Towards feasible strategies for reducing groundwater over-extraction in the Vietnamese Mekong Delta

by
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Towards feasible strategies for reducing groundwater over-extraction in the Vietnamese Mekong Delta

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Summary

The Vietnamese Mekong Delta (VMD) is home to nearly 18 million people and is of major importance to Vietnam's national food security. A major threat to the delta is land subsidence, because without addressing this issue parts of the delta will sink below sea-level. The main driver of subsidence is groundwater over-extraction. The depletion of groundwater resources and associated issues such as subsidence, in combination with the increasing vulnerability to climate change and sea-level rise make it of utmost importance that strategies are developed to reduce groundwater over-extraction. Therefore, this study assesses the feasibility of strategies based on the presence of physical and technical, governance and economic conditions required for a successful development of strategies in the delta.

This research uses multiple methods, including desk research, a workshop and expert interviews. Literature was reviewed to identify strategies and strategy-specific conditions. The following strategies are included in this study: rainwater harvesting, surface water use, wastewater reuse, seawater desalination and managed aquifer recharge. Subsequently, a workshop was organised which gave insight into the feasibility of strategies. Lastly, eleven semi-structured interviews were conducted with experts, to gather expert opinions on the presence of the required conditions in the VMD.

From the research assessment it was concluded that currently, for none of the strategies all conditions are present. However, in comparison to the other strategies, surface water treatment has the greatest potential to be successfully developed. Based on the assessment results, the main physical and technical barriers are the poor quality and availability of alternative water resources throughout the delta, and the impact of climate change on these alternatives. The main governance barrier is that the central government does not provide guidance on how to implement and enforce regulations locally. Furthermore, knowledge is lacking on the negative effects of groundwater over-extraction. The main economic barrier is the absence of capital for initial investments and maintenance efforts.

Based on the analysis, this study recommends that the government increases its knowledge on groundwater use in the delta. Furthermore, it is recommended that strategies are developed on a small-scale suited to local conditions, that a cost-benefit analysis is conducted on the different strategies, that technical measures are combined with governance measures and that the knowledge of stakeholders is increased on the negative effects of groundwater use. Further research should focus on developing strategies for sustainable groundwater management, which take the impacts of climate change into account.

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Table of Contents

Summary 3

Acknowledgements 4

List of Figures 8

List of Tables 9

Abbreviations and Acronyms 10

Chapter 1. Introduction 11

- 1.1 Problem definition: a subsiding delta 11
- 1.2 Previous research: towards an integrated approach 13
- 1.3 Research objective and questions 14
- 1.4 Outline of thesis 15

Chapter 2. Required conditions for sustainable groundwater management 16

- 2.1 Integrated groundwater management 16
- 2.2 Potential strategies 17
- 2.3 Assessment framework 19
- 2.4 Conclusion 21

Chapter 3. Methodology 22

- 3.1 Research area 22
  - 3.1.1 Physical characteristics 22
  - 3.1.2 Socio-economic characteristics 24
  - 3.1.3 Institutional characteristics 24
- 3.2 Data collection 25
- 3.3 Data analysis 28
- 3.4 Conclusion 28

Chapter 4. Feasibility of Rainwater Harvesting 29

- 4.1 Rainwater harvesting system 29
  - 4.1.1 Rainwater collection subsystem 30
  - 4.1.2 Rainwater storage subsystem 31
  - 4.1.3 Rainwater supply subsystem 31
- 4.2 Governance incentives for rainwater harvesting 32
- 4.3 Presence of conditions 33
  - 4.3.1 Physical and technical conditions 33
  - 4.3.2 Governance conditions 35
  - 4.3.3 Economic conditions 37
- 4.4 Conclusion 37

