements (Figure 8) was developed from a literature review (Rutten, n.d.), but adjusted to better match the prevailing terminology and language used in the various documents pertaining to the case study. The statements have been selected to cover the most frequently cited issues with adaptive management and engineering linked to water management, as identified in the literature review. The statements had to be ranked from -4 (don't agree) to +4 (agree) on a pre-defined matrix (Figure 7).

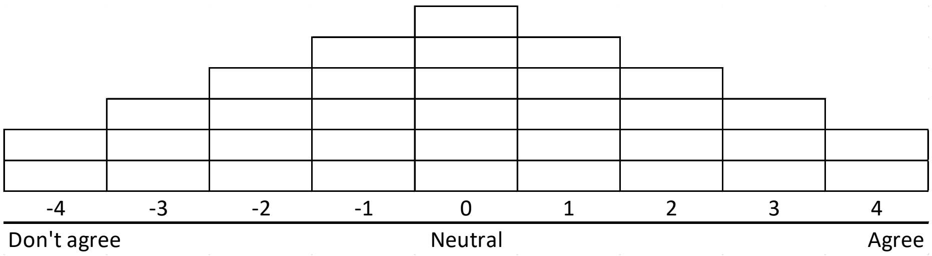


Figure 7 Ranking matrix used for Q methodology

The Q-sorting exercise was carried out after the semi-structured interview with 14 participants from the larger set of 17 interviewed. The participants were asked to think out loud while sorting the statements to enrich the information obtained from the exercise. The resulting *Q sorts* were analysed using the PQMethod software as developed by Peter Schmolck, using centroid factor analysis and varimax rotation (Brown and Stephenson, 1980) and a significance level of $p < 0.01$. The results, represented in generalized viewpoints or factor arrays, were interpreted using the qualitative data collected from the interviews.

Q statements used

1. Adaptive management is something we were doing all along
2. Adaptive management increases readiness for surprise events
3. Scenario use is an adequate tool to deal with future uncertainty
4. Many spontaneous initiatives for adaptation are blocked by laws and regulations
5. Authorities do not want to publicly acknowledge lack of certainty on important topics
6. There is enough stakeholder participation to allow for adaptive management
7. Physical structures often have greater and longer-term impacts than what we design them for
8. Organizational structures often have greater and longer-term impacts than what we design them for
9. Current-day physical infrastructure provides the system with more flexibility than in the past
10. The concept of tipping points is useful for real-life application
11. Tipping points need to be anchored in policies and regulations
12. Failure at lower system level may be needed to increase resilience at higher level
13. Policies are systematically reviewed to check if the assumptions made were correct
14. Adaptive management increases risks
15. The costs of adaptive management are preventing its adoption
16. Legacy physical structures significantly decrease the system's adaptive capacity
17. Legacy organizational structures significantly decrease the system's adaptive capacity
18. We've found a good balance between short-term gains and long-term sustainability
19. Current practice effectively prevents lock-ins and lock-outs
20. There is too much focus on studies and plans and too little on reality
21. Our ecosystem is over-engineered
22. Our ecosystem is over-managed
23. Economic interests decrease the system's flexibility
24. Regulations are changing too fast to provide stability for economic development
25. Some adaptation measures are implemented too early, before they are absolutely necessary
26. The use of adaptation pathways increases understanding of future uncertainties
27. We need to better harness nature's self-organizing capacity
28. Increased local decision-making increases risks
29. There is too much "command and control" in our system
30. Devolved or decentralized government decision-making increases adaptive capacity
31. Self-monitoring of devolved government functions increases adaptive capacity
32. Lower-level public entities have sufficient capacity to carry out devolved functions
33. Some physical structures have been put in place mostly for prestige or interest of builders, less for their function
34. Adaptive management encourages experimentation

Figure 8 Q statements used in study

3.3 Results

3.3.1 Case study background

The case study area in The Netherlands is a highly human-dominated river delta with a long history of water management interventions and institutions. Historically, water management interventions in the Netherlands were carried out at community or village level, and mostly focused on preventing flooding, reclaiming land, and to create military defence structures. Between 1600-1800, local communities created about 600 km^2 of polders, and by the end of the 18th century more than a thousand different organizations were involved in the Dutch public water works (Lintsen, 2002). In 1798 a national public works agency was created, Rijkswaterstaat, which would however take until 1850 to take a leading role in addressing flooding problems. They embarked on a large project of "river improvement", reshaping hundreds of kilometres of river to efficiently and more rapidly channel water to the sea and reduce flood risks, thereby completely changing the Dutch landscape.

In the 1920s and 1930s, human control over the ecosystem took another significant leap with considerable investment programme on canals, river canalization and the closing of the Zuiderzee in the north, creating a large freshwater lake called Ijsselmeer (see Figure 9). These measures were primarily intended to prevent riverine and coastal flooding. The 1953 flood in the southwestern delta, which claimed 1800 lives, was the impetus for another large infrastructural work programme, the Delta Works (Wesselink et al., 2007), guided by a special high-level Delta Commission. Implemented between 1958 – 1997, the Delta Works comprised a series of physical interventions aimed at closing off the southwestern delta and reducing the number of dikes needed inland. As the Delta Works were progressing and the global debate on environmental sustainability unfolded, criticism on the negative impacts the interventions increased. The physical barriers blocked fish migration, reduced the extent of tidal zones and imposed a sudden seawater/freshwater interface thereby removing important habitats, and created many other ecological problems. By the time the last major sea arm Oosterschelde was to be closed off and turned into a freshwater lake according to the Deltaplan, it was decided to install a barrier with large sluice gates instead, only to be closed under adverse weather conditions.

Famed for these efforts to control the water but increasingly experiencing ecological issues as a result of the large-scale interventions, it is argued that the Netherlands have in the last decades experienced a transition from technocratic water engineering to integral and participatory water management (Van der Brugge et al., 2005), in line with the EU Water Framework Directive . This transition is illustrated by directives and large-scale programs to reduce canalisation of rivers (the Room for the River programme (Rijke et al., 2012)) and the emergence of policy objectives such as "living with water" and "building with nature" which are now largely

Figure 9 Lay-out of the water management system in the Netherlands, here divided into five major areas: the main rivers (Rhine and Meuse) and associated canals and water control structures (weirs); the Ijsselmeer area, an artificial lake created in the 1930s; the southwest Delta with fully closed, semi-closed and open river arms; the closed coastal zone along the North Sea and the tidal mudflat areas of the Wadden Sea in the north; and the "high grounds" areas with small waterways. Source: Rijkswaterstaat (undated)

becoming part of the paradigm of nature-based solutions. Pahl-Wostl et al. (Pahl-Wostl et al., 2011) however state that, despite the changing policy narratives, water managers in one representative area in the Netherlands still have a mindset "very much in line with the traditional command and control approach".

The entry point for this case study is freshwater provision (Dutch: zoetwatervoorziening), a provisioning ecosystem service highly relevant for the society, economy and nature. Though freshwater provision was not the main reason for implementing the large-scale water control structures in the 20th century, it was an important co-benefit next to flood protection and transport connectivity. Following the creation of the Ijsselmeer in the north in the 1930s, the series of freshwater lakes in the Southwestern delta between 1958 and 1997 and various water control structures such dams and sluices, large parts of the country were provided with freshwater that previously only had access to saline or brackish water. The combination of land reclamation and increased availability of freshwater enabled strong growth in the agricultural sector.

Since the start of century, and in particular following a very dry summer in 2003 and a dry spring in 2005, increased attention is being paid to freshwater shortages. The *Delta commission new style* was instituted in 2007, and in 2011 a new Delta law was approved which aims to protect the country against flooding and ensure freshwater security through yearly *Deltaprogrammes* (Van Alphen, 2011). In case of freshwater shortage, water allocation is currently guided by a *sequence of priorities* (Figure 10), originally created after the drought of 1976, updated after the drought of 2003 and accompanied by further detailed guidance in 2019 (Kort and Hoppenbrouwers, 2019). However, this policy is not considered adequate to deal with the increasing stresses expected in the future, when climate change will reduce the inflow of freshwater through the major rivers and increase water demand, while a rising relative sea level will increase salinization through both surface waters as well as groundwater.

Sequence of priorities in allocation of freshwater (Dutch: *verdringingsreeks*)

- Category 1 (highest priority): safety and the prevention of irreversible damage
  - Stability of flood defence structures
  - Settling and subsidence of peat bogs and moorland
  - Nature, irreversible damage
- Category 2: utilities
  - Drinking water supply (only if critical supply risk exists, otherwise category 4)
  - Power supply (only if critical supply risk exists, otherwise category 4)
- Category 3: small-scale high-quality use
  - Temporary precision irrigation of capital-intensive crops
  - Process water
- Category 4 (lowest priority): other uses
  - Shipping
  - Agriculture
  - Nature, as long as no irreversible damage occurs
  - Industry
  - Water recreation
  - Lake fishing

Figure 10 Sequence of priorities in allocation of freshwater. Source: Kort and Hoppenbrouwer (2019)

The Delta (sub-)programme on freshwater availability, through the Delta decision, outlines the following strategy to secure freshwater availability (Deltaprogramma Zoetwater, 2014): (i) a coherent approach based on improvements to the water supply system, while stimulating self-sufficiency of water users, (ii) an adaptive approach, using regional adaptive pathways, (iii) regional agreements between public agencies and water users on roles and responsibilities, (iv) increasing freshwater buffer capacity, and (v) reducing water demand and vulnerability through more efficient water use. In this regard, the Delta decision also responds to an OECD study (OECD, 2014) on water management in the Netherlands which found that economic incentives to efficiently manage water are sometimes weak, and advocates for a more robust water allocation regime as well as a more transparent cost allocation across water users.

As part of the Deltaprogramme and research programmes on climate change adaptation, a large number of studies have been and are currently carried out to understand future freshwater demand and potential bottlenecks at national level (e.g. Klijn et al., 2012; Polman et al., 2012) as well as regional level (e.g. De Vries et al., 2009), under the Delta scenarios which combine climate scenarios (Attema et al., 2014) with socio-economic scenarios (PBL, 2015). Furthermore, separate guidance has been developed on adaptive management in the context of water management in the Deltaprogramme (van Rhee, 2012).

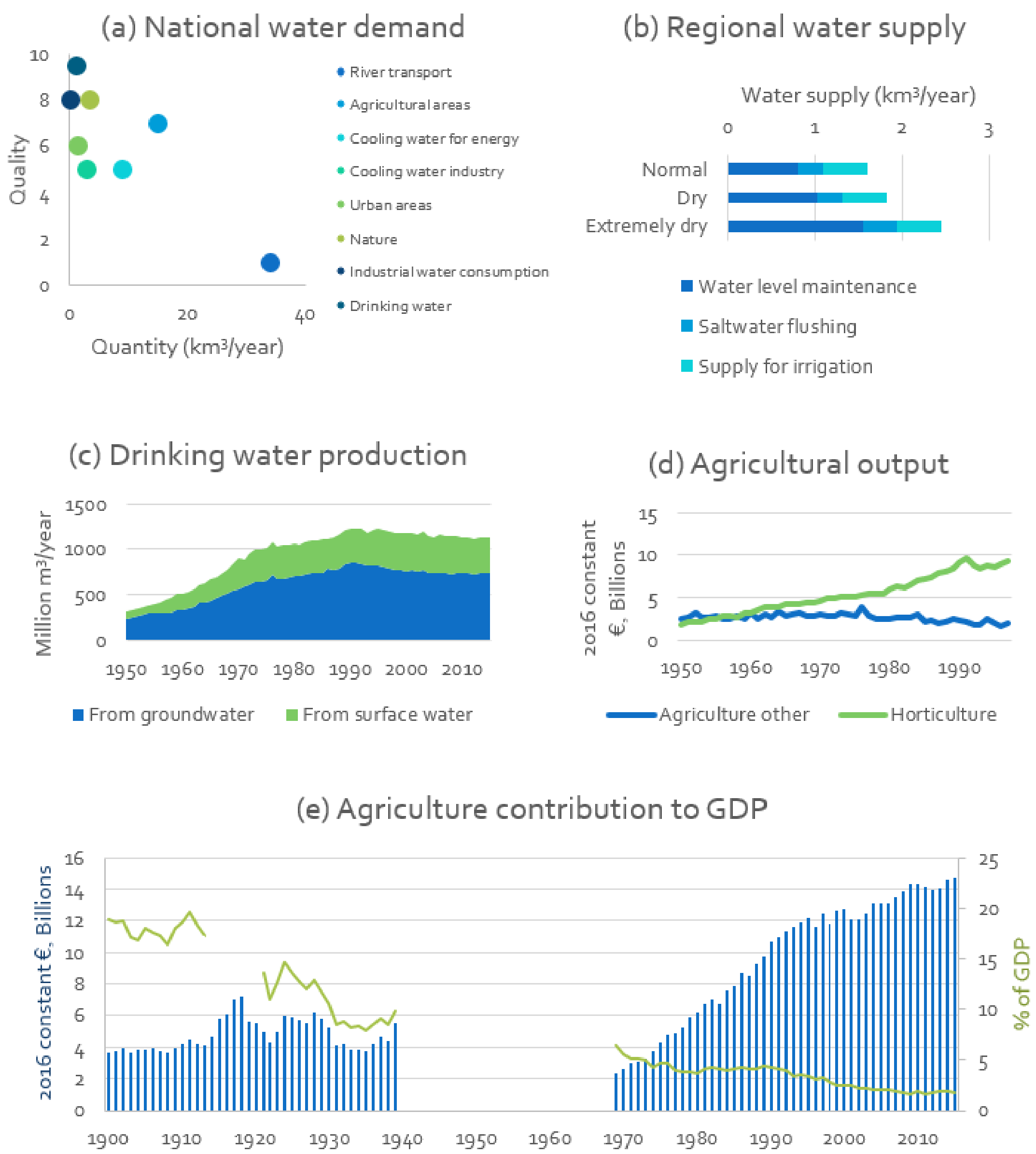


Figure 11 (a) National water demand by usage, with water quality (Y-axis) as a relative aggregate score (10 = highest) (Klijn et al., 2012); (b) Supply to regional water networks by purpose; (c) Trend in drinking water demand, (VEWIN, 2016); (d) Horticultural and other agricultural (without horticulture and livestock) output (CBS, 2001); (e) Agricultural Value Added in 2016 constant Euro (bars, left scale) and as percentage of GDP (line; right scale). Agriculture includes fisheries. Data sources: 1900 – 1940 (CBS, 2001); 1968 - 2016 World Bank and OECD (World Bank, n.d.); conversion historic CBS value in Guilder to 2016 Euro using (IISG, 2016).

An analysis of available quantitative data from secondary sources (Figure 11a-e) shows a complex picture in terms of freshwater availability, demand and dependency. Firstly, an analysis in terms of quantity and quality (Figure 11a) shows that though water transport has the highest water demand (driven by minimum river water levels to allow navigation) it puts no requirements on quality, whereas agriculture has the highest combined demand of quantity and quality. Similarly, in terms of the water supplied to regional networks (Figure 11b), the majority of water is needed to maintain water levels, with less than half of the water used to flush out salt water or for irrigation.

Drinking water production (Figure 11c) has stabilized over recent decades and is not expected to grow further; yet, some of the intake points are in zones prone to salinity intrusion during very dry years. In terms of agricultural output (Figure 11d), the importance of horticultural crops, which are more sensitive to water quality, has increased significantly. The overall added value of agriculture (including fisheries) to the GDP has increased (Figure 11e), but the significance for the national economy has declined from 12% of GDP in 1900 to 2% in 2016.

3.3.2 Adoption of adaptive management and nature-based solutions

Adaptive management was introduced as a formal water management paradigm in the 2012 Delta Programme (Deltacommissaris, 2011). At that time, pilots were initiated in selected sub-geographies to develop methodologies for applying adaptive management in practice based on an overarching guideline (van Rhee, 2012). One of these pilots was concerning the development of adaptation pathways and corresponding tipping points (Deltares, 2012). The pilot demonstrated that while a participatory analysis of adaptation pathways can rapidly bring valuable qualitative insights and lead to practical strategies, further (quantitative) detailed elaboration of consequences at the local level and cost-benefit analyses are a prerequisite for formalization of these strategies.

The 2015 Delta Programme (Deltacommissaris, 2014) included preferential strategies that were designed on adaptive management principles, explicitly specifying the areas of uncertainty and describing how strategies would need to be validated at least every six years and possibly adjusted. A dedicated monitoring and evaluation strategy was developed that adopted reflexive learning to specifically address aspects of adaptive management (Ligtvoet et al., 2016). At the time of the first major evaluation, the 2021 Delta Programme indeed found that adjustments were needed, including because of the higher-than-expected problems with drought and salinization and the changing climatic conditions (Deltacommissaris, 2021).

Nature-based solutions have become increasingly popular among water managers in the Netherlands. Examples include the large programmes of Room for the River, where the natural buffer capacity of floodplains are restored, and Building with Nature where natural sedimentation and erosion processes are used for coastal zone management . Researchers developed a 100-year vision for the nature-based future of the Netherlands (Baptist et al., 2019), however, further elaboration of design standards, analysis of costs and benefits and formal policy support are needed to apply nature-based solutions more broadly.

Table 7 Adoption of the principles of Adaptive Management and Nature-based Solutions as evidenced in case study. Legend: + = fully adopted; o = partially adopted; - = not adopted; ? = not yet established

Adaptive Management		Nature-based Solutions	
AM1 Participation of those outside the management institution in order to manage conflict and increase the pool of contributions	+	**NbS1** Embrace nature conservation norms and principles	+
AM2 Defining and bounding of the management problem, including the setting of management objectives	+	**NbS2** Can be implemented alone or in an integrated manner with other solutions to societal challenges	o
AM3 Representing existing understanding through system models that include assumptions and predictions as a basis for further learning	+	**NbS3** Are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge	o
AM4 Identifying uncertainty and alternate hypotheses based on experience;	+	**NbS4** Produce societal benefits in a fair and equitable way, in a manner that promotes transparency and broad participation	?
AM5 Implementation of actions/policies to allow continued resource management or production while learning	+	**NbS5** Maintain biological and cultural diversity and the ability of ecosystems to evolve over time	+
AM6 Monitoring of the effect of implementing new policies	+	**NbS6** Are applied at a landscape scale	+
AM7 Reflection on, and learning from, monitoring results, comparison with original expectation in order to revise	o	**NbS7** Recognise and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystems services	o

An analysis of the adoption of both approaches by considering their main principles (see Table 7) shows that based on the reviewed literature, most principles of adaptive management seem to have been fully adopted, while in the case of nature-based solutions important gaps remain. These relate to the integrated application of NbS as solution to societal challenge (NbS2), the use of traditional knowledge (NbS3) and the analysis of trade-offs (NbS7).

3.3.3 Mapping practitioners' perceptions of robustness and flexibility in water management

Figure 12 shows the results of the participants' perception of trends of robustness over time. Owing to the qualitative design of the mapping exercise, the interpretation of variables was rather diverse. In this way, the interpretation of the two system attributes as chosen by participants, and the development thereof, can be grouped as following:

1. **"Robustness is a function of water supply".** Participants who used this interpretation, focused on the large infrastructural works as major increases in robustness.
2. **"Robustness is a function of water supply and demand".** Participants who used this interpretation argued that though large infrastructural works increased robustness in steps, each of these increases were followed by an increase in demand, thereby gradually reducing robustness over time.
3. **"Robustness is a function of water supply, demand, and economic and social dependency".** Participants who used this interpretation, also included the social and economic dependency on freshwater into the definition. Robustness in this sense was seen as an inverse of vulnerability.

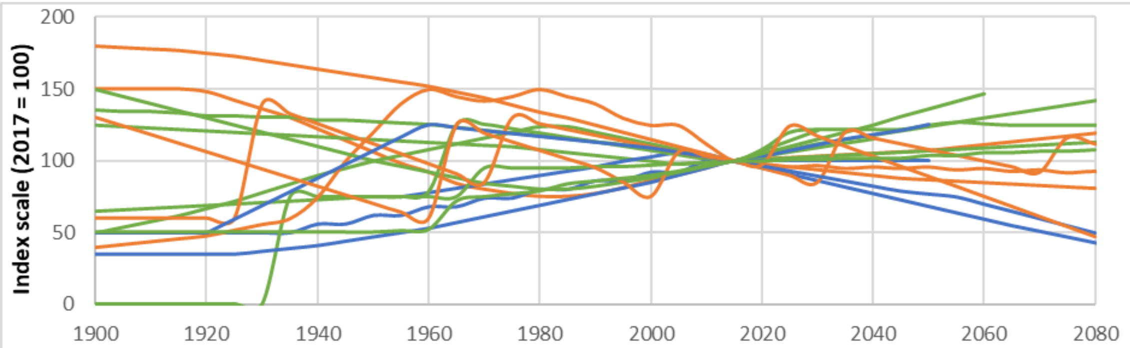


Figure 12 Trends of robustness over time, as perceived by participants, with y-axis as an index scale, 2017=100. Blue = robustness is a function of water supply, orange = robustness is a function of water supply a demand, green = robustness is a function of water supply, demand and economic and social dependency. Some lines do not cover the entire timeframe.

When looking at historic trends, the grouping of participants by definition of robustness, seems to have limited significance. Instead, three general trends can be observed: (a) general negative trend; (b) general positive trend; and (c) a trend of sudden increases followed by gradual reduction.

Looking forward, the uniformly positive future development of robustness given by participants using a "supply, demand and dependency" interpretation of robustness (green lines) stands out. The analysis of narratives provided by these participants suggests that the positive development in robustness will come from reduced economic and social dependency on freshwater provided through the central water systems, rather than improvements in the supply of (quantity of) freshwater. This is a trend many participants already observed among water users with adequate resources to reduce their dependency on the water management system, notably horticulturalists investing in private water storage and treatment facilities. An increase in robustness would thus need to come from a further widespread adoption of such individual or group-based adaptive measures.

For flexibility (Figure 13), the narratives can be grouped as follows:

1. **"Flexibility is keeping options for the future open**". Participants who used this narrative, interpreted flexibility as a forward-looking attribute linked to the availability of choices to deal with future changes, or the ability to adapt to future circumstances
2. **"Flexibility is the ability to deal with extreme situations**". Participants who used this narrative, focused on the current-day capacity of the system to continue functioning under extreme situations.
3. **"Flexibility is the ability to control or steer the system".** Participants who used this narrative looked at flexibility as mostly the human ability to control the system.

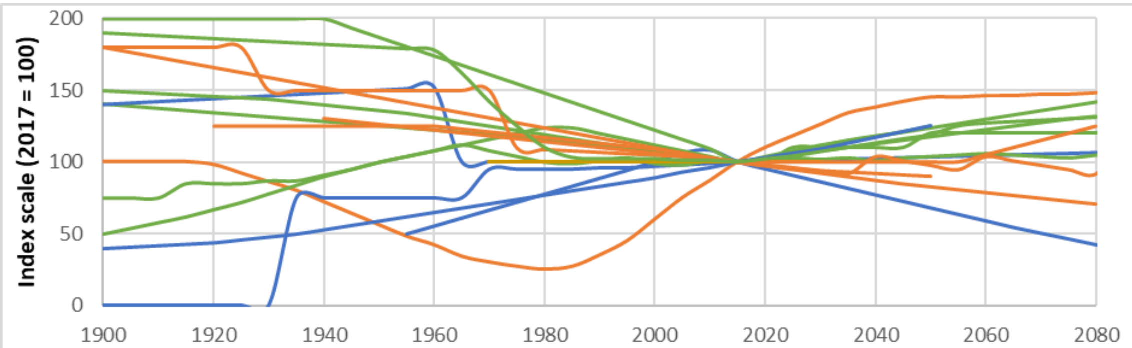


Figure 13 Sketched trends of flexibility over time, with y axis as an index scale, 2017=100. Blue = flexibility is the ability to control or steer the system, orange = flexibility is the ability to deal with extreme situations, green = flexibility is keeping options for the future open. Some lines do not cover the entire timeframe.

The analysis of results, whether participants are grouped by interpretation, organization or primary area of interest, shows only limited trends. Nevertheless, this experimental exercise can provide some emerging insights that could be investigated by further research.

In terms of flexibility, participants who used the interpretation "keeping options open", were similarly more positive about the future, and noted that the evolving thinking on adaptation pathways and regional studies to put this thinking to practice would contribute to the positive trend. Participants using a "ability to deal with extreme situations" interpretation showed a generally downward historical trend, but participants expressed optimism about current and near-future developments that would improve flexibility in this interpretation.

3.3.4 Determining practitioners' major viewpoints

The analysis of Q sorts revealed two significant viewpoints, which jointly explain 46% of the variance in the Q sorts.

Distinguishing statements for viewpoint A and their scores in the representative factor array include "adaptive management was something we were doing all along" (score +4), "legacy organizational structures significantly decrease the system's adaptive capacity" (+3), "the concept of tipping points is useful for real-life application" (-3) and "current practice effectively prevents lock-ins and lock-outs" (-3). This viewpoint could be interpreted as in line with the "traditional command and control mindset", being skeptical of the concept of adaptive management.

For viewpoint B, distinguishing statements include "the use of adaptation pathways increases understanding of future uncertainties" (score +3), "lower-level public entities have sufficient capacity to carry out devolved functions" (+2), "devolved or decentralized decision-making increases adaptive capacity" (-1) and "there is too much focus on studies and plans and too little on reality" (-4). This viewpoint supports much of the thinking of the adaptive management school, however it disagrees on the need for decentralization.

Seven participants scored significantly on viewpoint A, five participants scored significantly on viewpoint B, one participant scored significantly on both viewpoints (confounded) and one participant did not score significantly on either.

The responses to individual statements provide additional insights, bearing in mind that the scores are relative to other statements rather than scores on their own. The selected statements in Figure 14 are those with those with a significant score in terms of the analysis of narratives.

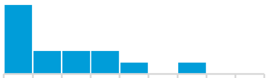
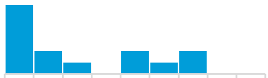
Statement	Responses	Statement	Responses
1. Adaptive management is something we were doing all along		21. Our ecosystem is over-engineered	
12. Failure at lower system level may be needed to increase resilience at higher level		27. We need to better harness nature's self-organizing capacity	
14. Adaptive management increases risks		33. Some physical structures have been put in place mostly for prestige or interest of builders, less for their function	
19. Current practice effectively prevents lock-ins and lock-outs		34. Adaptive management encourages experimentation	

Figure 14 Responses to selected numbered Q statements

3.3.5 Emerging themes from results

While the two system attributes selected for the mapping exercise are used very commonly in policies, plans and studies in the context of water management in the Netherlands, the results show a great variety in interpretation and assessment of historic and future trends among participants. While some of the participants focused on specific geographic areas which can partially explain the differences, similar lines of reasoning provided widely diverging results.

Four emerging themes from the results are discussed in further detail.

3.3.5.1 Space for self-organization in nature

Participants show high agreement in the Q sorts on the statements that the ecosystem is over-engineered (statement 21) and that there is a need to better harness nature's self-organizing capacity (statement 27). At the same time, respondents indicate that the operating space for using that self-organizing capacity is limited, because of the high pressures and demands on the system. As one participant said, "the system is becoming ever more restricted". Operating space in this matter could refer not only to physical space, but also to political, social and economic space.

3.3.5.2 Dependency and demand management

Dependency was one of the key terms most frequently mentioned in the interviews and seen as a slow variable gradually eroding robustness built up through physical interventions that increase water availability (see Figure 15). Dependency is manifested by demand of water, in terms of quantity, quality, location and timeliness, linked to the economic and social functions that would be damaged if the demand is not met.

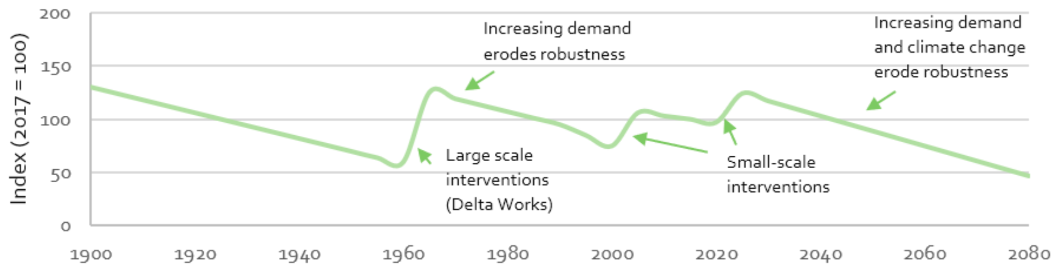


Figure 15 Representative mapping and narrative of robustness as a function of supply and demand, with interventions increasing robustness and increasing demand and climate change as slow variables. Small scale interventions can be minor canals or pumping stations. Source: author

Participants observe that overall, the dependency on freshwater has grown considerably, while some water users are taking private measures to reduce their dependency on the larger water system. The agricultural sector has intensified, and industry and drinking water companies are increasingly relying on the intake of freshwater from rivers. Farmers are demanding more and more strict water quality standards, primarily in terms of salinity level, and are less flexible in terms of timing of harvest as they increasingly produce under strict contract farming terms with large supermarket chains. Where in the past farmers could wait one or two weeks to harvest if the crop had not received enough water to grow, this flexibility is now gone. Horticulturalists in west-Netherlands are increasingly moving towards self-supply systems (groundwater, storage and desalination) as they feel that the public provision of freshwater is not reliable enough.

Comparing the results of participant interviews with quantitative data from existing sources (section 3.1), the latter do not support the statement of increased dependency on freshwater at the macro level. Instead, the dependency of the economy on agriculture has reduced significantly, and an increasing percentage of drinking water is derived from groundwater sources.

3.3.5.3 Trade-off between robustness and flexibility

The results suggest there exists a tight relationship and a partial trade-off between robustness at system level (the reliability of water provision) and the flexibility, or adaptive capacity at individual level. There are and have been efforts to actively manage demand, by encouraging individual freshwater storage through awareness raising, pilots and subsidies, but many participants argue that without freshwater scarcity, these adaptive measures will not be taken to scale. This links also the high agreement with the Q statement "Failure at lower system level may be needed to increase resilience at higher level" (statement 12). Many participants feel that a transition towards a system with lower dependency on freshwater provision from the rivers (increased resilience) will only occur after one or a series of consecutive dry summers and damage to the economy (failure at lower system level), which would provide an impetus to the political agenda and incentivize farmers to invest in alternative technologies.

3.3.5.4 Adaptive management

34% of respondents agree to a certain extent with the statement that adaptive management is something they were doing all along (statement 1), while another 43% score this statement as neutral. Evaluations of adaptive management (Walters, 1997) cite an increase of risks and costs linked to adaptive management, which is a view not shared by the majority of respondents (statement 14). 79% of the respondents do however slightly to highly agree with the statement that adaptive management encourages experimentation (statement 34). This suggests that experiments are carried out in such way that the risks are highly controlled. 79% of respondents somewhat disagree with the statement that current practice effectively prevents lock-ins and lock-outs, with exemplary statements that "locking something out is inevitable". This may particularly hold true in the densely populated Netherlands, where "each square meter has been claimed".

3.4 Discussion

The results confirm the relevance and criticality of complex adaptive systems thinking in an uncertain future, for the case study of freshwater management in the Netherlands. In line with scientific progress, policy makers and practitioners have moved beyond stationarity and fixation as paradigm, to embrace natural dynamics and build adaptive capacity under an uncertain future. It is within that new paradigm of improving adaptive capacity, that new and more advanced challenges arise concerning the practical application. Embracing uncertainty, analysing multiple possible development pathways, allowing more space for natural process to enable nature-based solutions and depending more on feedback loops have important consequences for management strategies and daily operations. A better, shared interpretation of complexity-related aspects and better complexity-informed application and assessment frameworks are critical to address these challenges.

It may not be a surprise that key concepts of complexity, in this case explored as a study robustness and flexibility around water management in the Netherlands, are interpreted in diverse ways by the actors involved. There have been recent attempts to introduce case-specific definitions (e.g. Mens, 2015; Slob and Bloemen, 2014), but achieving a common understanding as a solid basis for co-management or co-governance will require more time and effort and may only happen as a negotiation within one organization rather than be guided by national norms (van Wessel et al., 2015).

Even among people sharing a similar understanding of key concepts of complexity, their views on how these developed over time vary strongly. A joint analysis of the historical development of these concepts could provide an opportunity for decisionmakers to establish common grounds for negotiating definitions at organizational or national level.

Despite the limited significance in the results of the experimental mapping exercise per se, the method proved to offer valuable guidance for further discussion during the semi-structured interview. Many participants initially indicated their lack of confidence on the graphs they had drawn, but used it as basis to structure their further reasoning and even to question their own assumptions. This constructivist approach, using free and non-exact interpretation of the concepts, therefore gives good insights into the participants' view of the situation. Results may however be skewed by the fuzzy system boundaries. While the geographic coverage was in principle the Netherlands Rhine-Meuse delta, some of the participants were only professionally involved in parts of that system and others were involved in systems that are on the edge of the delta. Similarly, while the thematic coverage was focused on freshwater management, some of the examples provided by participants were more focused on flood management or coastal management. The definition of such system boundaries could be further improved in a second application of the experimental method, by either stricter selection of participants and more confined and controlled methods, or by more explicitly accounting for differences in the analysis phase. Such follow-up research could also be expanded in terms of number of participants.

While the Q-methodology exercise confirmed the existence of two dominant viewpoints linked to the dichotomy described in literature (command and control versus adaptive management), the narrative analysis and literature review point to a much less polarized situation. As indicated above, elements of adaptive management may be introduced without losing control over a system. Furthermore, most participants indicate that the Netherlands' ecosystem is fundamentally artificial or engineered, including nature. An example given is the existence of highly valued nature in some freshwater lakes in west-Netherlands, which would have been saline with a very different type of nature had large infrastructural works not changed the water system.

Rather than thinking in paradigm shifts or transitions, it may be more useful to assess which elements of adaptive management have been adopted, which have not, and why. If there is a lack of acceptance by traditional regimes (Mitsch, 2012), is it because of a loss of face effect where organizations rather pretend to have certainty (Walters, 1997) or are there other reasons? Many participants interpreted adaptive management primarily in terms of looking forward and using scenarios, and in some cases using adaptation pathways. Other elements of adaptive management as defined in literature, such as participation (in the sense of adaptive co-management, see (Olsson et al., 2004)) and the concurrent testing of management alternatives, were rarely cited. In a similar vein, the elements of using nature's self-organization has been primarily as a substitution for hard engineered interventions. Building with nature, the paradigm promoted, does not look at nature as a purpose in itself (van Rhee, 2017).

There is a strong view amongst participants that "the big steps have been made" in terms of increasing robustness through supply-side measures, and that further improvements to both robustness and flexibility are limited by physical and economic operating space. As a case in point, after the major interventions in the 20th century, the government struggles to implement recent more small-scale interventions such as the small-scale water supply as economic feasibility assessments give only marginal economic return rates and the (potential) negative environmental impact is high. This corresponds to the robustness trade-off theory of Janssen (Janssen and Anderies, 2007) who states that "when all 'low-hanging fruit' is taken to increase robustness cheaply, SESs will eventually reach a point at which it is no longer possible to generate additional robustness without a cost to performance and/or decreased robustness somewhere else in the system".

Finally, there is a certain paradox in the sense that freshwater is not scarce enough to encourage use efficiency, yet the abundance of water is engineered. The large-scale interventions in the

20th century created new freshwater areas in the Netherlands, where farmers and other water users now have a sense of entitlement to freshwater. Some argue that this robustness at system level has decreased flexibility on the side of the users and many state that small "collapse" is needed to increase flexibility, linking to the theory of transition management that states that short periods of non-equilibrium offer opportunities to direct the system in a desirable direction (Rotmans and Loorbach, 2009).

3.5 Conclusions

This case study provided some novel insights on how complex adaptive systems aspects are understood and used by ecosystem managers in practice, when applied to water management. By analyzing and discussing emergent system properties such as 'robustness' and 'flexibility' and by analyzing responses to statements around complexity, insights are gained on how familiar these ecosystem managers are with underlying complexity adaptive systems concepts, how they use these in their work and how these concepts can help in creating adaptive capacity to deal with environmental change.

The case study is particularly relevant as an example of an ecosystem that has become highly human-dominated, but where the management paradigm is shifting towards adaptive management and nature-based solutions. In creating more space for natural processes and dynamics, complexity thinking will be essential to understand these emergent properties at system level.

Though the results of the study show great diversity in the way ecosystem managers use complex adaptive systems theory, they also point to an opportunity for valorization of this type of explorative study. While the concepts related to complex adaptive systems thinking may not be used to predict future behavior, participatory diagnostic application offers an opportunity for establishing a common understanding of system dynamics and emergent properties. Such an exercise, as put forward in this case study, would be a starting point for establishing locally negotiated definitions of system attributes such as resilience, robustness and flexibility.

Understanding the viewpoints of actors in complex adaptive systems furthermore provides useful information for research and policy. The often-suggested dichotomy between command and control on the one hand, and adaptive management on the other hand, is not confirmed by the case study. Instead, the findings suggest that adaptive management is being introduced while maintaining control over the system. Furthermore, the results demonstrate areas of concern among practitioners that are currently not or insufficiently addressed in applied research.

Future in-depth research into the emerging findings of this case study could contribute to a developing a more reality-based, integrated ecosystem management paradigm where control and self-organization can reinforce each other, and where the lack of operating space is considered when devising policies and strategies. An integrated approach of scientific advances combined with practitioners' views as solicited in this case study, would be the right starting point to guide applied research in this field.

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4 Understanding Complexity in Freshwater Management: Practitioners' Perspectives in the Mekong Delta, Viet Nam

Abstract

Ecosystems have been stabilized by human interventions to optimize delivery of certain ecosystem services, while at the same time awareness has grown that these systems are inherently dynamic rather than steady-state. Applied research fields have emerged that try to increase adaptive capacity in these ecosystems, using concepts deriving from the theory of Complex Adaptive Systems. How are these concepts of complexity interpreted and applied by practitioners? How are these concepts applied in practice by stakeholders involved in managing the ecosystem? This case study looks at freshwater management in the Mekong Delta of Viet Nam, where water management interventions have been crucial to spur rapid economic growth over the past decades. Major environmental changes however now force a response from ecosystem managers to maintain the economic functions of the system. Through mixed methods research using interviews, mapping and literature reviews, this study finds that those ecosystem managers have very limited familiarity with complex adaptive systems thinking, interpreting and applying complex adaptive systems attributes in a normative manner rather than descriptive. Consistent with other researchers, it was found that a gap needs to be bridged between science, policy and practice. Understanding the viewpoints of actors in complex adaptive systems provides useful information for research and policy. In this case, it calls for more research on complexity in the Mekong Delta that involves local stakeholders and is grounded in analysis of historic biophysical and socio-economic developments within the region. The Mekong Delta thereby also provides an interesting learning opportunity for the global debate on nature-based solutions as part of climate change adaptation, and how this is influenced by adaptive management and governance conditions. An integrated, complexity-informed approach can assist in the further development of policies and practices that increase adaptive capacity in the Mekong Delta.

4.1 Introduction

The human quest for domination over nature is well documented and now broadly accepted to have led to a new geological era, the Anthropocene (Crutzen, 2006; Lewis and Maslin, 2015). In the Anthropocene, humans have a strong influence over the environment by trying to create ecosystems optimized for human usage. In global river deltas especially, human engineering is a major influence over morphodynamics (Syvitski and Saito, 2007) seeking to fixate river channels, control floods and salinity intrusion in an effort to maximize agricultural productivity, protect human livelihoods and assets. These human interventions coupled with an unusually stable climatic environment for the past 10,000 years (Rockström et al., 2009) haven given rise to a common belief that, through these management approaches, ecosystems can be maintained in an equilibrium state that allows maximum human usage.

At the same time, awareness is growing that ecosystems are inherently dynamic and that some environmental changes are inevitable, creating a need for adaptation. Across science and industry, traditional stability and equilibrium-oriented paradigms are being challenged by the perspective of resilience and dynamics (Folke, 2006; Milly et al., 2008). Applied research fields in ecosystem management and engineering have emerged that try to help managers to make ecosystems become more adaptive, using concepts and system attributes derived from the theory of Complex Adaptive Systems (Holland, 1992). Little research has however been carried out on whether these efforts have led to more adaptive, but still human dominated ecosystems.

This research aims to understand the perspective and opinions of actors involved in complex adaptive systems, with regards to the key features and concepts of complex adaptive systems theory, and the applied research fields building on it. It looks at ways in which actors use common system attributes in their own framing of these theories, how they see trends in these attributes, and how these relate to objective biophysical data.

The focus of this paper is on the Mekong Delta in Viet Nam, selected as a case study area because of the important choices that will have to be made in the coming decades on how to manage water in the face of rapidly changing local and regional environmental conditions (Chinvanno, 2011). This case study follows a similar investigation to one undertaken in the Netherlands (Rutten et al., 2020), selected as having a leading status in the field of water management, where a paradigm shift has occurred in terms of water management from strong interventions to living and building with nature.

4.1.1 Research Objective and Approach

The objective of this research is to get a better understanding of how complex adaptive systems thinking is applied in practice, through various linked applied research fields as adaptive management and nature-based solutions. This case study looks at freshwater provision in the Mekong delta in Viet Nam as an example of a complex adaptive system.

The approach of this study is to use actors' perspectives to get an understanding at system level, while acknowledging that the case study area is characterized by significant regional differences and great depth to many of the issues covered. It first analyses the way in which actors use these concepts and from there onwards seeks to expand on that thinking by collecting further evidence.

Furthermore, while some of the theoretical concepts used in this study are relatively recent, the approach aims to put current day thinking in a historic perspective. While most resilience and climate change studies are forward-looking, evaluations of how systems have developed in the past using modern-day theory, are scarce. Carrying out such historic back casting evaluations can however provide a grounding or calibration opportunity for assessments of expected future developments.

4.1.2 Methodology

To develop a thorough understanding of the case study, a mixed-methods has been applied using the logic of exploratory sequential mixed methods design (Creswell and Creswell, 2017). Mixed-methods research gained traction in the 1980s (Jick, 1979) as a way to combine the qualitative approach of exploring and understanding viewpoints of individuals and groups (Hay, 2000), whilst letting information emerge from the research, with a quantitative approach that is principally aimed at testing hypotheses through variables that can be measured. Integrating these two methods, through mixed-methods research, is a way to provide a more complete understanding of a problem under study. Exploratory sequential mixed-methods research starts with an investigative, qualitative phase. The analysis of the results of the first phase is then used to guide the second, quantitative phase.

This study starts with a literature review (qualitative) and an analysis of the application of adaptive management and nature-based solutions. This is followed by semi-structured interviews with key actors who are part of the complex adaptive system to gain an understanding of their individual perspective (qualitative). From the transcripts and exercises carried out during these interviews, patterns are identified in the different viewpoints of actors (qualitative and quantitative). The emerging viewpoints are then corroborated with objective data where possible (quantitative). The purpose of this analysis is to establish whether the shared subjective viewpoints of interview participants can be supported with objective data. For presentation purposes, the data collected for corroboration of insights is included in the background description of the case study.

The population group of interest to this research comprises actors who are professionally engaged in the governance and management of freshwater in Viet Nam as well as representatives of water users, both public and private sector. The participants were selected from Ben Tre and Tra Vinh provinces (see Figure 16), as well as from the regional and national level. The participants were identified based on a mapping of relevant actors and institutes, using published reports and participants lists from stakeholder meetings held on the subject. This was followed by a criteria-based sampling strategy, identifying potential candidates based on the type of organization they belong to and their primary area of interest (see Table 8). In addition to the participants initially identified through mapping, participants were identified through referrals by other participants. A total of 30 participants were interviewed during August 2017, in their respective offices or field location of farmers.

Figure 16 Map showing areas of study: the provinces of Ben Tre and Tra Vinh in the Mekong Delta, Viet Nam. Source: Author

The interviews were undertaken in either Vietnamese or English as preferred by the participants, with professional Vietnamese interpretation used for those wishing to conduct the interview in Vietnamese. Participants were informed about anonymized use of the data collected, prior to their consent to start the interview. Interviews were audio-recorded and transcribed, after which they were analysed using qualitative data analysis software.

Table 8 Overview of participant organizations and primary area of interest

Organisation	Primary area of interest: Water management	Environment and climate	Economy, laws and regulation	Agriculture	Total
Provincial government	5	3	1	3	12
Scientific institution	2	1	1		4
Central government	1	1		1	3
Water user representatives and CSOs	3		1	3	7
Independent consultants	3	1			4
Total	14	6	3	7	30

4.1.3 Mapping exercise

At the start of the semi-structured interview, participants were provided with a graph showing a horizontal timeline axis (from 1900 to 2080) and a vertical index scale (from 0 to 200, with a 100 mark at the year 2017). As an experimental qualitative-quantitative method, the participants were asked to sketch the development of two complex adaptive system attributes, *robustness* and *flexibility* of freshwater provision in the Mekong Delta, over time. Participants had not been told in advance of this exercise.

The two attributes, *robustness* and *flexibility*, were chosen because of comparison purposes with a similar case study in The Netherlands (Rutten et al., 2020). Robustness and flexibility can furthermore be regarded as attributes with considerable distance between them in terms of common interpretation, the former more often linked to reliability and continued functioning of a system under stress, the latter more often linked to capacity to adapt to changes.

During the interview, participants were asked to use their own definitions of the two attributes, to obtain their personal perspective and individual framing instead of imposing a particular definition. This qualitative, constructivist method is most fit to establish the meaning of a phenomenon from the view of the participant.

After sketching the historic trend in the two attributes, using the year 2017 as an index benchmark (2017 = 100), participants were asked to explain the trend they observed. From there, participants were requested to sketch their expectation in terms of future trends for both attributes, while indicating the factors they consider as being of influence. The remainder of the semi-structured interview was carried out using an interview guide, with the drawn graphs used as a reference point. The graphs were later analysed by visual inspection using Microsoft Excel combined with analysis of narratives, aiming to determine patterns in the responses.