Chapter 5. Feasibility of Surface Water Use 38
  5.1 Surface water treatment system 38
    5.1.1 Conventional surface water treatment 39
    5.1.2 Ultrafiltration technology 40
  5.2 Governance incentives for surface water use 40
  5.3 Presence of conditions 41
    5.3.1 Physical and technical conditions 41
    5.3.2 Governance conditions 44
    5.3.3 Economic conditions 45
  5.4 Conclusion 45
Chapter 6. Feasibility of Wastewater Reuse 46
  6.1 Wastewater reuse systems 46
    6.1.1 Wastewater treatment 46
  6.2 Governance incentives for wastewater reuse 47
  6.3 Presence of conditions 48
    6.3.1 Physical and technical conditions 48
    6.3.2 Governance conditions 49
    6.3.3 Economic conditions 50
  6.4 Conclusion 51
Chapter 7. Feasibility of Seawater Desalination 52
  7.1 Seawater desalination systems 52
    7.1.1 Desalination processes 52
  7.2 Governance incentives for desalinating seawater 53
  7.3 Presence of conditions 54
    7.3.1 Physical and technical conditions 54
    7.3.2 Governance conditions 56
    7.3.3 Economic conditions 57
  7.4 Conclusion 57
Chapter 8. Feasibility of Managed Aquifer Recharge 58
  8.1 Managed aquifer recharge systems 58
    8.1.1 Methods for managed aquifer recharge 59
    8.1.2 Potential water sources for recharge 60
  8.2 Governance incentives for managed aquifer recharge 61
  8.3 Presence of conditions 63
    8.3.1 Physical and technical conditions 63
    8.3.2 Governance conditions 64

    - 8.3.3 Economic conditions 65
  - 8.4 Conclusion 66
- Chapter 9. Conclusion and Recommendations 67
  - 9.1 Presence of conditions in the Vietnamese Mekong Delta 67
    - 9.1.1 Presence of physical and technical conditions 68
    - 9.1.2 Presence of governance conditions 69
    - 9.1.3 Presence of economic conditions 69
    - 9.1.4 Overall conclusion 69
  - 9.2 Limitations 70
  - 9.3 Recommendations 71
- References 72
- Appendices 79
  - Appendix I: Summary of the workshop 79
  - Appendix II: Expert interviews 82
  - Appendix III: Coding structure in NVIVO 85

List of Figures

Figures *Page*

1. Location of the Mekong Delta 11
2. Modelled cumulative subsidence and modelled groundwater extraction 12
3. Research Framework 14
4. Vietnamese Mekong Delta 22
5. The institutional structure for water management in Vietnam 25
6. Rainwater Harvesting system 29
7. Steps of the conventional and ultrafiltration treatment method 39
8. Illustration of a seawater desalination facility 52
9. The process of reverse osmosis 53
10. Confined aquifer with the aquifer storage and recovery method 58
11. Unconfined aquifer with the soil aquifer treatment method 59

List of Tables

Tables *Page*

1. Physical-technical conditions required to be present for sustainable groundwater management ... 19
2. Governance conditions required to be present for sustainable groundwater management 20
3. Economic conditions required to be present for sustainable groundwater management 20
4. Groundwater utilization in the Mekong Delta 23
5. Experts of the Rise and Fall project present at the workshop 26
6. Overview of the interviewed experts... 27
7. Presence of physical-technical conditions for rainwater harvesting... 33
8. Presence of governance conditions for rainwater harvesting 35
9. Presence of economic conditions for rainwater harvesting.. 37
10. Presence of physical-technical conditions for surface water use 41
11. Presence of governance conditions for surface water use 44
12. Presence of economic conditions for surface water use 45
13. Presence of physical-technical conditions for wastewater reuse 48
14. Presence of governance conditions for wastewater reuse... 49
15. Presence of economic conditions for wastewater reuse 50
16. Presence of physical-technical conditions for seawater desalination... 54
17. Presence of governance conditions for seawater desalination 56
18. Presence of economic conditions for seawater desalination.. 57
19. Presence of physical-technical conditions for managed aquifer recharge 63
20. Presence of governance conditions for managed aquifer recharge 64
21. Presence of economic conditions for managed aquifer recharge 65
22. Overview of the assessment results on the presence of the conditions in the delta 67