4.1.4 Q-methodology

Q-methodology is a method originally developed in the 1930s by William Stephenson. Q methodology combines qualitative and quantitative elements to investigate the subjective views held by those people directly involved in a topic (Herrington and Coogan, 2011). Q studies aim to identify patterns in individuals' responses to statements without imposing a priori meanings, in order to understand the range of viewpoints regarding a particular topic.

Participants are presented with a set of statements and asked to rank these. In order to be able to understand the viewpoints of participants, it is important that the set of statements reflects the full range of sentiments likely to be held on the topic of interest. For this case study, a set of 34 statements (see Figure 18) was developed from the literature review (Chapter 2) but adjusted to better match the prevailing terminology and language used in the various documents pertaining to the case study. The statements have been selected to cover the most frequently cited issues with adaptive management and engineering linked to water management, as identified in the literature review. The statements had to be ranked from -4 (don't agree) to +4 (agree) on a pre-defined matrix (see Figure 17).

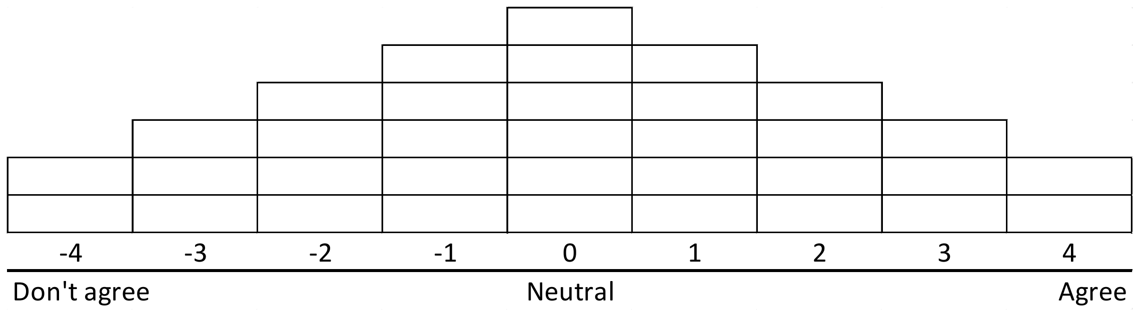


Figure 17 Matrix for sorting statements in the Q-methodology. Source: author

The Q-sorting exercise was carried out after the semi-structured interview with 14 participants, and participants were asked to think out loud while sorting the statements to enrich the information. obtained from the exercise. The Q sorts were analysed using the PQMethod software as developed by Peter Schmolck, using centroid factor analysis and varimax rotation (Brown and Stephenson, 1980) and a significance level of $p < 0.01$.

The results, represented in generalized viewpoints or factor arrays, were interpreted using the qualitative data collected from the interviews

Q statements used

1. Adaptive management is something we were doing all along
2. Adaptive management increases readiness for surprise events
3. Scenario use is an adequate tool to deal with future uncertainty
4. Many spontaneous initiatives for adaptation are blocked by laws and regulations
5. Authorities do not want to publicly acknowledge lack of certainty on important topics
6. There is enough stakeholder participation to allow for adaptive management
7. Physical structures often have greater and longer-term impacts than what we design them for
8. Organizational structures often have greater and longer-term impacts than what we design them for
9. Current-day physical infrastructure provides the system with more flexibility than in the past
10. The concept of tipping points is useful for real-life application
11. Tipping points need to be anchored in policies and regulations
12. Failure at lower system level may be needed to increase resilience at higher level
13. Policies are systematically reviewed to check if the assumptions made were correct
14. Adaptive management increases risks
15. The costs of adaptive management are preventing its adoption
16. Legacy physical structures significantly decrease the system's adaptive capacity
17. Legacy organizational structures significantly decrease the system's adaptive capacity
18. We've found a good balance between short-term gains and long-term sustainability
19. Current practice effectively prevents lock-ins and lock-outs
20. There is too much focus on studies and plans and too little on reality
21. Our ecosystem is over-engineered
22. Our ecosystem is over-managed
23. Economic interests decrease the system's flexibility
24. Regulations are changing too fast to provide stability for economic development
25. Some adaptation measures are implemented too early, before they are absolutely necessary
26. The use of adaptation pathways increases understanding of future uncertainties
27. We need to better harness nature's self-organizing capacity
28. Increased local decision-making increases risks
29. There is too much "command and control" in our system
30. Devolved or decentralized government decision-making increases adaptive capacity
31. Self-monitoring of devolved government functions increases adaptive capacity
32. Lower-level public entities have sufficient capacity to carry out devolved functions
33. Some physical structures have been put in place mostly for prestige or interest of builders, less for their function
34. Adaptive management encourages experimentation

Figure 18 Overview of Q statements used in this study

4.2 Results

4.2.1 Case Study Background

The Vietnam Mekong Delta is a highly productive ecosystem and at the centre of attention in the global discussion around the impacts of climate change. The delta is the world third largest (Coleman et al., 2003) with a surface of around 40,000 km^2 (Dang et al., 2019) of which 74% is situated in Viet Nam and the remainder in Cambodia (White, 2002). It splits into two distributaries at the apex near Pnomh Penh, the Bassac (Hau river) and the Mekong (Tien river), which further branch out into a fine-mazed network of smaller rivers, creeks and canals. The large multi-channel estuary has been relatively stable over the last 2000 to 3000 years (Li et al., 2017). While most of the land is only a few meters above mean sea level, subtle variations are crucial for socio-economic activity (Marchand et al., 2014).

Early evidence of human water management in the Mekong Delta dates to at least sometime between 300 BCE and 700 CE, when canals were constructed in the Long Xuyen Quadrangle in the upper part of the Delta (Biggs et al., 2012). This initial society disappeared and for about 1000 years the Delta was sparsely settled, until the expansion of Vietnamese and ethnic Chinese starting in the 18^{th} century CE which was accompanied by the construction of major canals. Starting in 1867, French colonial rule brought about large-scale works including canals and land reclamation, quadrupling the area under cultivation. During the 1945-1975 war times, few physical works were undertaken.

In the immediate aftermath of the conflict, the Mekong delta had limited productivity, which changed rapidly after. Agricultural production and economic growth have been high in the Mekong Delta since the *Đổi mới* liberalization reform in 1986. Rice production more than tripled from 1985 to 2015, while the agricultural economy diversified to include upland crops, fruit trees and aquaculture. The transition from a planned economy to a market economy through an export-led growth model, has enabled rapid and continued growth, resulting in a GDP per capita of 2,700 USD in 2017, above the national average of 2,343 (Malesky et al., 2018). Viet Nam has also become a major global exporter of rice, of which around 70% comes from the Mekong delta (Hoanh et al., 2014). In 2013, 32% of Viet Nam's agricultural gross value-added come from the Mekong Delta (World Bank, 2016).

A driving factor for this economic growth can be found in the increased government investments in irrigation works, availability of technical equipment, and decentralization of funds and responsibilities for hydraulic services to districts where state-owned enterprises took on most of the implementation. The resulting improvements in local water management infrastructure is a key factor explaining increased intensity in land use (Edmonds, 2008). Figure 19 illustrates these developments, showing major water control projects and the associated land use changes (Le et al., 2018).

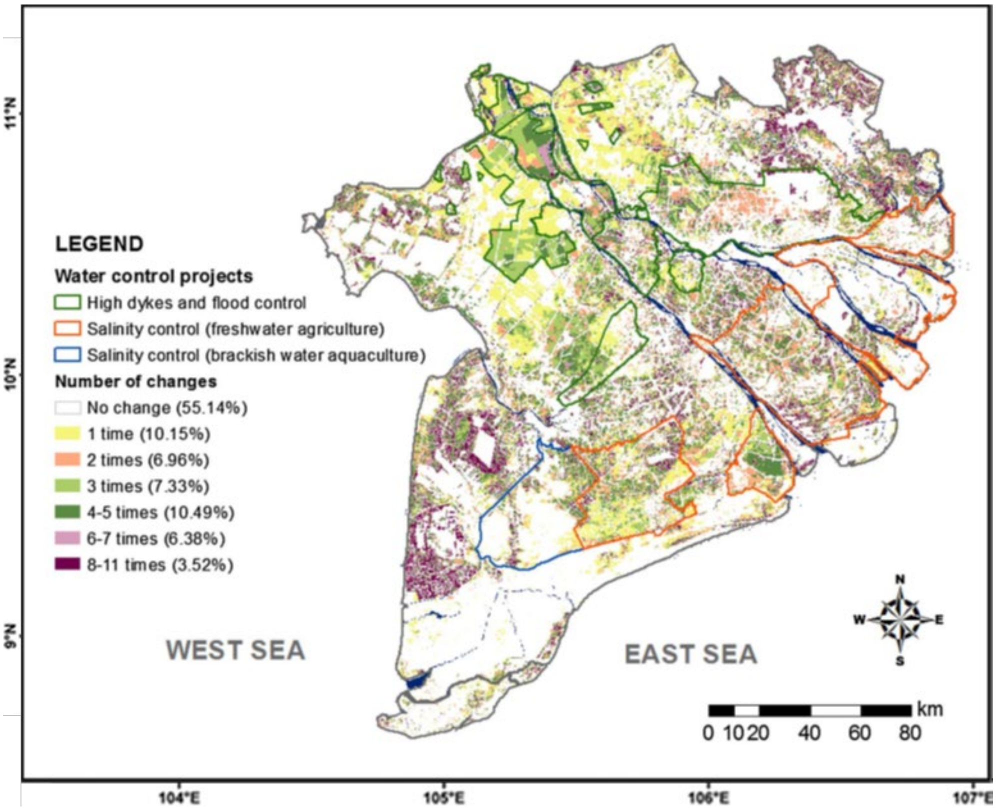


Figure 19 Water control interventions and land use change in the Mekong Delta. Shading of areas indicates the frequency of land-use change in the period 2001–2012. The percentages between brackets indicate the share of the total land surface. Source: (Le et al., 2018)

These economic gains are however challenged by the significant environmental changes that are predicted for the Mekong Delta. Global climate change models predict a sea level rise of 0.10-0.30 m by 2050 (Wassmann et al., 2004) compounded by land subsidence due to groundwater extraction of 0.35-1.40 m by 2050 if continuing in the current trend (Erban et al., 2014). Analyses of the recent evolution of the Mekong Delta (Besset et al., 2016; Li et al., 2017) show that it experienced a shift from growing (net accretion) to shrinking (net erosion) around 2005, caused not only by land subsidence, sea level rise and coastal sediment dynamics

(Marchesiello et al., 2019), but also by the installation of dams upstream blocking sediment, extension of irrigation, riverbed mining.

The changing dynamic of salinity intrusion in both surface waters and groundwater is one of the key factors that directly affect agriculture and other economic activities (Dang et al., 2019; Trung, 2014). Salinity levels in open river arms fluctuate both with tides and with seasons, where an early onset of the dry season can cause saline water to protrude deep into the delta, affecting areas that may not have infrastructural protection against such rare events. Figure 20 shows such maximum intrusion levels for selected (dry) years. Major dams and reservoirs upstream the Mekong river have already had an impact on the general shifting of the dry season from April towards February (Dang et al., 2019). Water management infrastructure such as dams and sluices can partly regulate freshwater availability provided enough freshwater can be provided from upstream. There are however multiple, sometimes competing interests at play. Sluices may need to be opened to allow traffic on waterways. At the same time, user demands in terms of salinity are variable across the mosaic of rice, shrimp and natural forest lands using the same water management systems. Managing salinity intrusion is therefore both socially and technically complicated, involving stakeholders from a wide variety of sectors, on local to international scales (Hoanh et al., 2014).

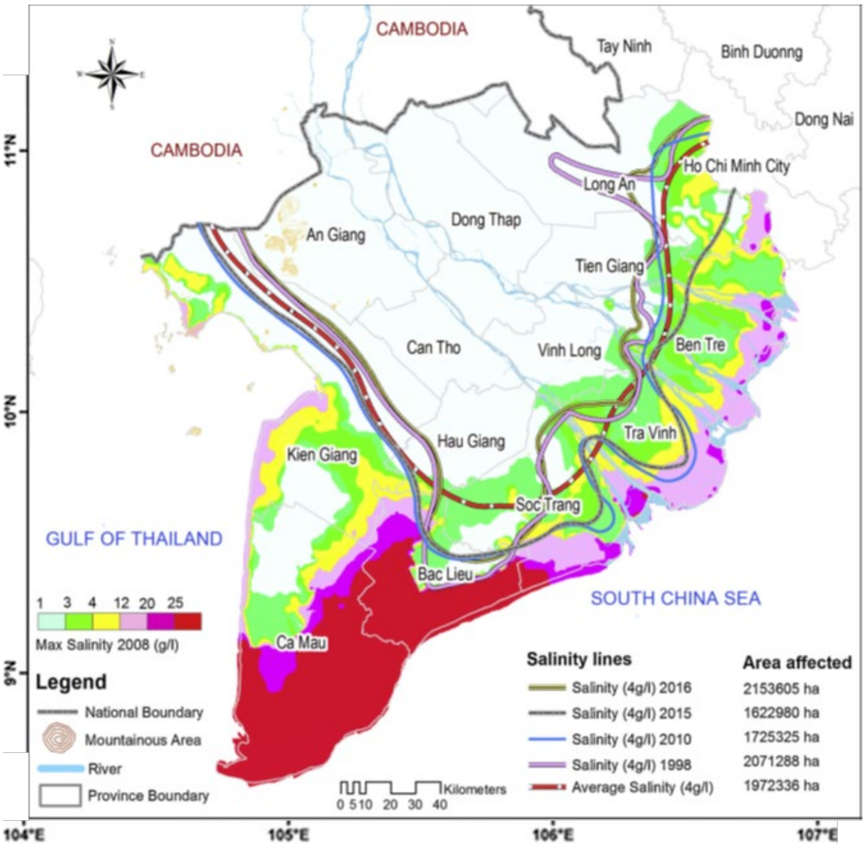


Figure 20 Map showing salinity intrusion into surface waters. Source (Tran et al., 2019)

An overarching issue facing decision-makers in the Mekong Delta is to navigate the space between preserving the current situation in terms of salinity intrusion patterns or adapting to the changes imposed by both internal and external factors (e.g. Marchand et al., 2014). Choices in this regard are closely linked to policy objectives of continuing rice production (with tightly controlled freshwater zones) versus crop diversification including brackish water zones for aquaculture (Hoanh et al., 2014). Analysing this issue, Käkönen (2008) states that water resources planners have underestimated the complexity of the ecology and society in the Mekong Delta, and that a shift in focus is needed from more control to more adaptation. Smajgl et al. (2015) argue that the political discussion has polarized between choices of either soft or hard options, but that rather an ensemble of these two options is likely to provide the most effective results. (Renaud et al., 2015) further analyse this space for the province of Ben Tre specifically, exploring complementary or alternative solutions to the development of engineered infrastructure.

In 2013, a Mekong Delta Plan was developed by a consortium of Dutch organisations in collaboration with the Vietnamese government (Partners for Water, 2013). This plan translated the globally renowned experience of the Dutch in delta management into an approach for management of the Mekong delta. It identifies four potential socio-economic development pathways (Figure 21) and finds that for the preferred pathways that integrate industrialisation and agricultural production ('dual node industrialization' and 'agro-business industrialisation' pathways), restoration of natural processes of sedimentation and the introduction of a sustainable brackish water management zone.

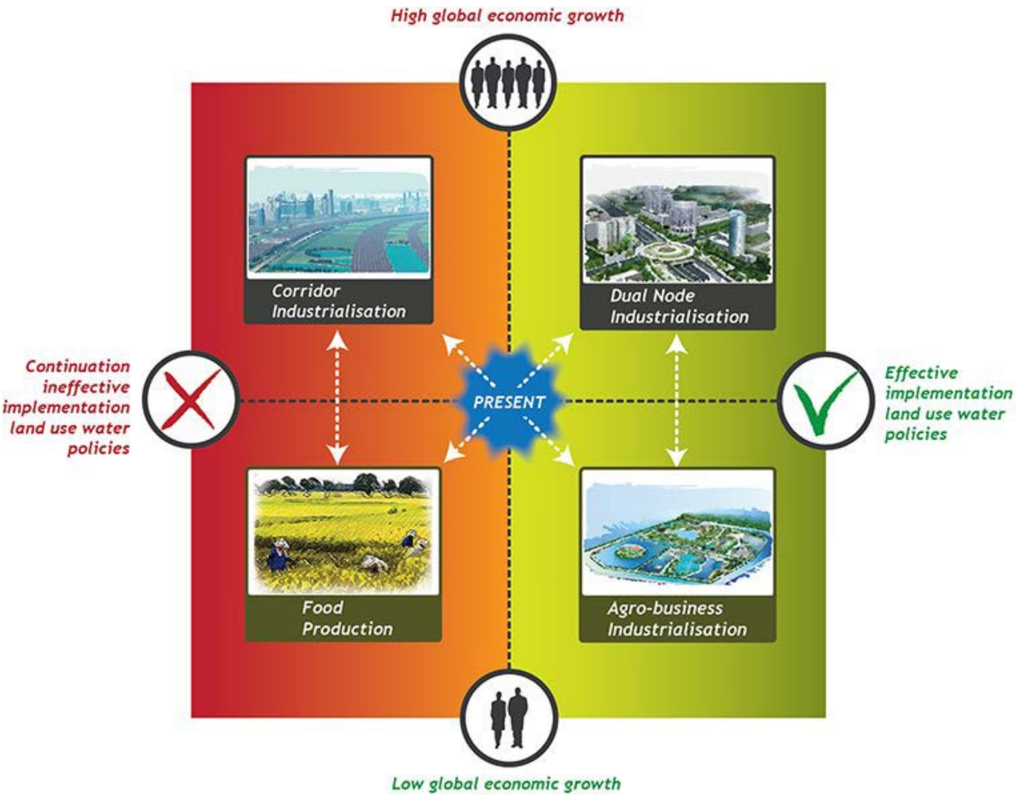


Figure 21 Potential socio-economic pathways for the development of the Mekong delta. Source: (Partners for Water, 2013)

While the transfer and translation of knowledge and experience under the Mekong Delta Plan involves similar concepts and narratives, the local interpretation of these was challenging (Laeni et al., 2020). The proposal to adopt saline agriculture proved to be unpopular, and the use of scenarios is contrasting the more deterministic nature of Vietnamese policies and planning. An evaluation three years after the completion of the Mekong Delta Plan found that it had been influential in introducing new ways of thinking about delta management, but that adoption remains limited to a small group of stakeholders while implementation at the local level lags behind (Seijger et al., 2019) and that there is limited evidence of adaptive capacity (Ha et al., 2018) which is confirmed by studies looking at drought response (Nguyen et al., 2020). Policy transfer as attempted in the Mekong Delta Plan therefore requires a longer-term support to ensure an effective translation into the local context (Hasan et al., 2019) and the effective adoption of adaptive management may require more poly-centric water management governance and collaborative learning (Hoanh et al., 2014; Nguyen et al., 2020; Tran et al., 2019).

Nevertheless, recent developments (after field visits and interviews in this study were carried out) point to a stronger adoption of adaptive management. In November 2017, the Vietnamese government adopted 'Resolution 120' on the Sustainable and Climate-Resilient Development of the Mekong Delta (Government of Viet Nam, 2017). This policy indicates a further shift away from a rice-export and "total water management" approach (Van Kien et al., 2020), to an approach that is adaptive to the changing climate, environment and market.

Over the same period, evidence was also produced that 'softer' interventions such as supporting changes in cropping systems have an overall more positive economic impact when considering environmental and social externalities compared to hard investments. Studies have found that a high dike system (a 'hard' intervention) in the upper areas of the delta, is the least economical and environmentally sustainable option as the loss of free sediment-bound nutrients is not compensated by the increased value from triple cropped rice, and that the such high dike systems exacerbate the divide between land-rich and land-poor farmers (Chapman et al., 2016; Tran et al., 2019).

A synthesis of the developments in the Mekong Delta, from a water management and socio-economic development perspective, can be found in Table 9

Table 9 Key periods and events in the development of the Mekong Delta from a water management and socio-economic perspective. Periods II – IV adapted from (Le et al., 2018)

Period		Important characteristics and events
I	**18th and 19th century** First major physical interventions	• Expansion of human settlement • Construction of major canals for irrigation • Land reclamation • Quadrupling of land under cultivation
II	**Mid 20th century till early 1990s** Period of conflict and post-conflict recovery	• End of Vietnam war, start of land liberalization (1975) • Start of the Đổi mới economic reform (1986) • Introduction of high-yielding rice varieties
III	**1990s** Rice economy boom	• Construction of freshwater supply infrastructure in pursuit of total water control • Vietnam becomes major global rice exporter
IV	**2000s – late 2010s** Diversified market-oriented farming	• Government resolution allows high-value fruit and shrimp farming to replace rice (2000) • Boom in aquaculture shrimp and tilapia (2001 onwards) • Increasing concerns around shrimp industry sustainability, water use conflicts
V	**Late 2010s –** Climate resilient management	• Resolution on Climate Resilient Management (2017) • Development of integrated regional plan 2021-2030 incorporating adaptive measures

A synthesis of available socio-economic and biophysical data (see Figure 22) highlights the limited temporal depth of data available, where earliest data points are from 1965 and most time series commence only in 1995. The synthesis furthermore revealed a very limited availability of data on water use and physical interventions in the water system.

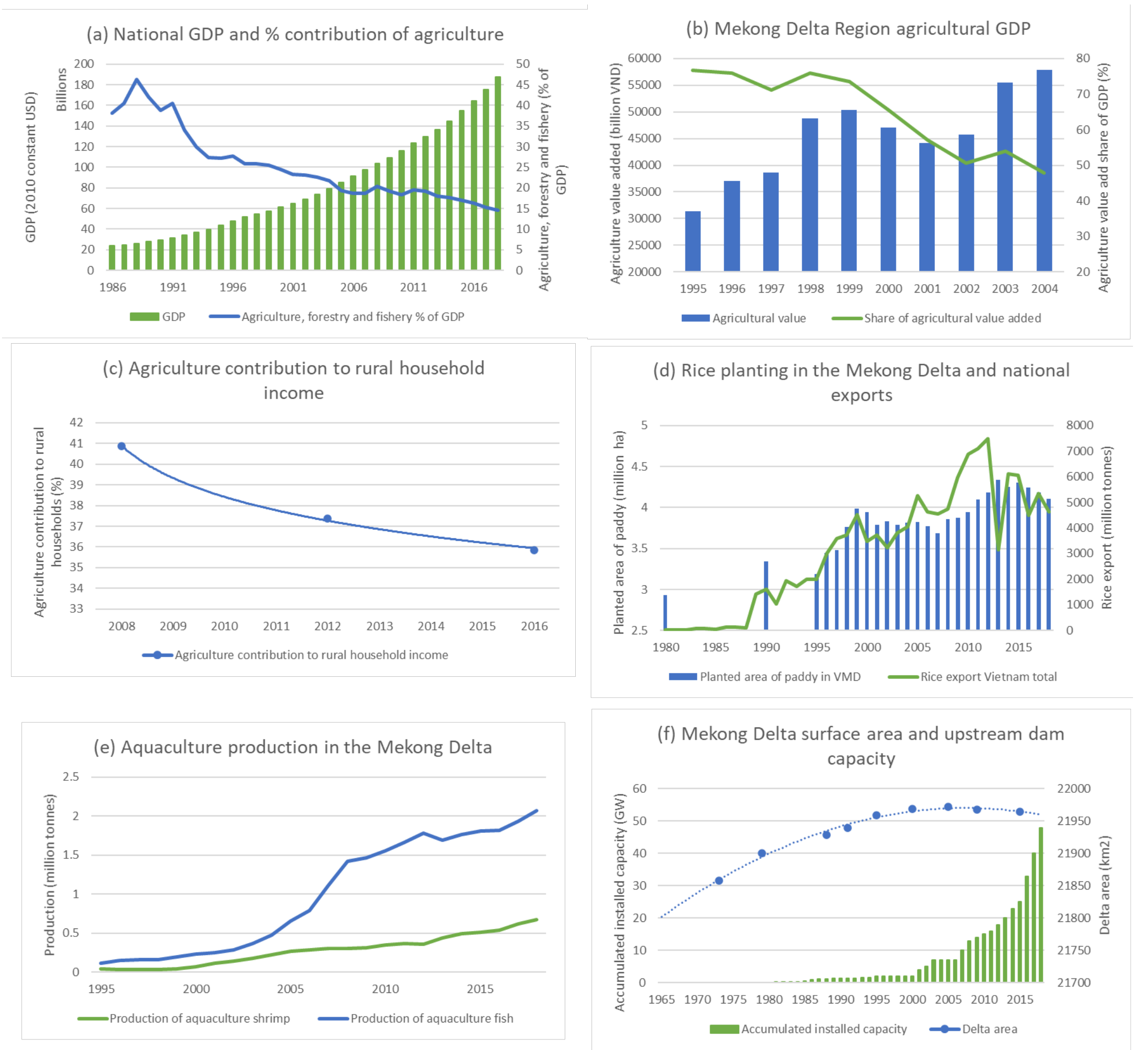


Figure 22 Overview of relevant socio-economic and biophysical indicators. (a) National GDP in 2010 constant USD and contribution of agriculture, forestry and fishery in %. Source: GSO (2020). (b) Mekong Delta regional GDP and % contribution from agriculture. Source: (c) Agriculture contribution to rural household income. Source: (d) Rice planting area in the Mekong Delta and national rice exports. Source: (e) Aquaculture shrimp and fish (tilapia) production in the Mekong Delta. Source: (f) Mekong Delta surface area and upstream dam capacity. Modified from: (Li et al., 2017)

4.2.2 Adoption of adaptive management and nature-based solutions

Adaptive management of water resources is still a relatively new concept in the context of the Mekong Delta. A study by Ha et al. (2018) showed that prevailing water management practices and governance regime in the Mekong Delta only partially corresponds to the conditions for adaptive management. While there is progress around data sharing and evidence-based decision making, planning processes do not explicitly address uncertainties or different options. The study also found limited public participation in the development strategies and no systematic process for evaluating the effectiveness of policy choices. Nevertheless, the recently introduced resolution 120 on climate resilient development departs from fixed targets for productivity, to allow more flexibility for farmers in terms of crop choice in connection with the water management choices.

The adoption of nature-based solutions is experiencing an acceleration over the last years. Following experiments with new mangrove plantings as protection against coastal erosion (Schmitt et al., 2013), nature-based solutions are now increasingly incorporated into the development planning process. Beyond the use of mangroves as a natural coastal defence, the solutions include integrated rice and shrimp production that uses natural processes to replace chemical fertilizers and is more tolerant of changes in surface water salinity.

Table 10 Adoption of the principles of Adaptive Management and Nature-based Solutions as evidenced in case study. Legend: + = fully adopted; o = partially adopted; - = not adopted; ? = not yet established

Adaptive Management		Nature-based Solutions	
AM1 Participation of those outside the management institution in order to manage conflict and increase the pool of contributions	-	**NbS1** Embrace nature conservation norms and principles	+
AM2 Defining and bounding of the management problem, including the setting of management objectives	+	**NbS2** Can be implemented alone or in an integrated manner with other solutions to societal challenges	o
AM3 Representing existing understanding through system models that include assumptions and predictions as a basis for further learning	o	**NbS3** Are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge	+
AM4 Identifying uncertainty and alternate hypotheses based on experience;	o	**NbS4** Produce societal benefits in a fair and equitable way, in a manner that promotes transparency and broad participation	?
AM5 Implementation of actions/policies to allow continued resource management or production while learning	+	**NbS5** Maintain biological and cultural diversity and the ability of ecosystems to evolve over time	+
AM6 Monitoring of the effect of implementing new policies	o	**NbS6** Are applied at a landscape scale	+
AM7 Reflection on, and learning from, monitoring results, comparison with original expectation in order to revise	o	**NbS7** Recognise and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystems services	o

An analysis of the adoption of both approaches by considering their main principles (see Table 10) shows that based on the reviewed literature, significant gaps remain. For adaptive management, five of the seven principles have not yet been fully adopted, while for nature-based solutions, three out of seven principles have not been fully adopted.

4.2.3 Mapping robustness and flexibility in water management

Participants in the interviews were asked to provide their own definitions of robustness and flexibility, however only 5 participants were able to provide a definition significantly elaborate for analysis, which all focused on being a function of the actual supply of freshwater.

The results of the mapping exercise were subsequently analysed both with and without taking into account the categorization of participants in terms of organization and primary area of interest. The results show however no (visual) significance in terms between the different types of categorization. All responses, both for the case of robustness as well as flexibility, show an increasing trend starting over the past decades, continuing in the near future.

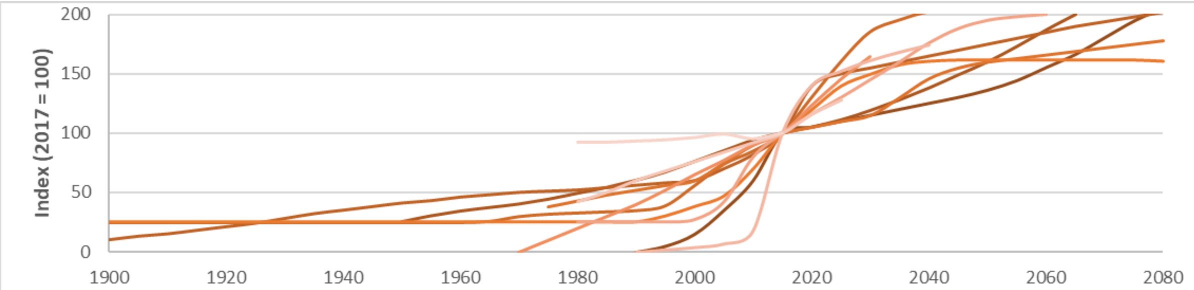


Figure 23 Sketched trends of robustness over time, with y-axis as an index scale, 2017=100. Each line corresponds to one participant. Some lines do not cover the entire timeframe.

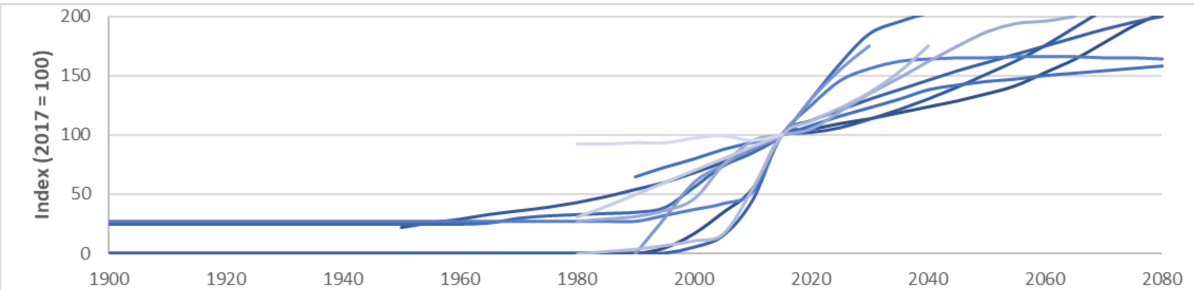


Figure 24 Sketched trends of flexibility over time, with y-axis as an index scale, 2017=100. Each line corresponds to one participant. Some lines do not cover the entire timeframe.

While this exercise yields limited results with regards to the perspectives of different organizations or primary areas of interest, there are some observations that could be made for the total set of responses. Firstly, only 27% of respondents felt confident enough to sketch the graph for the timeframe prior to 1950, and only 36% felt confident to do so for the period prior to 1980. Participants clearly stated that they had limited to zero knowledge about the past.

Secondly, most of the participants drew a very similar graph for development of robustness over time, as for the development of flexibility. Linking this to the narratives and the individual's interpretation of the two terms, it seems this may be linked to the fairly narrow interpretation of both concepts as a function of the actual supply of freshwater, rather than the combination of supply and demand.

4.2.4 Determining practitioners' major viewpoints

The analysis of Q sorts revealed three significant viewpoints, which jointly explain 59% of the variance in the Q sorts. Distinguishing statements for the three main viewpoints and their scores in the representative factor array are described in Table 11.

Table 11 Major viewpoints and distinguishing statements from Q method

Viewpoint	Relative disagreement	Relative agreement
A	• Current practice effectively prevents lock-ins and lock-outs (-3) • Current-day physical infrastructure provides the system with more flexibility than in the past (-3)	• Authorities do not want to publicly acknowledge lack of certainty on important topics (+2)
B	• Our ecosystem is over-engineered (-3) • Failure at lower system level may be needed to increase resilience at higher level (-4)	• Economic interests decrease the system's flexibility (+3)
C	• Some physical structures have been put in place mostly for prestige or interest of builders, less for their function (-4)	• Current practice effectively prevents lock-ins and lock-outs (+4)

Apart from the three major viewpoints, the Q method analysis gives interesting insights on a high number of consensus statements, which are non-significant at $P>0.05$. The responses to individual statements provide additional insights, bearing in mind that the scores are relative to other statements rather than scores on their own. The selected statements (see Figure 25) are those with those with a significant score in terms of the analysis of narratives, as follows.

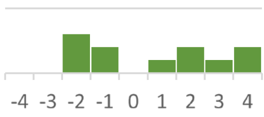
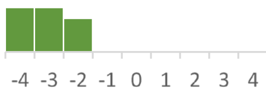
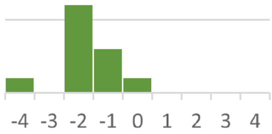
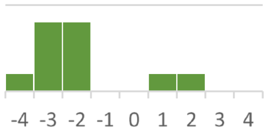
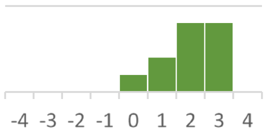
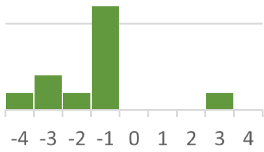
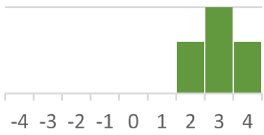
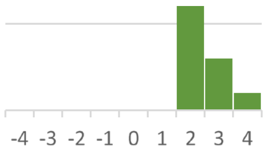
Statement	Responses	Statement	Responses
1. Adaptive management is something we were doing all along		14. Adaptive management increases risks	
6. There is enough stakeholder participation to allow for adaptive management		16. Legacy physical structures significantly decrease the system's adaptive capacity	
10. The concept of tipping points is useful for real-life application		18. We've found a good balance between short-term gains and long-term sustainability	
13. Policies are systematically reviewed to check if the assumptions made were correct		27. We need to better harness nature's self-organizing capacity	

Figure 25 Responses to selected Q statements. Negative scores denote disagreement, positive scores indicate agreement with the statement.

4.2.5 Emerging themes from results

The quantitative and qualitative findings from the interviews with interviewed practitioners in the Mekong Delta, show some significant differences from the analysis of literature and synthesis of relevant socio-economic and biophysical data. While this can partially be attributed to limited familiarity of the participants with the concepts introduced through this study, the differences also provide other insights.

Three emerging themes are discussed here in further detail.

4.2.5.1 Limited temporal depth and historic perspective

The mapping exercise highlighted limited historic perspective among participants. Currently, most graphs start in or after the 1980s when new liberalisation policies had come into effect and significant investments were made in "total water management" (Biggs et al., 2012) in order to boost rice production. Most participants, regardless of age group, indicated that they did not have any knowledge of what happened prior to this period and /or did not feel comfortable in drawing trends for these periods. This suggests there is, for this group of participants, a 'new beginning' in terms of their framing of development and how to assess progress over time. This may be aided by the long gap in significant developments in terms of water management, over most of the 20th century.

The analysis of available data shows a similar temporal depth, as most data is only available from the 1990s onward. This limited availability of quantitative data to base analysis on, may also partly explain the limited historic perspective among participants.

4.2.5.2 Deterministic interpretation of complex adaptive systems attributes

The results of the two exercises, combined with the narratives from the semi-structured interviews, clearly show that there is a high uniformity in the interpretation of attributes flexibility and robustness as a function of the system's ability to supply or secure freshwater. This dominant interpretation is primarily that of a "positive" attribute and very few participants were able to provide a detailed definition or understanding. Furthermore, results show that there is consensus that these system attributes have improved over time, and that all participants expect they will continue to do so.

The uniform, upward trend as drawn by participants on the development of flexibility and robustness, is best reflected in the development of rice planting in the Mekong Delta and national rice exports (Figure 22d), aquaculture production (Figure 22e) and agricultural value added to the economy in the Mekong Delta (Figure 22b). All these graphs show strong growth from the mid-90s. While there are no statistics on freshwater availability, the above indicators can serve as general proxies. Rice production is especially strongly correlated to freshwater availability. While aquaculture as such is not necessarily dependent on freshwater, it does need water control to ensure high productivity.

4.2.5.3 Data analysis and literature review show important system developments not reflected in interviews

While some of the data show uniform, upward trend that can serve as proxies of "general development" and "water control" and thereby corroborate the participants' perspective, the data also shows some other important system-level developments that did not emerge from the interviews, neither through the quantitative nor the qualitative aspects.

This includes the steady, gradual decline of the contribution of agriculture value added to Viet Nam's overall economy from 40% in 1990 to 15% in 2017 (Figure 22a), or a 25 percentage point decrease in 27 years, and the even faster decline of this share when looking at the Mekong Delta only, from 75% in 1995 to 48% in 2004 (Figure 22b) or a 27 percentage point decrease in 9 years. The potential impacts of this trend as observed in other countries, in terms of shifting government policy and budget priorities and ultimately in terms of decision making in water management (e.g. between different water users of agriculture, industry, domestic use and transport), did not emerge from the discussions with participants about the historic and future developments.

The more direct biophysical changes are also not reflected in these interviews. Recent studies have shown that after centuries of continues growth, that around 2005 the Mekong Delta experienced a shift from growing to shrinking (Figure 22f). This is particularly interesting when juxtaposed against the participants' scoring on the Q method statement "the concept of tipping points is useful for real-life application".

It should be noted that the interviews have been held in 2017, before the introduction of the new climate resilient development resolution and that start of "period V" as identified from literature review. These more recent developments in policy, are therefore not reflected in the interviews.

4.3 Discussion

The analysis of literature and existing data clearly shows that the Mekong delta has undergone significant changes over the last decades, with regards to freshwater management and socio-economic trends that are linked to water use. These include major interventions into the water management system, policy changes from rice production-focused to demand-driven to climate resilient planning and resulting land use changes. These changes have happened over a relatively short time span of around 25 years, after a long period of relatively little development in water management.

The results of this case study show that, when looking at longer timeframes, characteristics of complex adaptive systems can be identified. Policy choices and water management interventions, particularly increased control over salinity levels, have played an important role in creating the right conditions for a significant increase in rice output in the first post-conflict phase in a determinist, "command & control" manner. Yet the market-driven policy in the early 2000s, farmers' responses to changing policies and new economic opportunities by shifting to alternative production systems with different water management requirements and the meantime rapidly changing understanding of the current and future state of the environment, show complex interaction resulting in emerging system properties such as adaptive capacity. These interactions are likely to become more complex when the overall socio-economic development in the region begins to shift government priorities regarding different economic sectors and their water management requirements.

In that rapidly evolving system, one could expect a richer and more diverse result when discussing complexity-related aspects with people directly involved in management of the system from different disciplines and interests. In this section, we discuss some of the plausible causes and other insights derived from the study results.

4.3.1 Interviews: depth of interpretation, limited familiarity with new concepts and normative interpretations

One of the plausible causes of the uniform responses from participants can be found in the depth of interpretation and familiarity with complex system attributes**.** The majority of participants showed limited depth in terms of understanding complex system attributes in the context of this case study. This may be partially attributed to the design of the research using foreign concepts and the translation of these specific concepts and the entire interview, however, the interview set-up also provided sufficient space to deeply probe the participant's viewpoint. The results show that there is a broad lack of familiarity that needs to be considered when interpreting the results. It should be noted that there is equally a lack of data to correlate water engineering to agricultural development (Vormoor, 2010) which limits the participants' ability to deepen their interpretation.

It is however also an important finding of this study in itself, in the sense that adaptive management requires key stakeholders to have a shared understanding of major descriptive, complexity-related attributes of the system they are managing. For the participants in this study, the concepts and system attributes used are so unfamiliar that they become practically useless to describe and discuss potential ecosystem management strategies. This not only involves ecosystem managers at provincial and lower administrative levels, but also national or central government level. Similar 'implementation gaps' have been reported for other new development paradigms in Viet Nam (e.g. Wolf et al. (2020).

Few participants were able to provide detailed definitions of robustness and flexibility yet had no reservations in mapping the development of these parameters over time. This may be attributed to a normative interpretation of the two system attributes as inherently positive: that is, since that there has been a lot of development and improvement in water management in the Mekong Delta in general, the trend in these two attributes should also be positive. Such interpretations may also be influenced by cultural-political considerations, with participants aligning to prevailing narratives within their organisations.

4.3.2 Dichotomy in paradigms and policy-implementation gaps

While the discussion on the development strategy of the Mekong Delta seems to be polarized at the strategic level, the majority of practitioners interviewed for this case study does not seem to regard the problem in the same manner. The dichotomies presented in literature and strategic documents between "hard" and "soft" choices as well as between "control" and "adaptation" do not appear to be reflected in the reality of these practitioners. Shorter term ecosystem management choices faced by these participants comprise a mix of hard, soft, control and adaptation strategies. This space would need to be further detailed, for complex systems attributed to be of guiding value to key stakeholders participating in this study, confirming the finding of other researchers such as (Garschagen, 2010; Smajgl et al., 2015).

The policy-implementation gap is even more pronounced when focusing on farmers understanding and adoption of these paradigms. A particularly interesting part of the biophysical analysis is on the role that floods play in the Mekong Delta. Prior to the 1970s development in the Mekong Delta, farmers largely regarded floods as an integral part of their ecosystem and an essential phenomenon to upkeep the fertility of their lands. With the arrival of water managers and engineers, these floods were to be controlled and minimized, which on the one hand increased agricultural productivity, but at the same time required the farmers to use more agricultural inputs. Yet, in the last decade this paradigm has again shifted to a more "adaptive" stance, yet this time one that is instructed by policy. Tran (2020) analysed this evolving debate at the policy and research level from the perspective of farming groups and identified three corresponding stages: free adaptation to transitional adaptation to forced adaptation.

Some researchers have ventured to apply research findings by proposing management strategies bringing complex adaptive systems thinking closer to reality (e.g. Renaud et al., (2015). These studies however mark a significant departure from the existing understanding and thinking among key stakeholders in the Mekong Delta. Without connecting such elaborate theoretical framework to the current knowledge and attitudes of key stakeholders, by means of making explicit comparisons with the status quo and providing intermediate steps towards those new strategies, they may not prove to be adopted in practice.

4.3.3 Potential for complexity-informed dialogue, adaptive management and nature-based solutions

The results of the case study point to the potential for complexity-informed dialogue around water management in the Mekong Delta, to improve adaptive capacity.

A better understanding of key complex systems attributes may help stakeholders better assess the possible future scenarios in terms of development in the Mekong Delta, and thereby allow for adaptive management. In this regard, it is interesting that most participants agree to the Q statement that “the concept of tipping points is useful for real-life application”. In their narratives, participants however did not discuss the different pathways that are plausible for the development of the Mekong Delta, rather, they focused on the optimistic development pathway they had described in the mapping exercise.

Such a dialogue can be assisted by a better grounding in historic development and development pathways in other river deltas. Towards the end of each interview and after having completed the mapping and Q method exercises, participants were confronted with additional information regarding historical developments in the Mekong Delta (pre-1970s), as well as results from a similar case study in the Netherlands. Participants indicated that a better understanding of historical developments as well as other similar cases (delta ecosystems around the world) would be helpful for them to better manage their ecosystem. Such understanding could help better understand possible development scenarios or pathways, as well as avoid negative effects to occur.

Another element linked to this is potential limited knowledge of trade-offs that exist or may exist in managing ecosystems. This can be exemplified by the fact that all participants scored positively on the Q statement “we need to better harness nature’s self-organizing capacity” (see figure 3) and “our ecosystem is over-engineered”, while at the same time most of these participants were supportive of the idea of substantial engineering interventions which go against these statements.

Scholars have consistently pointed to the potential for adaptive management in the Mekong Delta, while indicating the need for different, polycentric governance arrangements to enable that adaptive management (Hoanh et al., 2014). These findings are consistent with and complementary to those of Ha et al. (2018) who find that the Mekong Delta only partially responds to the conditions thought to be important to enable adaptive management. This study finds that knowledge and information are not shared pro-actively and that policy development and implementation do not adequately integrate uncertainties.

The Mekong Delta provides a strong test case for the application of nature-based solutions in tandem with adaptive management and complexity-informed dialogue. The strong impetus for large-scale programmes to address increasing salinization and potential loss of land due to rising sea levels, subsidence and dam construction, means that important decisions will need to be taken as to the application of different 'hard' and 'soft' interventions. Systematic adoption of nature-based solutions and adaptive management hinges on evidence of their effectiveness and on a better complexity-informed analysis of the potential consequences of adoption primarily 'hard' interventions focused on preserving the status quo.

Nature-based solutions thereby need to quickly need to be scaled up and integrated into a broader management paradigm. While farmers have been using natural flood processes for centuries to fertilize their soils and partially stopped those practices as a results of large-scale interventions in the delta, the same use of natural processes now needs to be done within the new adaptation paradigm where state-led action plays a much stronger role. Beyond the use of floods and sediment deposition processes for management agricultural lands, the nature-based solutions space also involves the recognition of mangroves as coastal defence mechanisms (van Wesenbeeck et al., 2014). An integrated approach to several nature-based solutions that are now receiving increasing recognition (Oanh et al., 2020) would be an important ingredient to move the complexity-informed dialogue on different management paradigms forward at the strategic level.

4.4 Conclusions

How does complex adaptive systems thinking connect to the understanding of key stakeholders managing the Mekong Delta? The findings of this case study point to a very limited familiarity of those key stakeholders with the concepts and system attributes used in complex adaptive systems thinking, despite a rapidly growing body of international literature on this topic and emerging evidence of transitions in system state.

Understanding the viewpoints of actors in complex adaptive systems provides useful information for research and policy. In this case, it calls for more research on complexity in the Mekong Delta that involves local stakeholders and is grounded in analysis of historic biophysical and socio-economic developments within the region. The Mekong Delta thereby also provides an interesting learning opportunity for the global debate on nature-based solutions as part of climate change adaptation, and how this is influenced by adaptive management and governance conditions. Such an integrated, complexity-informed approach will assist in the further development of policies and practices that increase adaptive capacity in the Mekong Delta.

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5 Intermezzo: Comparative analysis of case studies

5.1 Background

This intermezzo brings together the results of two case studies, in the Netherlands and Viet Nam. We aim to add value to the individual case studies by discovering patterns or similarities through comparative analysis, enabling the development of new hypotheses. The combined results from this comparative analysis and the literature review, provide the basis for the development of a conceptual model describing the dimensions of dealing with complexity of deltas in transition (Chapter 6). This chapter is not intended as a stand-alone paper, rather it synthesizes results and refers to the individual case studies for further details on methods and results.

5.2 Method

Comparative case studies use an iterative analysis of multiple cases, or experiments, leading to a comparison of emergent themes and explanations (Mills et al., 2009). We chose the case study method because of the ability it provides to use rich descriptions and investigations, including historical analyses and extensive interviews, to identify new hypotheses. By using the comparative case study method, we aim to discover patterns or similarities across the case studies that can help further the thinking on our research topic. Bearing in mind the limitations of the comparative method, one of its most valuable features is that it “engenders an extensive dialogue between the investigator’s ideas and the data” (Ragin, 2014).

The underlying case studies both use the same explorational mixed-methods research method (Creswell, 2014), combining qualitative and quantitative research methods, which are described in detail in each case study and summarized here. Each study starts with a literature review (qualitative) followed by semi-structured interviews with key actors who are part of the complex adaptive system to gain an understanding of their individual perspective (qualitative). This included an experimental graph exercise was used to understand the participants’ view on the development of key system attributes over time, using a relative index scale with 2017 = 100. Participants were asked to sketch their interpretation of how the system had developed over time for two attributes (robustness and flexibility), using their own definitions of these terms. It also included a Q method with sorting of statements between disagreement and agreement in a pre-determined matrix. From there, patterns were identified in the different viewpoints of actors (qualitative and quantitative). The emerging viewpoints are then corroborated with objective data where possible (quantitative). The population group of interest to this research comprises actors who are professionally engaged in the governance and management of freshwater as well as representatives of water users in both case study areas.

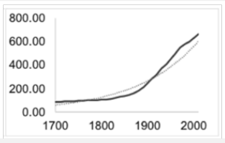
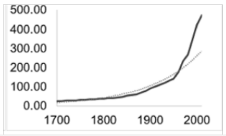
In carrying out this comparative analysis, we added relevant biophysical and socio-economic data not contained in the individual case studies as well as recent literature, that provide further insight into the similarities and differences between the two case studies. Furthermore, we evaluate the chose case study design in the light of the ability to carry out comparative analysis and potential further generalization.

5.3 Synthesis and comparison

5.3.1 Summarized history of water management in two case studies

The two case studies are both river delta ecosystems with high socio-economic activity: The Rhine-Meuse Delta in the Netherlands and the Mekong Delta in Viet Nam. The case studies are focused on water management, particularly freshwater management (or framed differently, salinity management in surface waters). Both river deltas have a long history of human interventions in water management but exhibit at a different level of human influence over the natural ecosystem, while also their position along the socio-economic development trajectory differs (see Table 12).

Table 12 Key characteristics of two case studies. (a) approximate surface area. Sources (Berendsen, 1998; Dang et al., 2019); (b) population density for delta area and historic development, source (Santos and Dekker, 2020); (c) GDP per capita in current USD (national average), source (World Bank, 2020)

	Netherlands Rhine-Meuse Delta		Viet Nam Mekong Delta	
Surface area (km2)[a]	± 35.000 km²		± 40.000 km²	
Population density (inh/km²)[b]	± 650		± 530	
GDP per capita in 2019 (USD)[c]	52,331		2,715	

In the Netherlands, the first water management interventions were carried out at community or village level, mostly focused on preventing flooding, reclaiming land, and to create military defence structures (Rijkswaterstaat, 2011). Starting around the 11th century CE, the reclamation of land and creation of polders was at its peak between 1600-1800, driven by local communities and organizations. The early 20th century saw another major boost in interventions, sealing off a river arm and creating a large freshwater lake. A major flood in 1953 subsequently gave rise to a series of physical interventions in the 1960s-1990s aiming to fully close off river arms along the southern coast called the Delta Works (Wesselink et al., 2007). Over the course of the same period, agricultural production increased dramatically. By the end of the 20th century however and as environmental sustainability became a global topic of concerns, the large-scale water management interventions focused on flood control faced increasing scrutiny, leading to a transition from technocratic water engineering to integral and participatory water management (van der Brugge et al., 2005). This transition is illustrated by current directives and large-scale programs to reduce canalisation of rivers and the emergence of paradigms such as “living with water” and “building with nature” (Rijke et al., 2012).

In the Mekong Delta, Viet Nam, early human water management interventions date between 300 BCE and 700 CE. Following a prolonged period of sparse settlement, the expansion of Vietnamese and ethnic Chinese in the 18th century CE brought the construction of major canals (Biggs et al., 2012). Starting in 1867, French colonial rule brought about large-scale works including canals and land reclamation, quadrupling the area under cultivation. During the 1945-1975 war times, little physical works were undertaken. After the *Đổi mới* liberalization reform in 1986 and as a result of increased decentralized government investments in infrastructure and equipment, water management interventions were a key driver for increased productivity and economic growth, particularly concentrated in rice production (Edmonds, 2008). In the early 2000s, the government allowed market-driven production, which hailed a strong shift to aquaculture, while more control of water was pursued. Recently however, the Vietnamese government indicated a shift to more climate-resilient development and adaptive management of the delta (Government of Viet Nam, 2017).

When comparing the historic development trajectories of the two case studies, there is a significant difference in the extent to which human interventions dominate the ecosystem, where the Rhine-Meuse Delta is considered to be in a ‘locked-in’ situation (Santos and Dekker, 2020; Seijger et al., 2017) whereas the Mekong Delta is not. The extent of human intervention in the Rhine-Meuse Delta is very high, with the Delta Works closing off most of the estuarine inlets, thereby also effectively minimizing natural salinity intrusion cycles with tides. In the Mekong Delta, infrastructure works have thus far focused on smaller rivers and canals, leaving the major river arms uncontrolled, although there has been extensive discussion regarding the potential advantages and disadvantages of such an intervention. At the same time, a timeline comparison of the development trajectories in both cases (see Figure 26) suggests that the developments in the Mekong Delta leading towards a similar lock-in situation, may happen at a faster pace than they did in the Rhine-Meuse Delta.

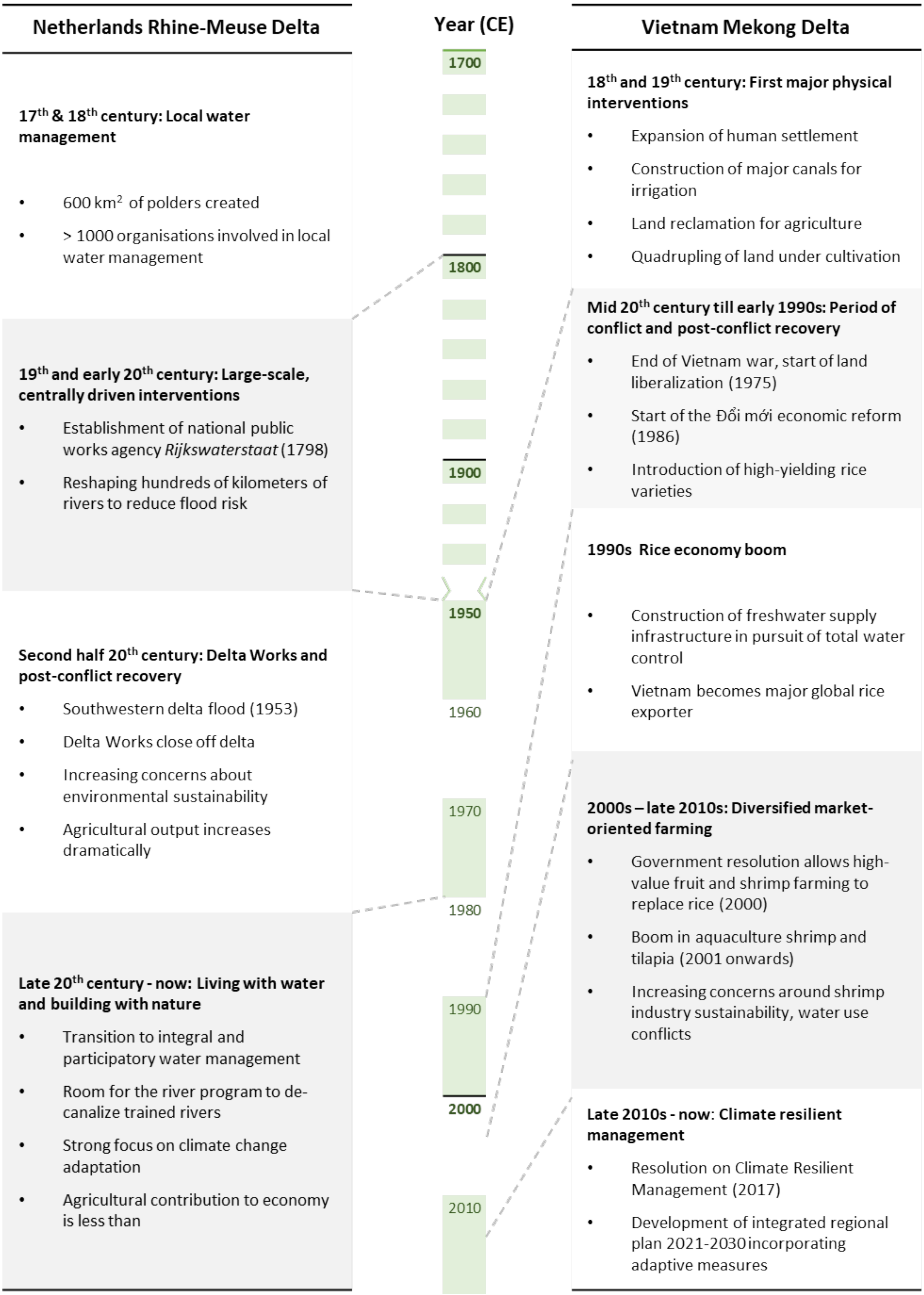


Figure 26 Overview of main periods of development of the water management system in two case studies. Source: author.

An analysis of the adoption of the adaptive management and nature-based solutions frameworks in both case studies (Table 13) shows a great contrast in the adoption of adaptive management. In the Netherlands, the explicit adoption of adaptive management in the delta-wide planning process is reflective in full adoption of 6 and partial adoption of 1 principle as defined by Rist et al. (2013), while in the Viet Nam important gaps are identified in terms of stakeholder participation, use of scenarios or pathways and the structural monitoring of new policies. In both cases there was limited evidence of the adoption of learning from monitoring results, which is directly related to the only recent adoption of adaptive management measures.

Table 13 Adoption of the principles of Adaptive Management and Nature-based Solutions as evidenced in case studies in the Netherlands (NL) and Viet Nam (VN). Legend: + = fully adopted; o = partially adopted; - = not adopted; ? = not yet established

Adaptive Management	NL	VN	Nature-based Solutions	NL	VN
AM1 Participation of those outside the management institution in order to manage conflict and increase the pool of contributions	+	-	**NbS1** Embrace nature conservation norms and principles	+	+
AM2 Defining and bounding of the management problem, including the setting of management objectives	+	+	**NbS2** Can be implemented alone or in an integrated manner with other solutions to societal challenges	o	o
AM3 Representing existing understanding through system models that include assumptions and predictions as a basis for further learning	+	o	**NbS3** Are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge	o	+
AM4 Identifying uncertainty and alternate hypotheses based on experience;	+	o	**NbS4** Produce societal benefits in a fair and equitable way, in a manner that promotes transparency and broad participation	?	?
AM5 Implementation of actions/policies to allow continued resource management or production while learning	+	+	**NbS5** Maintain biological and cultural diversity and the ability of ecosystems to evolve over time	+	+
AM6 Monitoring of the effect of implementing new policies	+	o	**NbS6** Are applied at a landscape scale	+	+
AM7 Reflection on, and learning from, monitoring results, comparison with original expectation in order to revise	o	o	**NbS7** Recognise and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystems services	o	o

In terms of the adoption of nature-based solutions, there is less contrast between case studies. In both cases, a change in policy and practice can be observed that embraces nature conservation norms and principles. In both cases, challenges are reported in terms of integrating nature-based solutions within large-scale programs. In the Netherlands, nature-based solutions are found to be large driven by technological advancements, whereas in Viet Nam nature-based solutions are applied more within the community-based development context. In both cases, a need is identified for better tools to recognize and address trade-offs and to carry out cost-benefit analyses of the introduction of nature-based solutions as opposed to traditional, ‘hard’ measures.

5.3.2 Local stakeholder understanding of complexity

The results of the stakeholder interviews in both case studies show strong contrasts, particularly regarding the participants' interpretation of the development of complex adaptive systems attributes over time, within their respective geographic areas (see **Figure 27**).

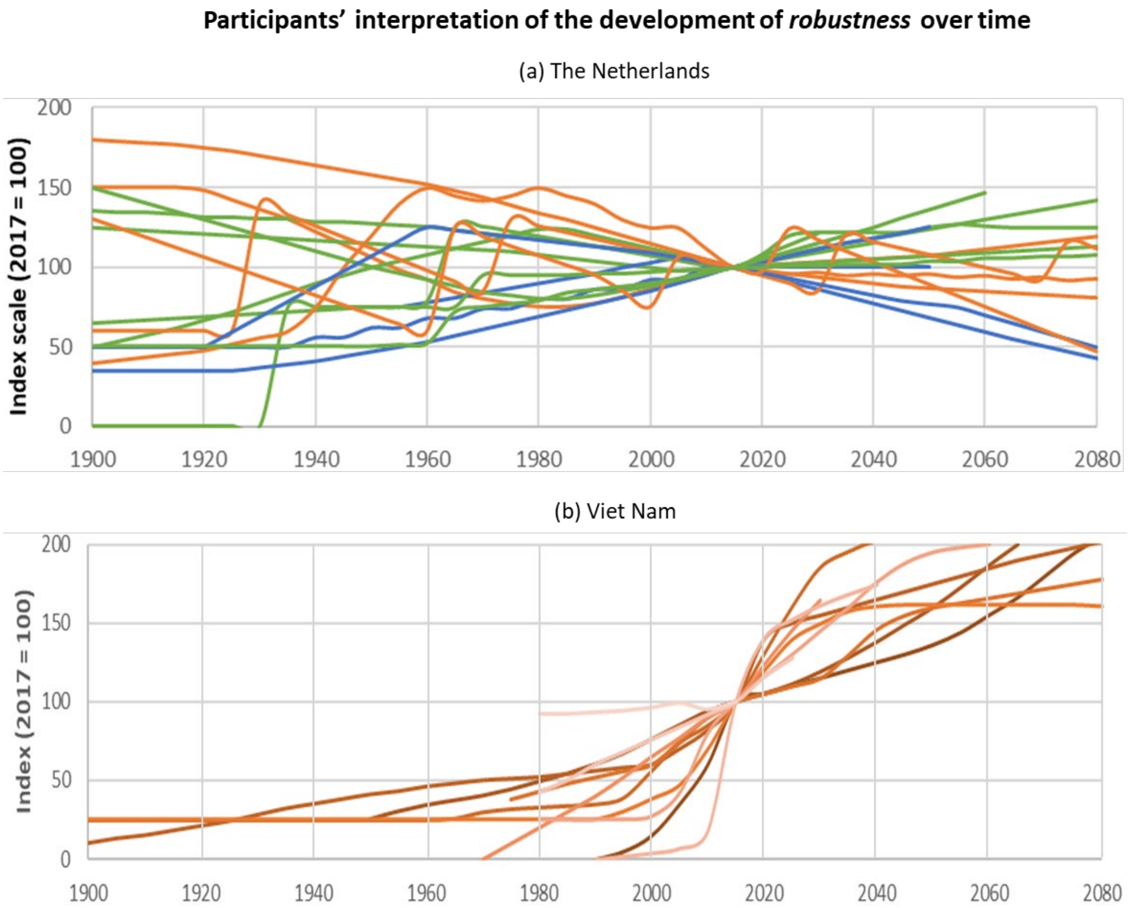


Figure 27 Graphs showing case study participants' interpretation of the development of 'robustness' of their system over time, with the left graph showing results from The Netherlands, the right graph showing results from Viet Nam. Colours in the left graph depict the three categories of definitions for robustness.

There is a significant difference in the amount of information that participants were able to convey in this exercise, both in terms of temporal depth of the graphs as well as in the qualitative information contained in the participants' narratives. The timeframes over which Viet Nam participants felt comfortable drawing the graphs was much shorter (typically starting in the 1970s-1980s only) than in the Netherlands.

The depth of interpretation of key system attributes is also highly variable between the two case studies. In the Netherlands, participants were able to draw rich graphs for the development of "robustness" and "flexibility" in their ecosystems, while participants in Viet Nam drew simple upward trends. In the Netherlands, participants were able to define these attributes in their own words, though their definitions were variable. Their definitions were predominantly informed by logic reasoning from known and measurable variables, that could be categorized as (i) robustness is a function of water supply, (ii) robustness is a function of water supply and demand, and (iii) robustness is a function of water supply, demand, and economic and social dependency. In Viet Nam on the other hand, participants were less descriptive in their definitions and defined robustness from general indicators of progress, such as the amount of effort put into the management of the water system or the general socio-economic development of the area. Results for the attribute "flexibility" showed a similar difference between the two case studies.

With that deeper interpretation of complexity-related attributes, participants in the Netherlands were able to construct an analysis of their development over time linked to key events or trends within that system. While participants in Viet Nam did not come up with similar analyses, they were shown these graphs of the Netherlands once the interview was completed, which provided a basis for further discussion and reflection on the graphs they had drawn up for Viet Nam.

The Netherlands case study confirmed, using Q method, the existence of two dominant

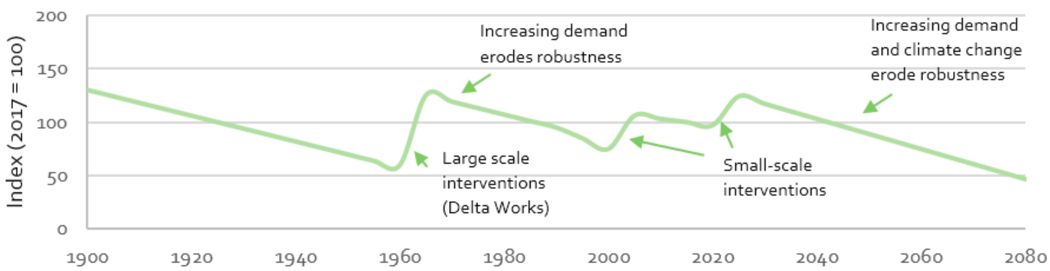


Figure 28 Representative mapping and narrative of robustness as a function of supply and demand, from the Netherlands case study

paradigms amongst stakeholders as a reflection of the debate in literature: the viewpoint of "traditional command and control" on the one hand and a viewpoint in line with the school of adaptive management on the other hand. These viewpoints were however not found in the Vietnam case study.

5.3.3 Analysis of socio-economic and biophysical data

In the sequential mixed-methods set-up of the case studies, the analysis of socio-economic and biophysical data was guided by the emerging themes from interviews with local stakeholders.

One theme that frequently featured in the interviews in the Netherlands, was the interlinkage between choices in freshwater management and the socio-economic dependency on freshwater management.

In both case studies, a clear trend can be seen in increasing human dominance over the natural environment. Significant investments in water-related infrastructure, and the resulting decrease in flooding and increase in salinity control, contribute to the strong growth of the agricultural sector. In both case studies, this period of growth is concentrated in the post-conflict period of 1960s – 1970s (Netherlands) and 1990s – 2000s (Viet Nam). Over the same periods however, while agricultural production was increasing, the percentage contribution of the sector to the national or regional GDP was decreasing.

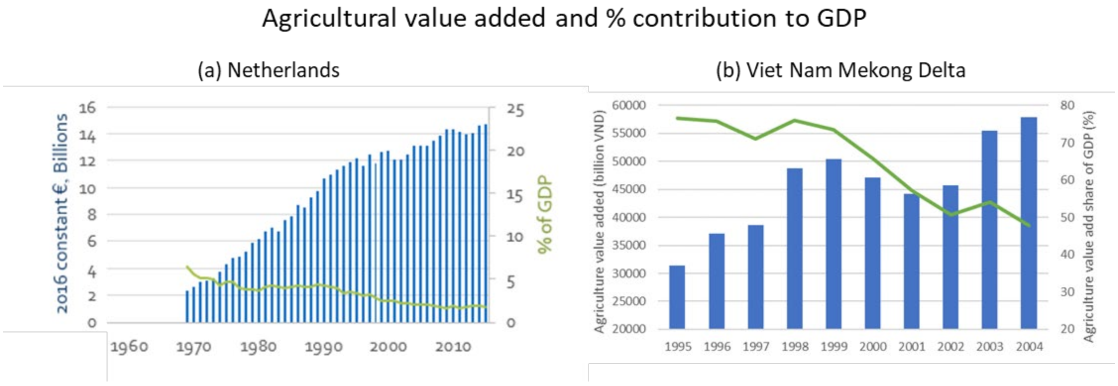


Figure 29 Agriculture value added and relative contribution to GDP. (a) Netherlands, national figures (b) Viet Nam, Mekong Delta regional figures.

In both countries, the increasing agricultural production was also accompanied by a significant change in agricultural crop and fisheries species choices, linked to the availability of freshwater or the control of salinity levels. In the Netherlands, the economic output of horticulture production rapidly exceeded that of other agricultural sectors, whereas in Viet Nam the production and export of high-value aquaculture shrimp and tilapia is experiencing faster growth than that of low-value paddy rice. These changes are interconnected with changes in the water management system. Horticulture requires freshwater and has high sensitivity to salinity levels (Niu et al., 2019), aquaculture tilapia is mostly focused on fresh and low salinity water (Suresh and Lin, 1992), while aquaculture shrimp is focused on low salinity levels (Leigh et al., 2017). In all cases however, productivity is greatly affected by changes in salinity levels and therefore the increased production requires greater control of those salinity levels.

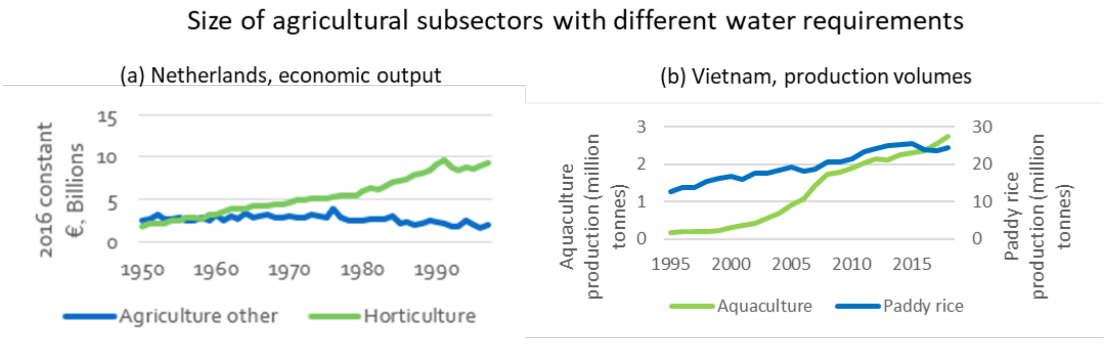


Figure 30 Size of agricultural subsectors with different water requirements. Sources (CBS, 2001; General Statistics Office, 2020)

The analysis of interviews with participants in the Netherlands, pointed to the influence of changing economic importance of different sectors and subsectors associated with water management choices. In that regard, the analysis of water demand by different sectors in the Netherlands (Figure 31) provides valuable insights, for which no evidence exists within the Viet Nam Mekong Delta context (Nhan et al., 2007). While agriculture has a high combined demand when combining quantity and quality requirements, greater requirements are found along those two dimensions individually by the river transport sector (quantity requirements) and the drinking water, nature and industrial water sectors (quality requirements).

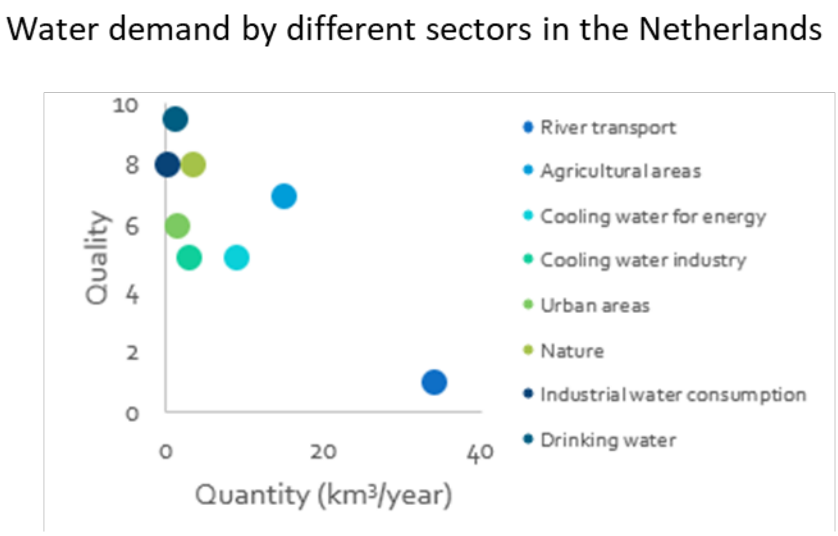


Figure 31 Water demand by different sectors in the Netherlands (Klijn et al., 2012)

5.4 Discussion

Here, we discuss four major insights and associated directions for further research arising from the comparative analysis, while we also reflect on the research strategy chosen in each of the case study from the perspective of carrying out a comparative analysis.

5.4.1 Patterns and pathways

The comparative analysis of the two case studies can provide relevant inputs into models of deltas in transition from nature-dominated to human-dominated previously proposed by researchers (Renaud et al., 2013; Santos and Dekker, 2020), to analyse patterns and to explore the predictive ability of such a model regarding the potential future pathways of a delta in transition.

The results of both case studies stress the importance of interlinkages between water management choices and socio-economic developments, and the reflection of that in complexity thinking. As ecosystems become more human-dominated, water management interventions provide a more stable environment and more socio-economic activity takes place, there is a tendency to lock-in into a certain state of the environment and a build-up of dependency on an environmental variable, such as freshwater provision. At the same time, some of the (sub-) sectors that become heavily reliant upon a certain state in terms of water management, may become less important socio-economically.

Such interactions can be viewed from a complex adaptive systems perspective, as negative and positive feedback loops. The process observed by stakeholders in the Netherlands is akin to Jevon's paradox, which states that an increase in efficiency in using a resource leads to increased use of that resource, rather than a reduction (Polimeni, 2008). While the Jevon's paradox in its original form has been analysed in water management and irrigation context (Dumont et al., 2013; Sears et al., 2018), the variation in this case is that human interventions aimed at reducing vulnerability to changing environmental conditions (by controlling salinity levels), actually results in greater vulnerability in the longer term (a negative feedback loop), because of the induced heavy reliance on salinity control measures that cannot be sustained in the long run. These salinity control measures can only provide temporary protection from salinization, while they cannot prevent the slower process of salinization through groundwater infiltration, compounded by the effects of subsidence. A more explicit, pro-active approach by government to govern the spatial planning and local natural resource (freshwater)-dependency of economic activities informed by a longer-term view, could help in addressing this issue.

Another pattern that emerged in the Netherlands case study is the evolving recognition of the need to reserve physical space for natural dynamics to occur, if the policy direction is indeed to increase adaptive capacity, to pursue adaptive management and to make use of nature-based solutions. Rivers and channels in the Netherlands had already long been trained into fixed positions, thereby taking less physical space than meandering rivers. One of the priority programs of the government under the new 'living with water' paradigm was the 'room for the river' program, where riverbanks were widened and rivers were given space to flood the outer riverbanks in order to buffer river floods.

While these patterns of development in the Netherlands cannot be used to predict future developments in the Mekong Delta, they can be used to construct complexity-informed pathways to inform anticipatory governance (Triyanti et al., 2020). More than theoretical exercises for the strategic level only, the use of real-world examples such as through the case studies in this thesis, offers an opportunity for ecosystem managers to understand what those pathways look like.

5.4.2 Triggers for paradigm shifts and avenues for dialogue

The comparative timeline of prevailing water paradigm (Figure 26) also points to the existence of triggers for paradigm shifts. In the Netherlands, this was most pronounced in the paradigm shift following the 1953 flood event. Subsequent triggers in the Netherlands were not events, but rather the symptoms of more slow processes such declining biodiversity from reduced salinity intrusion dynamics or the gradually increasing vulnerability to flooding as a result of sea level rise and subsidence. Researchers have noted that these triggers do not necessarily need to be biophysical in nature, but may also have cultural origins. Tàbara and Ilhan (2008) for example noted that the transition in water management paradigm in Spain, from being engineering and hydrology-focused to being more holistic and considering broad socio-economic and environmental dimensions, was triggered by civic organisations that started a "New Water Culture" movement out of concern that the existing water management paradigm and particularly the construction of more dams was causing environmental and social problems.

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Triggers can help to progress in closing the implementation gap and support a transition to a new paradigm. A requirement for this is the existence of avenues of dialogue. In the Netherlands, where there are extensive cross-sectoral and cross-spatial avenues for discussion around water management, this dialogue around the use of complexity-informed water management is already underway. With an initial centrally-led effort to define complexity-linked attributes in the overarching Delta programme (Slob and Bloemen, 2014), these concepts are now integrated into planning and monitoring processes at lower levels of organisations, and leading to negotiations between policymakers, practitioners and their organisations on the usability of such attributes (van Wessel et al., 2015).

In the Mekong Delta, these avenues seem to be appearing of recent. Following the 2017 resolution on climate-resilient water management (Government of Viet Nam, 2017), researchers have found that in some places there is a shift underway towards hybrid modes of governance that combine hierarchical and participatory components at the local level (Tran et al., 2020), thereby effectively opening up an avenue for dialogue and addressing previously identified limitations to the implementation of adaptive management (Ha et al., 2018).

5.4.3 Between physical interventions and control

A common aspect of the interviews with local stakeholders in both case studies was the search for analytical tools to understand the difference between degrees of physical intervention in an ecosystem, and the level of control that can be exercised over such systems.

In the Mekong Delta, participants clearly linked their narratives around the development of *robustness* and *flexibility* to the expansion of physical interventions into the water management systems and the ability to deliver freshwater to users. In the Netherlands, one group of participants organised their analysis and narrative along similar lines ("flexibility is the ability to control the system"), while others took contrasting views. In both cases, participants explored in their narrative how the construction of physical infrastructure such as dikes, dams and weirs, relates to the amount of control.

The aspect of *control* is poorly explored in this context, while it is a prominent point of attention for ecosystem managers. One widely cited study about the Mekong Delta, "Mekong Delta at the Crossroads: More Control or Adaptation?" (Käkönen, 2008) presents control as the antithesis of adaptation and equates control with large-scale infrastructural development. This framing may however not be accurate and comprehensive, as control can also be exercised locally and adaptation may be centrally planned, whereas large-scale infrastructural works can also be seen as one of multiple possible adaptation pathways (Sovacool, 2011).

5.4.4 Limitations of a delta in transition model

By juxtaposing two case studies that are in a different stage of transition from nature-dominated to human-dominated, the differences become apparent for the observer and general patterns can be identified.

It also becomes clear, however, that complexity-related challenges in water management in each delta are highly context-specific and that each delta needs to be analysed in its own right.

The 'delta in transition' model can thereby continue to serve as an analytical tool for researchers, and to some extent be used to assist decision-making by local actors. Such models can go beyond the "command and control" to "adaptive management" paradigm only, to incorporate broader aspects of human interventions in water management and the general socio-economic trends in a particular area.

Moreover however, such models and the large number of studies reviewing deltas globally for aspects such as climate change adaptation, vulnerability or lock-ins, could be enhanced by more locally grounded case studies such as presented in this thesis and related recent literature (Nolf et al., 2020). To do so, it would be imperative to increase the evidence base to establish historic socio-economic and biophysical trends and to involve local stakeholders in providing context to those numbers.

5.4.5 Evaluation of case study design

While each of the case studies evaluates the adequacy of the chosen research methods for that specific case, there is additional value in evaluating the case study design in light of carrying out a comparative analysis and subsequently drawing broader conclusions. Already in the individual evaluations, it became clear that while the 'open', sequential mixed-methods research approach enables a deeper conversation with interviewees, it limits the comparability of results within a single case study. This limited comparability is further propagated when carrying out a comparative analysis between the two case studies.

At the same time, the results of the experimental mapping exercise show that even when (or perhaps especially when) allowing such diversity in framing as input to a data collection exercise, the results can provide novel insights – exactly as intended in the exploratory research design.

Further enhancement of a multiple case study design could include an element of interaction between the biophysical and socio economic data collected and the interviews, whereby an extra step is added to compare the interviewee-defined mapping exercise with the collected data and to have the interviewee re-assess their own graphs in light of that data. Another extension of the research design could be to include an element of dialogue between the two case studies, whereby participants in one region are asked to reflect upon the development pathway in the other case study as observed from literature and data. Such a research design would thereby include an element of participatory learning and offer the possibility to study what the effect is of better knowledge sharing on complexity-related aspects of river delta management.

5.5 Conclusions

This comparative analysis provided insights to key commonalities and differences between the case studies in the Netherlands and Viet Nam. The different position of these two case studies along the delta in transition model, with the Netherlands being in a 'locked in' situation while the Mekong Delta is still 'at the crossroads', is reflected in the results of interviews with local stakeholders in terms of depth of engagement.

The analysis points to more specific aspects of the transition that could help decisionmakers in better understanding the complex behaviour of the delta ecosystem. This includes a broader analysis of pathways and associated system feedbacks, such as the unplanned and potentially undesired building up of economy dependency on freshwater resources when areas are protected from flooding but cannot be protected from slow salinization processes. This is especially relevant for deltas that are in earlier stages of transition, but works also vice versa, if 'locked in' deltas want to transition to a situation where more space is given to natural processes.

Future research with embedded participatory learning between different case studies can help local decision makers in water management to better understand complexity-related aspects, while at the same time offering an opportunity for researchers to study the effect of practical knowledge sharing on the understanding of complexity.

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6 DIMENSIONS OF DEALING WITH COMPLEXITY IN RIVER DELTA ECOSYSTEMS OF THE ANTHROPOCENE

ABSTRACT

River delta ecosystems worldwide are going through a transition from nature-dominated to human-dominated, epitomizing the onset of the Anthropocene. Concurrently, scientific advancements have demonstrated that deltas, and other social-ecological systems alike, can be better analysed using the complex adaptive system framework that sees these systems as inherently dynamic rather than steady-state. Several fields of research address complexity-related aspects with the objective to help increase the adaptive capacity of these delta ecosystems. In this study, I develop a conceptual framework for analysing complexity in deltas undergoing transition from nature-dominated to human-dominated. We identify critical dimensions, synthesize the state of scientific advancement in each and subsequently analyse opportunities for interlinkages. I find five critical dimensions: availability of application frameworks, availability of assessment frameworks, availability of relevant data, stakeholder dialogue and triggers. I also identify opportunities for exchanges between these dimensions, to work towards integrated approaches for increasing adaptive capacity.

6.1 Complexity in river delta ecosystems of the Anthropocene

River delta ecosystems worldwide are going through a transition from nature-dominated to human-dominated, epitomizing the onset of the Anthropocene (Nicholls et al., 2020; Renaud et al., 2013). Human interventions in these ecosystems, in terms of natural and social infrastructure, are increasingly controlling natural processes (van de Giesen, 2020). This includes dam construction in feeding rivers blocking sediment delivery (Dunn et al., 2019) and groundwater extraction accelerating subsidence (Shirzaei et al., 2021). Human-dominated deltas are thereby locking in to stable situations (Santos and Dekker, 2020), reducing the natural capacity of those systems to adapt to external changes, such as climate change-induced sea level rise. Climate change impacts have exposed the vulnerability of locked-in river delta systems that, in their current stabilized situation, cannot cope with current and projected changes in sea level, river flooding and droughts.

Concurrently, scientific advancements have demonstrated that deltas, and other social-ecological systems alike, need to be seen as complex adaptive systems that are inherently dynamic rather than steady-state (Brondizio et al., 2016; Holling, 1973; van Wesenbeeck et al., 2014). Consequently, complexity-informed themes such as resilience and adaptation have become a priority for policymakers and researchers.

Research fields in the applied sciences have emerged that try to help increase the adaptive capacity of ecosystems. This includes fields of adaptive management and adaptive governance (Pahl-Wostl, 2007; Pahl-Wostl et al., 2012) and of nature-based solutions (IUCN International Union for Conservation of Nature, 2016; Mitsch and Jørgensen, 2003). While these research fields peruse different aspects of complex adaptive systems theory, they both help in furthering the ability of humans to deal with complexity. A large amount of research is available specifically for river deltas, but more practical guidance is needed for local decision-makers to deal with complexity (Toimil et al., 2020), such as decision support tools for understanding how nature-based solutions can help in achieving climate change adaptation goals or modelling software to analyse the probable long-term impact of adaptive management strategies.

Similarly, much progress is being made on the measurement and assessment of complexity-related aspects. The general understanding of complex adaptive systems aspects of ecosystem management is advancing, for instance through the promotion of a general resilience measurement framework (Jones et al., 2021).

Across these scientific disciplines, there is a persistent need for better frameworks and tools to understand how delta ecosystems behave as complex adaptive systems, in their transition from being nature-dominated to being human-dominated.

In this study, I explore how an integrated, broad perspective on the dimensions of dealing with complexity within the context of river deltas in transition, can help to advance the adaptive capacity of these ecosystems.

6.2 Developing a conceptual framework for analysing the dimensions of dealing with complexity

6.2.1 Method

I develop a conceptual framework for analysing the different dimensions of dealing with complexity in transitioning deltas and analyse how these dimensions relate to the different states of transition of a river delta. Such a conceptual framework can be defined as a “network of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena". The advantages of conceptual framework analysis are its flexibility, its capacity for modification, and its emphasis on understanding instead of prediction (Jabareen, 2009). In a mixed-methods exploratory research set-up (Creswell and Creswell, 2017), I use grounded theory as method to build a context-based description and explanation of the phenomenon. In doing so, I draw on lessons from two case studies on the understanding of complexity in river deltas in the Netherlands (Chapter 3) and Viet Nam (Chapter 4).

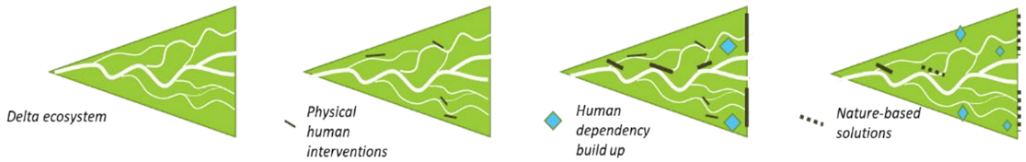
I first determine critical dimensions to be considered. These dimensions are derived from literature review (Chapter 2) and case studies (Chapters 3,4 and 5). I include dimensions that: (i) deal with the application of complex adaptive systems thinking in ecosystem management; (ii) deal with generating knowledge about past, current and future states in river delta ecosystems; (iii) describe the enabling conditions for local stakeholders to understand and apply complexity-informed frameworks. The dimensions are not necessarily pre-conditions, rather axes along which to analyse the state of complexity understanding.

I subsequently, for each dimension, synthesize the current state of scientific advancement by analysing the available recent literature (including grey literature) and datasets where applicable. To develop a comprehensive analysis across the dimensions identified, I analyse each dimension mapped to the delta transition model (see below), in terms of their relevance for each stage and for each transition variable.

6.2.2 Delta transition model

To guide this research, I define an underlying delta transition model. I adapt the model proposed by (Renaud et al., 2013) and define four system states of delta ecosystems: (i) nature-dominated; (ii) locally human-dominated; (iii) stabilized; and (iv) controlled adaptive. While (Renaud et al., 2013) use a geomorphology-based approach to identify three states similar to states (i-iii) and identify a fourth state of a collapsed system, I choose a "controlled adaptive" state in our framework as a representative state of balance between human intervention and natural dynamics.

I furthermore propose three major variables pertaining to the transition model: (a) space for nature; (b) human physical interventions and (c) adaptive management practices. Each dimension describes the critical and defining characteristics of the system within the transition state (see Figure 32).



transition variables	(i) Nature-dominated	(ii) Locally human-dominated	(iii) Stabilized	(iv) Controlled Adaptive
(a) Space for nature	Full freedom	Locally constrained	Severely constrained at system level	Limited, some processes conserved or reintroduced for human benefits
(b) Human physical intervention	None or very limited	Local grey infrastructure	Major grey infrastructure	Balanced green-grey infrastructure, nature-based solutions
(c) Adaptive management practices	None	Traditional	Limited	Formal

Figure 32 Delta transition model, based on four system states (i-iv), with illustrations of system state and characteristics of three transition variables.

The delta transition model is a hypothesis of the transition characteristics of delta ecosystems which we use as a canvas to analyse the different dimensions of understanding complexity. It is recognized that that there are several pathways possible for a delta in transition, and that a delta may not exhibit the characteristics of a single system state across the geography.

Transition variable (a) *space for nature* describes the extent to which natural processes and dynamics are unconstrained. I identify *full freedom*; *locally constrained* where local human physical interventions hinder natural processes or reduce natural variability; *severely constrained at system level* where major human physical interventions fundamentally alter the natural dynamics; and *limited* where some natural processes are purposefully preserved or re-introduced for human benefits.

Transition variable (b) *human physical intervention* describes the extent and type of physical interventions by humans in the ecosystem. I identify *local grey infrastructure*, where small structures like flood control measures are implemented in river branches; *major grey infrastructure* where hard infrastructure is used to alter major river branches or maintain geomorphological stability; and *balanced grey-green infrastructure* where hard infrastructure interventions are combined with nature-based solutions.

Transition variable (c) *adaptive management practices* describes how adaptive management practices are adopted and applied in the management of the ecosystem. I identify *traditional* adaptive management practices *sensu* (Berkes et al., 2000), *limited* adaptive management in system state III where command and control practices dominate, and *formal* adaptive management practices *sensu* Pahl-Wostl (2007).

The case studies in the Netherlands and Viet Nam can serve as an illustration of the application of this delta transition model. From the early water works in the Netherlands in the 17th century, the country has gradually moved from state ii to state iii, accelerating from the end of the 19th century. The second half of the 20th century in the Netherlands present an archetype of state iii, where major grey infrastructure was constructed, space for nature severely limited and management practices dominated by command and control. At the onset of the 21st century, a transition towards state iv has been initiated. The Mekong Delta has experienced a similar gradual transition from state ii to state iii over the 19th and 20th century, while a major acceleration to fully match state iii has been under discussion but not implemented. Instead, an evolving understanding may help in bypassing an ‘extreme’ state iii, and progress directly into state iv.

6.3 Dimensions of dealing with complexity

6.3.1 Determining critical dimensions

Based on literature review (Chapter 2) and case studies (Chapters 3-6), I determine the following five critical dimensions for understanding complexity. I describe each dimension and establish whether the dimension is globally or locally specific (Table 14).

Table 14 Critical dimensions of dealing with complexity in river deltas

#	Dimension	Description	Specificity
1	Availability of application frameworks	Frameworks that use complex adaptive systems theory to provide practical guidance for human interventions in river delta ecosystems to increase adaptive capacity.	Global
2	Availability of assessment frameworks	Frameworks and indicator studies that aim to help decisionmakers to understand the state of an ecosystem using complexity-informed concepts such as resilience and adaptive capacity	Global
3	Availability of relevant data	Availability of data corresponding to identified indicators over appropriate timescales to analyse complex behaviour	Local

4	Stakeholder dialogue	Presence of channels through which stakeholders engaged in delta ecosystem management can exchange knowledge involving complexity	Local
5	Trigger	Presence of a trigger for complexity thinking, such as an extreme event or occurrence of an unexpected phenomenon.	Local

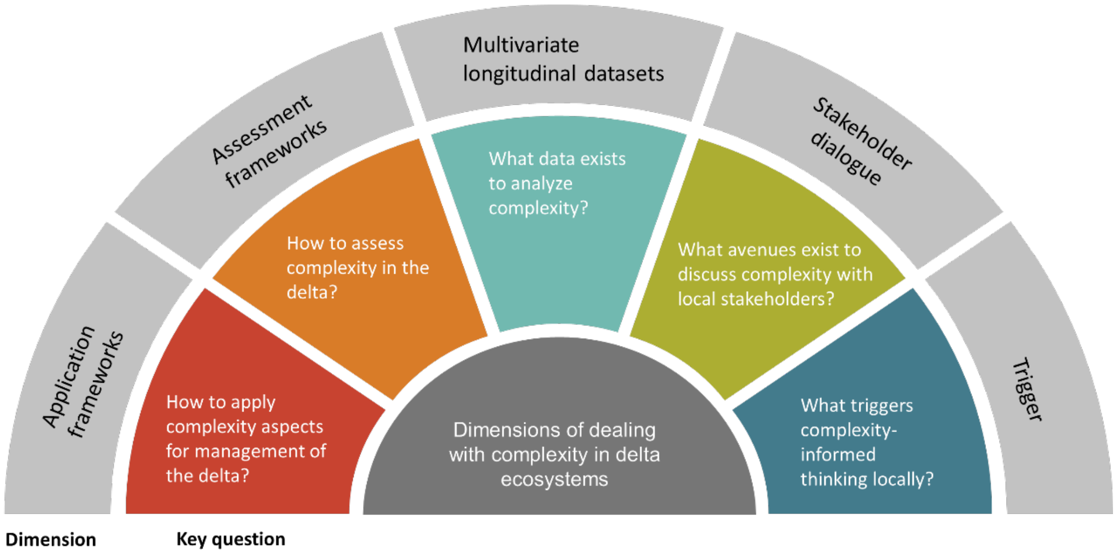


Figure 33 Dimensions of understanding complexity and associated key questions

6.3.2 Dimension 1: Availability of Application Frameworks

This dimension involves frameworks that use elements of complex adaptive systems theory to provide practical guidance for human interventions in river delta ecosystems to increase adaptive capacity. In a literature review (Chapter 2), we considered frameworks within the realm of management of social-ecological systems, adaptive management and nature-based solutions for their relevance to delta ecosystems in transition, whereas the case studies provided further insights into the use of adaptation pathways thinking (Wise et al., 2014).

The adaptive management framework posits that as complex ecosystems have self-organizing properties that cause uncertainty to grow over time, understanding should be continuously updated, and policies should be seen as hypotheses which are tested through management actions (Walters, 1986; Williams, 2011). Adaptive management researchers promote sets of social and political conditions that are considered to enable these feedback loops (Pahl-Wostl, 2007). Adaptive management thereby offers a solution for ecosystem managers to deal with emergent behaviour.

The nature-based solutions framework promotes “living solutions inspired by, continuously supported by and using nature, designed to address various societal challenges in a resource efficient and adaptable manner and to provide simultaneously economic, social and environmental benefits” (Maes and Jacobs, 2017). As a relatively recent ‘umbrella concept’, it spans several pre-existing disciplines such as ecological engineering (Mitsch and Jørgensen, 2003), green infrastructure and ecosystem-based adaptation (Nesshöver et al., 2017). Nature-based solutions thereby focus on self-organization as a key aspect of complex adaptive systems theory (Chapter 2).

The adaptation pathways framework aims to build adaptive capacity by promoting a scenario-based approach (Wise et al., 2014). It thereby recognizes that transitions in ecosystems are complex, that same starting conditions that produce different outcomes and that they are influenced by evolving conditions as well as legacy and cross-scale effects (Fazey et al., 2016).

Combined, these frameworks provide elements to ecosystem managers to understand and manage their system informed by complexity thinking. Departing from existing stability-based frameworks, they provide ‘best practice’ standards for adaptive management from a social perspective (adaptive management assessment), instruct engineers how they can use natural processes (nature-based solutions) and give ecosystem managers hands-on tools to analyse future scenarios and critical decision moments to steer between these scenarios (adaptation pathways).

While the frameworks have common recognition of complex adaptive systems, there is limited cross-learning and alignment between them. Researchers have called for the nature-based solutions framework to adapt elements of adaptive management and adaptation pathways thinking (Cohen-Shacham et al., 2019), and further integrations of and interlinkages between these frameworks could help advance towards the shared objective of assisting ecosystem managers to improve the adaptive capacity of their ecosystems.

6.3.3 Dimension 2: Availability of Assessment Frameworks and Indicators

This dimension involves frameworks and indicator studies that aim to help decisionmakers to understand and monitor the state of a river delta ecosystem using complexity-informed concepts such as resilience and adaptive capacity.

Assessment frameworks tend to have a normative character, assessing the extent to which a social-ecological system corresponds with a desired system state, for instance whether the right conditions for adaptive management exist (Ha et al., 2018; Huntjens et al., 2011). Whereas assessment frameworks depart from a desire to the relationship between theory and practice and often involve a high degree of qualitative assessment, indicator studies more narrowly focus on identifying variables that can be measured and quantified. A transparent protocol to achieve a transparent and consistent metric can thereby be guiding (see (Béné et al., 2019) for an example). Table 15 shows relevant assessment frameworks and indicator-based studies that use structured methods to identify most relevant indicators (Sebesvari et al., 2016a).

Table 15 Relevant assessment frameworks and indicator-based studies

Reference	Study focus
(Anderies et al., 2004)	Robustness of ecosystem management
(Tessler et al., 2015)	Risk and sustainability in coastal deltas
(Sebesvari et al., 2016a)	Vulnerability indicators for deltaic social-ecological systems
(Byers et al., 2018)	Exposure to multi-sector risks
(Béné et al., 2019)	Food system sustainability
(Pahl-Wostl et al., 2012)	Adaptive water governance

From these assessment frameworks and indicator-based studies, I mapped the most relevant indicators to the three identified transition variables (Table 16). I subsequently analysed to which extent these indicators provide a comprehensive view on each transition variable, and what gaps exist.

Table 16 Overview of most relevant indicators per transition variable

#	Indicator	Study source
Transition variable: space for nature		
1	Habitat degradation	(Byers et al., 2018)
2	Percentage of change in major land use categories	(Sebesvari et al., 2016a)
3	Percentage of vegetation loss	(Sebesvari et al., 2016a)
4	Natural Capital Index	(Sebesvari et al., 2016a)
Transition variable: human physical interventions		
5	Population density	
6	Anthropogenic Conditioning Index	(Tessler et al., 2015)
7	Agricultural land as % of arable land	(Béné et al., 2019)
Transition variable: Adaptive management		
8	Polycentric regime architecture	(Pahl-Wostl et al., 2012)
9	Capacities for an advanced handling of uncertainties	(Pahl-Wostl et al., 2012)
10	Agricultural water stress index	(Byers et al., 2018)

For the transition variable *space for nature*, I identified four proxy indicators. Habitat degradation (Byers et al., 2018) measures the percentage change from the share of land area that is converted from natural land to agricultural land. This can be complemented by a more general analysis of change between major land use categories and vegetation loss across land use categories, to develop an understanding of the relative changes in space for nature. The Natural Capital Index (ten Brink, 2007) is a composite indicator that measures the product of changes in ecosystem quantity (land use conversion) and changes in quality. While all these indicators are relative, they need to be combined with absolute indicators to derive at a proxy for space for nature.

For the transition variable *human physical interventions*, I identify population density as an often-used proxy, such as in the study on locked-in deltas of Santos and Dekker (2020). A more comprehensive indicator is the anthropogenic conditioning index, which combines weighted means of population density within the delta and upstream basin, artificial reservoir volume upstream, wetland dysconnectivity, impervious surface fraction, groundwater abstraction, petroleum extraction, subsidence and local sea level rise. Another, more direct indicator is the percentage of agricultural land compared to total arable land. While these indicators give a broad view on human activity, they disregard those human interventions that are most directly impacting on water management, such as length of dikes constructed or area protected from flooding.

For the transition variable *adaptive management*, Pahl-Wostl et al. (2012) identify polycentric regime architecture and capacities for an advanced handling of uncertainties as critical elements to increase adaptive capacity. These indicators have qualitative scoring that describe the concentration of power and engagement of various actors in decisionmaking (polycentric regime architecture) and the extent to which planning takes into account climate change predictions and uses scenario building. The agricultural water stress index is the fraction of net human-economic water demand to available renewable surface water supply. The combination of development of the agricultural water stress index and adaptive management indicators over time, could give valuable insights into the effectiveness of adaptive management.

A shared challenge for assessment and indicator frameworks is their strong theoretical thrust and often limited degree to which they have been informed by the feasibility of data collection, especially in a repeated manner over longer time frame. Wolters and Kuenzer (2015) identified in their reviews of vulnerability assessment frameworks, that only 12 of the 54 reviewed frameworks (23%) included a temporal dimension. Moving forward, theory-driven assessment frameworks could be augmented with indicators that have a higher feasibility and ease of collection, such as demonstrated in the study of Kuenzer et al. (2020) who use the perspectives of local experts to arrive at quantified metrics involving complexity.

6.3.4 Dimension 3: Availability of relevant data

This dimension considers the availability of data corresponding to identified indicators over appropriate timescales to analyse complex behaviour.

Technological capability to record, store, access and analyse large amounts of data poses unprecedented opportunities to reveal spatiotemporal patterns of human interaction with their environment (Lindersson et al., 2020). Recently, various studies have been carried out bringing together global datasets, assisting the evaluation of data availability.

These data can serve large-scale studies studying one phenomenon over time across multiple locations, detecting patterns and reaching generalizable results that can be used for building hypotheses. They can equally assist in-depth analysis of a single case study, by guiding the development of assessment frameworks that are better suited to the actual availability of data.

Lindersson et al. (2020) analysed 124 freely available datasets for the study of floods, droughts and their interactions with the environment. They identify a lack of temporal depth in these data, with almost 40% of their datasets only offering snapshots. Such lack of temporal depth can also propagate when such static indicators are used as parameter in the analysis or construction of other indicators. Moreover, authors of datasets with longer temporal records caution against use of that data to analyse change over time, due to changes in methods and data sources between records.

The constraints on temporal depth contribute to the limited availability of studies analysing human-environment interactions over longer time periods. With the recent acceleration on the availability of data and efforts to synthesize historical datasets, this may however soon change. A notable example is the work of (Santos and Dekker, 2020) who examine the dynamic coupling between population and land-use development over 300 years for 48 deltas globally, using data on population size and land use change from several sources. Analysing the interplay between these parameters over time, they are able to construct a notion of deltas being ‘locked in’. Further understanding of complexity will require more such evidence of dynamic coupling, analysing for instance emergent system behaviour over time of the uptake of adaptive management and nature-based solutions.

6.3.5 Dimension 4: Stakeholder dialogue

This dimension considers the presence of channels through which stakeholders engaged in delta ecosystem management can discuss aspects of management involving complexity. Such exchanges are generally aimed at problem-setting, direction setting and structuring of implementation actions (Scarlett, 2013).

Yet for such problem-solving exchanges to adequately integrate aspects of complexity, achievement of a common understanding of complex behaviour is a prerequisite. Achieving such common understanding is a process that take time and effort and may only happen as a negotiation within one organization rather than be guided by national norms (Chapter 5, (van Wessel et al., 2015)). Furthermore, when pursuing system level delta planning, dialogue is needed for negotiating consent (Seijger et al., 2017a).

Stakeholder engagement a very broad area of research, but there are specific examples of researchers how have aimed to use stakeholder engagement for a dialogue on complexity-related matters. One example is the reflexive application of resilience thinking (Sinclair et al., 2017), where assumptions are politicized and problematized within actual case studies and subsequent lessons are drawn to improve the analytical utility of theory. Similarly, (Fernández-Giménez et al., 2019) carried out a longitudinal study of collaborative adaptive rangeland management and found that complexity-related aspects such as time-lags, trade-offs and path-dependency both constrain decision making and foster learning by creating disorienting dilemmas that challenge the pre-existing mental models of stakeholders involved.

6.3.6 Dimension 5: Trigger

This dimension considers the presence of a trigger for complexity thinking, such as an extreme event or occurrence of an unexpected phenomenon.

While researchers globally have thoroughly analysed river deltas for their vulnerability (Sebesvari et al., 2016b), lock-in effects (Santos and Dekker, 2020; Seijger et al., 2017b) and adaptation needs (Kuenzer et al., 2020) to generate knowledge and create awareness, such findings do not necessarily constitute a trigger for complexity thinking among managers of an delta ecosystem in question.

A case study in the Netherlands (chapter 3) shows how complexity-informed thinking was triggered by the consequences of a ‘hard’ physical intervention into the delta system. These consequences included unforeseen and undesired effects that emerged from the complex responses to human interventions, in particular the degradation of ecosystems in areas where previously dynamic water bodies turned into stagnant, oxygen-deprived reservoirs with excessive nutrients fuelling algae growth. In turn, managers of the delta system moved to adopt softer, nature-based solutions that were deemed to increase adaptive capacity and avoid such undesired consequences.

A case study in Viet Nam shows that while a delta ecosystem (Mekong delta) may be ranked high in vulnerability and adaptation needs analyses, the trigger for complexity thinking may take time to materialize. Whereas the Mekong delta has gone through a tipping point at the onset of this century in terms of its geomorphological evolution (from growing to shrinking) and in terms of land use dynamics (from a strong rice production focus to a diversified production system), complexity-related behaviour was not (yet) observed by managers of the delta ecosystem.

6.4 Discussion

6.4.1 Mapping dimensions against a delta transition model

Based on the synthesis of current advancement in each of the identified dimensions, I analyse the relevance of each dimension against the delta transition model’s system states and transition variables (Figure 34).

Dimension of dealing with complexity

		Availability of application frameworks	Availability of assessment frameworks	Availability of data	Stakeholder dialogue	Trigger
Relevance by state of transition						
I	Nature dominated			• Develop long-term datasets that cover relevant indicators		
II	Locally human-dominated	• Analyse future pathways and path-dependency • Identify nature-based solutions to be preserved.	• Assess vulnerabilities • Assess capacity building and governance needs for effective adaptive management		• Engage stakeholders to discuss future pathways	• Triggers to shift to stabilization (floods, droughts, irregular freshwater supply, socio-economic demand)
III	Stabilized	• Analyse future pathways and path-dependency • Identify options to shift from 'hard' solutions to nature-based solutions	• Assess vulnerabilities • Assess capacity building and governance needs for effective adaptive management		• Engage stakeholders to discuss future pathways • Use complexity-informed dialogue to concretize indicators and assessments	• Triggers to shift to controlled adaptive (unintended negative effects, inability to maintain state)
IV	Controlled adaptive	• Use adaptive management to maintain status • Keep updating future pathways	• Assess vulnerabilities			• Triggers to stabilize (socio-economic demand)
Relevance by transition variable						
	Space for nature	• Expand nature-based solutions to incorporate space for nature at landscape level	• Develop new indicator to measure space for nature at landscape level	• Collect data for new indicators	• Negotiate space for nature	
	Human physical intervention	• Use nature-based solutions to provide alternatives to 'hard' interventions	• Modify Anthropogenic Conditioning Index to include water management infrastructure		• Discuss advantages and disadvantages of nature-based solutions	
	Adaptive management practices	• Use adaptive management guidance to increase uptake of adaptive management	• Use available assessment framework, evaluate effectiveness over time		• Discuss advantages and disadvantages of nature-based solutions	

Figure 34 Analysis of dimensions of dealing with complexity against the delta in transition model

Application frameworks are relevant across delta transition state, while the relevance may differ between serving primarily to avoid a locked-in, stabilized situation in state II, to identifying options to exit from that situation once the delta is already locked-in. The available application frameworks are relevant across transition variables, where the nature-based solutions framework can be applied not only at the level of planning for certain interventions, but moreover at the level of an entire ecosystem and thereby integrate practical ways to deal with the aspect of “space for nature”.

Assessment frameworks have similar relevance across delta transition states, although their relevance may be higher in situations where there is a stronger need for transition. Once deltas have transitioned to a “controlled adaptive” state, the primary relevance may be to help evaluate the effectiveness of the management approach over time. Available indicator frameworks need however to be adapted to correspond more closely with the most important physical interventions in the system.

The relevance of data is independent of system state or transition variable. Gathering data, also in deltas that are in nature-dominated state, can help in understanding the differences between human- and nature-dominated deltas. New data may need to be collected if new indicators are developed.

Stakeholder dialogue serves different purposes along the delta transition model. Whereas in the locally human-dominated state, such dialogue will be focused around potential pathways and possibly learning from other deltas in transition, once in the stabilized state, the dialogue can use complexity aspects to trigger deeper discussions and concretize the use of application and assessment frameworks. Analysing the relevance against the different transition variables, the dialogue can be used to negotiate space for nature as well as the advantages and disadvantages.

Finally, the relevance of triggers differs per transition states. Whereas in state II, triggers tend to work in the direction of stabilization to reduce risk, in state III triggers can be directed towards increasing adaptive capacity.

6.4.2 Opportunities for exchange between dimensions

In Figure 35, I analyse the opportunities for exchanges between different dimensions, to help improve the overall capacity to deal with complexity.

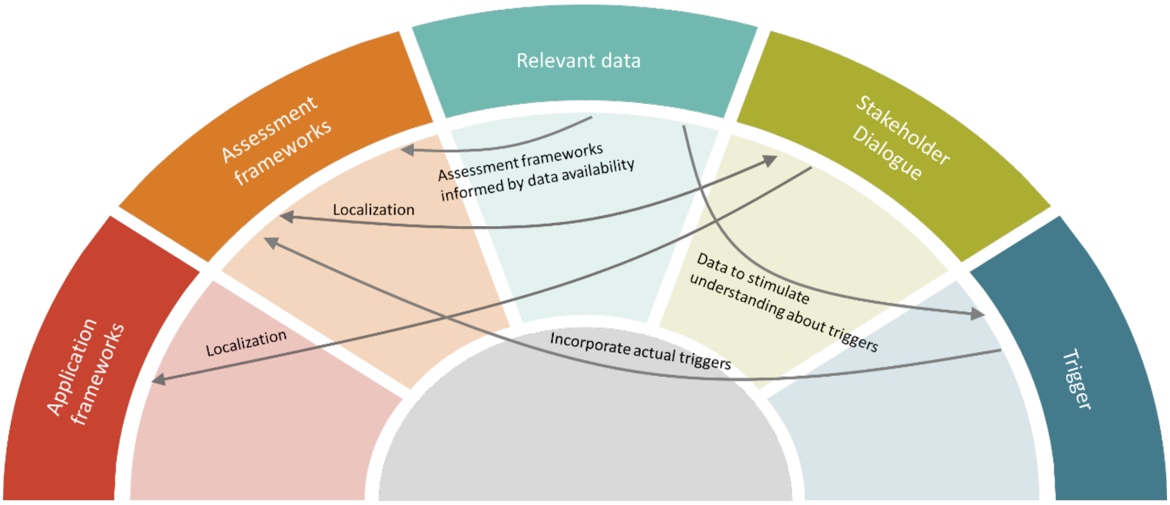


Figure 35 Opportunities for exchanges between dimensions

One of the important opportunities is to ensure that assessment frameworks are informed by availability of relevant data. While most of the assessment frameworks are largely theory-driven and are limited in their consistent application, the increase visibility on data availability can help in updating these frameworks to ensure applicability.

Similarly, there is an opportunity to ensure that assessment frameworks are better informed by actual triggers. Case studies on complexity thinking can help identify actual triggers for improved understanding of complexity, which can be integrated into assessment frameworks. In this manner, the assessment frameworks can help local stakeholders identify those triggers, stimulate discussion and encourage early action.

The increased availability of data with greater temporal depth can help stimulate triggers, by allowing local stakeholders to analyse trends and identify triggers sooner. Moreover, such data can be used to proactively identify thresholds and likely tipping points, that can serve as inputs to policy-making processes.

Both assessment frameworks and application frameworks can benefit from localization through stakeholder dialogue. The number of solutions and potential activities included under the umbrella of nature-based solutions is large, which may increase the difficulty for local stakeholders to identify the most relevant elements. Similarly, transition to adaptive management is highly context-specific as management and governance conditions are highly culturally determined.

6.5 Conclusions

In this article, I analysed five dimensions of dealing with complexity, in deltas that are in transition from nature-dominated to human-dominated. An integrated approach in delta ecosystem management that considers complexity across these five dimensions can help in avoiding unwanted lock-in to certain system states, thereby reducing vulnerability in the long term.

While an integrated approach can help strengthen the different dimensions of dealing with complexity, complex adaptive systems theory will likely continue to be used through intermediate frameworks such as nature-based solutions, adaptive management and pathway thinking. Cross-fertilization between these intermediate frameworks, as described above, can ultimately help in advancing the use of complex adaptive systems thinking as an underlying theory.

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7 CONCLUSIONS AND DISCUSSION

7.1 Conclusions

The central research question of this thesis was:

How can complex adaptive systems thinking, within adaptive management and nature-based solutions approaches, be used to improve the adaptive capacity of river delta ecosystems?

Here, we develop an answer to the central research question by formulating conclusions for each sub question.

7.1.1 How are approaches aimed at improving adaptive capacity of ecosystems, including adaptive management and nature-based solutions, linked in theory and in practice?

The broad range of approaches aimed at improving adaptive capacity of ecosystems share features of complex adaptive systems theory. The adaptive management approach has been explicitly built on complex adaptive systems theory, while nature-based solutions originate predominantly from practice. Adaptive management has a focus on adaptive capacity and learning as means to deal with surprise or novelty. The nature-based solutions approach is, in terms of complex adaptive systems thinking, primarily focused on the aspect of self-organization (Chapter 2).

In practice, the approaches face similar barriers of implementation. Review of empirical research shows that the dichotomies assumed by these approaches, between command-and-control and adaptive management and between "hard, engineered" interventions and "soft, nature-based" interventions, do not adequately reflect reality: no ecosystem is fully characterized by a single extreme archetype. Also, some of the practices promoted by these approaches existed well before their formalization in literature (Chapter 2), which can result in reduced adoption of the framework and dismissal by local stakeholders as 'something we've been doing all along' (Chapter 5). A more balanced, realistic theoretical positioning of the approaches can help in improving their adoption.

The lessons learned in adaptive management on stakeholder engagement, monitoring and learning when departing from the status quo and explicitly embracing uncertainty, will help proponents of nature-based solutions to mobilize the required support from policy makers and financiers, and enable them to document evidence of success as a key to further replication. Vice versa, experiments with nature-based solutions can provide a testing ground for those specializing in adaptive management (Chapter 2).

7.1.2 How are key attributes of complex adaptive systems understood by ecosystem managers in case studies of river delta ecosystems?

Key attributes of complexity are interpreted in diverse ways by the actors involved in the case studies of Viet Nam and the Netherlands.

In the Netherlands, clear categories of understanding were found for the attributes of *robustness* and *flexibility*. Their definitions were predominantly informed by logic reasoning from known and measurable variables, that for the *robustness* attribute could be categorized as (i) robustness is a function of water supply, (ii) robustness is a function of water supply and demand, and (iii) robustness is a function of water supply, demand, and economic and social dependency (see Figure 36). Yet even among people sharing a similar understanding, their views on how these developed over time varied strongly (Chapter 3).

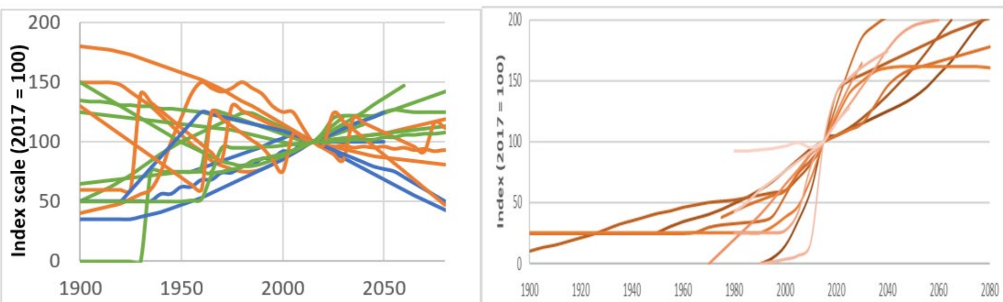

Figure 36 Graphs showing case study participants' interpretation of the development of 'robustness' of their system over time, with the left graph showing results from The Netherlands, the right graph showing results from Viet Nam. Colours in the left graph depict the three categories of definitions for robustness.

In Viet Nam, the depth of understanding of attributes of complex adaptive systems is very limited. The dominant interpretation is primarily a deterministic "positive" one, where participants sought to define robustness from general indicators of progress, such as the amount of effort put into the management of the water system or the general socio-economic development of the area. Furthermore, results show that there is consensus that these system attributes have improved over time, and that all participants expect they will continue to do so (Chapter 4).

Though in the Netherlands there have been recent attempts to stimulate uptake of localized definitions, achievement of a common understanding as a solid basis for management of these ecosystems will require more time and effort and may only happen as a negotiation within one organization rather than be guided by national norms (Chapter 3).

7.1.3 How can an integrated approach based on complex adaptive systems thinking help the transition of ecosystems from nature-dominated to human-dominated river delta ecosystems?

This thesis identified five crucial dimensions of dealing with complexity: (i) availability of application frameworks; (ii) availability of assessment frameworks; (iii) availability of relevant data; (iv) stakeholder dialogue; and (v) presence of triggers (Chapter 6).

An integrated approach can help build bridges between these different dimensions. Application and assessment frameworks can be better informed through case studies of the transition of deltas over time (Chapters 3-5) and the increased availability of spatiotemporal datasets (Chapter 6). The availability and analysis of relevant data with more temporal depth, through assessment frameworks, can help proactively identify and stimulate triggers of complexity thinking.

An integrated approach combining adaptive management and nature-based solutions will help in resolving the relative weaknesses of each individual framework (Chapters 5, 6). Scholars are already developing methods to expand nature-based solutions to integrate aspects of adaptive management (Chapter 2).

7.1.4 What prospects exist for the use of complex adaptive systems theory for the management of deltas in transition, and what actions are needed to achieve successful implementation?

While an integrated approach can help strengthen the different dimensions of dealing with complexity, complex adaptive systems theory will likely continue to be used through intermediate frameworks such as nature-based solutions, adaptive management and pathway thinking (Chapter 6).

At the same time, the intermediate frameworks cover only selected elements of complex adaptive systems theory. A broader, integrated view and the use of in-depth, participatory comparative analyses of deltas that are at different points along the transition model can help to recognize complexity-related patterns that are not currently addressed by application frameworks, such as the feedback loops regarding induced dependence on freshwater as identified in the case study of the Netherlands (Chapter 6).

There is a strong gap in making climate change adaption policies and plans a reality, affecting the livelihoods of 7% of the global population who live in river deltas (Chapter 2). Integrated, practice-oriented approaches that are organized in a participatory manner and that use data to identify triggers for stimulating complexity thinking can help in advancing local decisionmaker' understanding of complexity and help them in their management of river delta ecosystems, (Chapter 6).

7.2 Limitations of this research

This study on the use of complex adaptive systems thinking has important limitations inherent with its subject.

Challenges associated with system definition affect both case study and general or conceptual research aspects. Boundaries in complex adaptive systems theory are ill-defined (Cilliers, 1998) and also in the study of social-ecological systems there is no clear 'inside or outside' (Preiser et al., 2018). The case studies in this research do not go into depth on providing precise geographic boundaries of the delta ecosystems under study, nor on providing exact and explicit boundaries of the thematic coverage. Many participants in the interviews of the case studies have deep knowledge about certain sub-systems of the larger Netherlands Rhine-Meuse Delta or the Viet Nam Mekong Delta, such as a specific watershed or administrative unit. The interviews and exercises focused on surface water salinity management, yet they are in their exploratory semi-structured set-up not absolutely confined to those themes. As a result, participants could infuse their perspective on the main theme (salinity management) with insights from other closely linked themes such as flood control, coastal erosion and drought. Though the mixed-methods research methods were chosen to accommodate such flexibility in soliciting practitioners' views and to subsequently identify and reduce the impact of these deviations on the analysis, it cannot be precluded that unprecise system definitions have an impact on the results reported. It should however be noted that such impact is inevitable for this type of case study research involving reflexive methods, as there will always be heterogeneity in terms of the exact geographical and thematic boundaries that participants are familiar and concerned with. A larger sample size could enable a more extensive analysis of the effect of different input variables on the final results, though this would significantly increase the research effort.

The breadth of the Complex Adaptive Systems theory is reflected in the large number of scientific fields of research, frameworks and concepts that it interfaces with, which could not all be reviewed extensively within the scope of this thesis. These scientific fields partially overlap and may result in conflicting interpretations and narratives, such as has been demonstrated for the vulnerability and resilience frameworks (Béné et al., 2012). In the literature review of this research, I chose to analyse two frameworks (adaptive management and nature-based solutions) in depth while considering other strongly linked frameworks (such as resilience thinking and ecosystem-based adaptation) only as peripheral. In developing a synthesis on the dimensions of dealing with complexity, though I chose a holistic approach in determining crucial dimensions and analysing interlinkages between these dimensions, I use reductionist methods to identify frameworks of relevance within those dimensions. While such narrowing of focus is a resource-availability driven necessity from the perspective of the investigator, it does obscure the view on scientific advancements within those fields that may be relevant for this study.

Time and resource limitations on both the side of the investigator as well as on the side of the participants in case study interviews, also affect the depth of engagement. Participants in the interviews conducted for the case studies are exposed to a large number of different frameworks. The frameworks and concepts I presented to them, are dense and complex, and are likely to differ from the dominant frameworks they use in their daily work such as those used in the national water resources planning processes or progress monitoring systems. While participants received briefings upfront about the general topic of inquiry and time was allocated to explain the study and its background in detail, it is likely that longer, deeper and/or repeated engagement with participants would yield different results as participants would familiarize themselves more deeply and possibly assimilate some newly acquired theory into their own perspective. This notwithstanding, the design of the case studies was such that participants would be able to participate and primarily express their own worldview, by using their own definitions and by using semi-structured set-ups where participants could accompany quantitative elements of the investigation (Q sorting and graph development) with narratives explaining and contextualizing their choices. This exploratory set-up, and the fact that some of the participants' views evolved during the course of the interview, have also contributed to the identification of themes that may not have surfaced in less open forms of research.

Choices in the overall framing of the research and the development of materials (particularly the Q statements) may unintentionally propagate Western modern worldviews, which has not been dealt with in depth in the design of the research. The Anthropocene is emerging as a globally dominant narrative on the relationship between humans and nature, but with its strong roots in Western philosophy it may evoke problematic normative narratives about progress (Simpson, 2020). Moreover, it may delegitimize other worldviews and forms of cultural knowledge and practices (Schmidt et al., 2016), which is particularly relevant when it comes to analysing locations where ecocentrism may dominate as opposed to anthropocentrism such as in Viet Nam (Kopnina, 2016). This field of research ethics has evolved considerably since I designed my research and would have likely led to a more culturally-ethically sensitive research set-up if it had been included at that time.

More generally, the protracted period of investigation due to the mode of part-time study limits the extent to which all its contents are synchronized with the latest available research across the different fields of research. While these include "slower" fields of research such as the underlying theory of complex adaptive systems theory, where most seminal publications quoted date from the last century, other faster evolving fields of research have during my research period caused inefficiencies. Particularly the sharp rise in popularity of nature-based solutions during my PhD period, has led me to redo parts of the initial theoretical review, and the most recent publications may not be included in these parts of the thesis.

The availability of data for studying complexity in river delta ecosystems over time, also posed limitations. The conceptual framework (Chapter 6) and analysis of data availability contained therein, shows that there are only few indicators for which data is available over longer time periods, and even in those cases the authors of datasets caution against use of their data for time-series analysis given the different data collection methods for one single indicator, over time. While this dissertation argues for the use of temporal perspectives in understanding complexity, the extent to which I have been able to do so in this thesis is limited.

7.3 Discussion

The conclusions of this thesis offer a broad view on how complex adaptive systems theory, adaptive management and nature-based solutions can and are being used to increase the adaptive capacity of river delta ecosystems.

With its much longer track record in science, adaptive management offers insights for the proponents of the fledgling field of nature-based solutions regarding the adoption of such new approaches. Since its initial introduction, adaptive management has progressed from a much-hailed solution to natural resource management challenges, to a field of applied research that can only show limited success in practice (Allen and Gunderson, 2011). Already in its early days, researchers recognized pitfalls related to the exclusion of non-scientific knowledge and the neglect of the importance of the political economy in promoting uptake (McLain and Lee, 1996). Twenty-five years later, adaptive management has matured and addressed those weaknesses, including by expanding the participatory and political dimensions through adaptive co-management and adaptive governance, but it remains vulnerable to imprecise use of the concept. As a case in point, a recent study on the use of adaptive management in the Murray-Darling Basin identified five different interpretations of adaptive management, and a disconnect between literature, policy and practice (Schoeman et al., 2019). The field of nature-based solutions, in its starting point already a diverse collection of approaches (Chapter 2), may undergo a similar pathway.

The emergence of new frameworks and approaches that incorporate aspects of complex adaptive systems theory is, in the meantime, likely to continue. The theory of Complex Adaptive Systems itself, with its origins in physics, chemistry and mathematics and wide-spanning applications across social sciences, humanities, management studies and several other societal domains (Preiser, 2019), is not likely to be influenced much by feedback loops from empirical studies specifically on social-ecological systems, or by the evolving application frameworks in this space. Intermediate frameworks, both those aimed at practitioners and policymakers such as adaptive management and nature-based solutions, and those aimed at helping researchers use complexity (Preiser et al., 2018) will therefore need to continue to bridge this divide.

Any attempt to make complexity thinking accessible to a broader audience and even applicable in the management of ecosystems, needs to not only provide concrete and actionable insights to decisionmakers, but also study how such insights are applied. A more explicit integration of the political dimensions of such adoption of new frameworks and approaches is needed (Smith and Stirling, 2010) and can be assisted by reflexive learning (Tàbara and Chabay, 2013), to which the case studies in this thesis contribute.

Panning our focus to the study of river delta ecosystems as examples of complex adaptive systems, it becomes apparent in this thesis that in the current usage of application and assessment frameworks, much of the temporal perspective is lost. Assessment frameworks take a static snapshot of resilience, vulnerability or adaptive capacity through composite indicators. Whether a result of the limited temporal depth of available data (Lindersson et al., 2020) or a deliberate reduction for purposes of empirical studies, this poses a critical handicap to the furthering of the understanding of complexity. In seeing social-ecological systems as complex adaptive systems lies a recognition of emergent behaviour. Human interventions, whether top-down hard interventions or nature-based 'soft' interventions, become part of a larger dynamic and the consequences of these interventions can only be assessed over time. An analysis of complex behaviour should therefore always involve a temporal perspective.

This thesis uses water management, and particularly surface freshwater management, as a lens of study. Scholars have argued that there is too much focus on surface water and that interconnections to other categories of water resources, including groundwater and 'green' soil water (Zeitoun et al., 2016) are too often ignored in studies that focus on system-level behaviour. Surface waters are more easily monitored and controlled and are therefore not necessarily representative for the other categories. In the choice of reductionist and integrative approaches and the judicial use of research capacity, this thesis has taken a broad integrative view on frameworks and approaches that peruse complex adaptive systems theory and a pragmatist, reductionist stance on thematic coverage by focusing on freshwater resources.

An unexplored line of scientific inquiry in this thesis is the use of agent-based modelling to simulate the behaviour of complex adaptive systems. Agent-based models contain active components or decision makers conceptualized as agents, with rules for each agent's interaction with other agents, to subsequently study emergent behaviour from the system of agents. While being a principal strategy in furthering the understanding of societal systems as complex adaptive systems, it is also a highly specialist field of research that needs a strong framing to be representative of societal problems. This involves real data to be used to inform the development of categories of agents and the rules associated with them, as well as defining the spatial structure on the basis of actual case study geographies. With the many uncertainties and assumptions involved in this process, there is deep scientific debate on the extent to which agent-based modelling can serve as a simulation of the real world, or rather serve as a theoretical exploration tool only (Manzo, 2014). In this thesis, I did not pursue agent-based modelling for the lack of a sufficient mature framing and adequate datasets, however, such inquiry could assist once more empirical case studies with adequate temporal depth become available to guide development of the model.

The methods used in this thesis, in its mixed-methods philosophy, are diverse. Some are novel, such as the graph sketching exercise in case studies. Also, the general qualitative – quantitative sequenced research in both the case studies as well as in the conceptual framework can merely generate comparative analyses from the viewpoint of various scientific disciplines, rather than provide definitive proof of correlation or causalities. This has been a deliberate choice in the design of the research, as researchers have noted that the best strategy for developing an integrated understanding of such systems is to explore a variety of models that span a broad spectrum of methodologies and disciplinary divides (Preiser et al., 2018). Moreover, scholars have called for other researchers to move from characteristics of parts to systemic properties, from analysing objects to analysing relations and from measuring to capturing complexity (Capra and Luisi, 2014). Whilst this thesis explores and synthesizes information in such a more ‘open’ manner, it produces new framings and starting points for analysis following methods that produce deeper results on a well-confined space, such as modelling exercises.

7.4 Directions of further research

This thesis points to the value of more localized, spatiotemporal analyses of complexity in social-ecological systems, where river delta ecosystems provide fertile grounds for more case study research. Such in-depth case studies, that use analyses of historical developments and reflexive methods to combine quantitative analysis with qualitative insights from local stakeholders, can help local decisionmakers in understanding complexity in their ecosystems. Comparative analyses between different river delta ecosystems that are at a different point of the delta transition model as proposed in this study, will help decisionmakers in identifying and concretizing different development pathways. A comparative in-depth analysis of a larger set of river delta ecosystems (e.g. 4-8), using the same delta transition model and interactions with local stakeholders, can complement the global studies of river delta ecosystems that consider tens or hundreds of locations but are only using secondary datasets and do not include a temporal perspective.

Future research could also focus specifically on those aspects of complex adaptive systems theory, that are currently not addressed by intermediate frameworks. This includes anticipating positive and negative feedback loops and developing better analytical tools to understand the relation between physical intervention in a system and levels of control.

Beyond research, the research fields discussed in this study could benefit from more convergence with regards to definitions and use of concepts and terminologies. Recognizing that the topic is indeed complex and that a single interpretation of a certain concept or terminology is not feasible nor desirable, a too high diversity in interpretations can hamper overall progress. Concrete, measurable definitions for complexity-related attributes such as robustness, adaptive capacity and resilience (while recognizing that there is no 'perfect' definition') and a consistent monitoring of such metrics over time will further ground the discussions.

Finally, the larger and most important objective for further research would be to establish whether the adaptive capacity of river delta ecosystems is indeed increasing as a result of the adoption of adaptive management and nature-based solution.

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8 APPENDICES

APPENDIX 1 FIELDWORK PROTOCOL 154

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Approach

The fieldwork will be carried out on two case studies: the Netherlands, Rhine Delta; and Viet Nam, Mekong Delta. A total number of around 20 people will be interviewed for each case study, using the sampling strategy detailed below. The interviews will be semi-structured interviews, using an interview guide to ensure the breadth of topics is covered with each discussant, but allowing flexibility to go into greater depth on emerging issues. The interview will also include a Q-method card sorting exercise and other questions aimed at quantification, thereby facilitating mixed-methods research. Two weeks are initially reserved for the fieldwork in each location.

Sampling strategy

The population group of interest to this research comprises actors who are professionally engaged in the management of the social-ecological system. A mapping of relevant institutions and actors for each case study will be developed, based on existing network analyses and own research. For institutions, specific (subsets of) individuals may be identified that have the most relevant knowledge and experience.

From this stakeholder map, participants will be identified using a purposive or criteria-based sampling strategy in order to guarantee the diversity of participants and their viewpoints. The following key criteria are used:

- **Hierarchy level**. Two levels of hierarchy are distinguished: (i) operational level: actors whose primary responsibilities relate to day-to-day decision-making, mostly implementing policies and procedures; and (ii) strategic level: actors whose primary responsibilities relate to longer-term decision making, creating policies and procedures and monitoring implementation at operational level.
- **Primary role**. Four categories of primary roles are distinguished: (i) engineering: actors working on the design, operation and maintenance of physical structures and machines; (ii) management: actors working on the management of a social-ecological system excluding the engineering category; (iii) science: actors conducting research on the functioning of the social-ecological system; (iv) governance: actors in legislative and compliance-related functions.

Table 17 Criteria-based sampling quota

Hierarchy level → ↓ Primary role	Operational level	Strategic level
Engineering	3-4	3-4
Management	3-4	3-4
Science	n/a	3-5
Governance	n/a	2-4

Invitation to contribute

Dear (name)

My name is Guido Rutten and I am contacting you with regards to the PhD research that I am carrying out with the University of York (UK) and the Stockholm Environment Institute. My research focuses on changes in the environment, and especially how organizations and professionals are trying to create engineered ecosystems that can deal with those changes. In doing so, I will use the perspective of complex adaptive systems theory and focus on the role of physical and social *structures* as well as *self-organization*. The research aims to contribute to a better understanding of how we can deal with changes, and what engineers can learn from managers and vice versa.

NL: The Netherlands, and particularly the Rhine-Meuse Delta, is a particularly interesting case study given the leading thinking on adaptive management and the actual implementation of this thinking, including through *Room for the River,* the *Sand Engine* and the new *Delta Plan*. My research aims to bring new insights into how aspects of complex adaptive system theory are being used in reality, and into the different perspectives of organizations and individuals involved in managing the ecosystem. The comparator case study will be the Mekong Delta in Viet Nam.

VN: Viet Nam, and particularly the Mekong Delta, is a particularly interesting case study given the rapid socio-economic development and, related to that, the increasing importance of certain ecosystem services such as freshwater provision. My research aims to bring new insights into the trade-offs between increasing control on the one hand, and managing adaptively on the other hand. An example would be the construction of dikes and sluices and development of organizations to manage this infrastructure one the one hand, versus promoting more tolerant agriculture and increasing monitoring on the other hand. The comparator case study will be the Rhine-Meuse Delta in the Netherlands.

Given your experience on this topic, I would like to conduct an interview with you to get your views on the subject. I have selected you based on (relevant criteria).

The interview would last up to 1.5 hours. There will be some standardized questions guiding our conversation.

Please let me know if you are interested to participate, and if so please indicate a preference for date, time and venue of the interview and a phone number to reach you. I aim to conduct the interviews between Tue 28 March and Fri 14 April.

I will follow up to confirm the appointment. Should you wish any further information, please do not hesitate to be in touch using this email address or my contact details given below. I have also included the details of my supervisor at the University of York. Alternatively if you do not feel able to participate but are willing to nominate a suitable colleague, that could be very helpful.

With best regards,

Guido Rutten

PhD student, University of York / Stockholm Environment Institute
glr515@york.ac.uk
skype: glrutten

Supervisor:
Dr. Steve Cinderby
steve.cinderby@york.ac.uk

Interview Guide

Objective: To get an understanding of the discussant's professional perspective on adaptive social-ecological systems with regards to the specific case study, with particular attention to the two angles of "adaptive engineering" and "adaptive management".

Interview set-up:

- The location will be identified by the discussant.
- The time requested will be 1.5 hours, can be reduced to 1 hour if requested by discussant.
- The interview will be audio recorded for later data analysis.
- For interviews in Viet Nam, the discussant will be asked prior to the interview in which language the interview should be conducted with the default option in English. In case the discussant has a preference for Vietnamese, an interpreter will join the discussion and the length of the interview may be increased to 2 hours. The interpreter will be briefed on the questions prior to the interview to ensure key concepts are translated adequately.
- No compensation will be offered for interviews; but discussants may request a copy of the research outcome (paper on the case study).

#	Topic	Goal	Time (min)
1	**Introduction of research** • Self • Objectives of the study • Expected results and timeline for completion • Confidentiality • Consent in audio recording and perusal of information	*Introduce research* *Free prior informed consent*	5
2	**Introduction of discussant** • Full name, age • Education • Professional experience • Current job title • Place in organigram (draw if useful)	*Understanding participant's perspective*	10
3	**Description of own role in management of ecosystem** • Day-to-day activities • Role in defining longer-term strategy • Most regular interactions	*Understanding participant's role*	10
4	**Description of ecosystem** • Important longer-term trends and recurrent events • Recent developments	*Getting to know dynamics of system*	20
5	**Assessment of adaptive capacity** • Introduce different definitions of adaptive capacity • Discuss participant's interpretation of adaptive capacity • Draw graph of robustness and flexibility over time, including milestone events and trends • Role of structures – social and physical • Role of self-organization – social and physical (natural) • Interactions between social and physical robustness, self-organization • Trade-offs	*Getting participant's view on adaptive capacity*	20
6	**Views on way forward** • (if needed, provide options) • Increasing adaptive capacity • Own responsibility in increasing adaptive capacity	*Getting participant's view on possible action*	10
7	**Q-sorting exercise** • (statements to be developed)[1]		10

[1] Statements will be developed from the literature review and will be the sa

8	**Closing** • Any other question • Repeat timeline and consent, contact for follow-up	*Closing and consent*	5

Form for free, prior and informed consent.

Name of study: Adaptive capacity in engineered social-ecological systems

Researcher: Guido Rutten

Supervisor: Steve Cinderby

Purpose of research: The project aims to understand the adaptive capacity of engineered social-ecological systems. The specific fieldwork in question deals with interviewing people who are professionally engaged in the management of social-ecological systems, and the objective is to get their viewpoints on the subject matter.

Important to note:

- Your participation in the research is completely voluntary; you may choose to stop participating at any time. A decision not to continue participating will not influence your relationship with researchers or with staff of the University of York either now or in the future.
- The interview will be audio recorded and transcribed. Any information obtained will be anonymized and stored in a secure storage environment and be accessed only by the researcher and the research supervisor. Confidentiality will be provided to the fullest extent possible by law
- The research has been reviewed and approved by the Ethics Committee of the Environment Department, University of York.

Statement of consent:

I, ____, consent to participate in the study "adaptive capacity in engineered social-economic systems", conducted by Guido Rutten. I have understood the nature of this research and wish to participate. I am not waiving any of my legal

me for both case studies. The statements will be developed in the local language.

rights by signing this form. My signature below indicates my consent.

Signature: ___________________________ Date: ___________________________

Name of participant:

Signature: ___________________________ Date: ___________________________

Principal investigator: Guido Rutten

Data handling and analysis

Interviews will be audio recorded and analyzed using qualitative data analysis software such as Atlas.ti or Nvivo (tbc). Records will be encrypted and backed up using secure online storage services.