Abbreviations and Acronyms

ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Transfer and Recovery
DARD	Department of Agriculture and Rural Development
DONRE	Department of Natural Resources and Environment
ED	Electrodialysis
FAO	Food and Agriculture Organization
IGM	Integrated Groundwater Management
IWRM	Integrated Water Resources Management
MAR	Managed Aquifer Recharge
MARD	Ministry of Agriculture and Rural Development
MED	Multiple Effect Distillation
MDP	Mekong Delta Plan
MONRE	Ministry of Natural Resources and Environment
MSF	Multi Stage Flash
NF	Nanofiltration
NGO	Non-Governmental Organisation
NWO	Netherlands Organisation for Scientific Research
RCE	Rainwater Collection Efficiency
RO	Reverse Osmosis
RWH	Rainwater Harvesting
SAT	Soil Aquifer Treatment
SD	Solar Distillation
UF	Ultrafiltration
VC	Vapour Compression
VMD	Vietnamese Mekong Delta
WHO	World Health Organization

Chapter 1
Introduction

1.1 Problem definition: a subsiding delta

The Vietnamese part of the Mekong Delta is situated in the far south of Vietnam, at the downstream-most end of the Lower Mekong Basin (Huu-Thoi & Gupta, 2001). It is a vast floodplain that is divided by the nine arms of the Mekong River (explaining its name as the '*Nine Dragon river delta'),* which all flow into the East Sea (Borchardt, Bogardi & Ibisch, 2016; FAO, 2011). The Vietnamese Mekong Delta (VMD) has a land area of about 40,519 km^2 and is home to nearly 18 million people (Cosslett & Cosslett, 2014; Stewart & Coclanis, 2011). The delta is of major importance to Vietnam's national food security. For hundreds of years, rice cultivation has been the main economic activity sustaining the livelihoods of people in the VMD. Although rice cultivation remains the foremost industry, aquaculture is growing rapidly and has become an important export product in the economic development of the delta (Cosslett & Cosslett, 2014). Since the VMD is a low-lying delta, it is particularly prone to changes in the environment. A major *hidden* threat to the delta is land subsidence, because without addressing this issue parts of the VMD will sink below sea level. This in combination with the adverse impacts of climate change, including sea-level rise and an increase in peak flows, river floods and saltwater intrusion, makes it an urgent threat (Deltares, 2013; Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013).

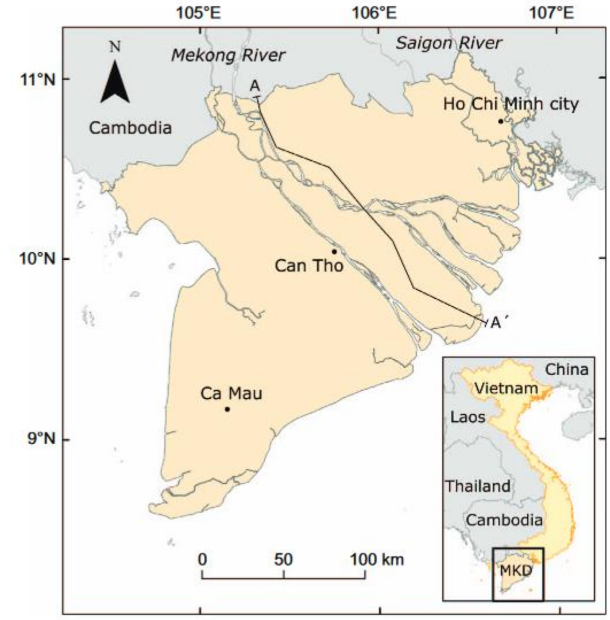


Figure 1*: Location of the Mekong Delta (Minderhoud et al., 2017)*

Land subsidence can be caused by natural and anthropogenic processes. Natural land subsidence can result from glacial isostatic adjustment, natural sediment compaction or from tectonic and volcanic activities. Whereas anthropogenic subsidence can result from processes such as fluid or solid withdrawal, sediment loading or as a result of drainage (Chaussard et al., 2013; Deltares, 2013). Although natural subsidence often takes place in areas such as deltas, anthropogenic subsidence is in general "*one order of magnitude faster than natural subsidence"* (Chaussard et al., 2013, p. 151).

In the VMD, severe land subsidence is mainly caused by groundwater extraction. The study of Minderhoud et al. (2017) showed that 25 years of groundwater extraction in the delta has resulted in an average total subsidence of approximately 18 cm (see Figure 2).

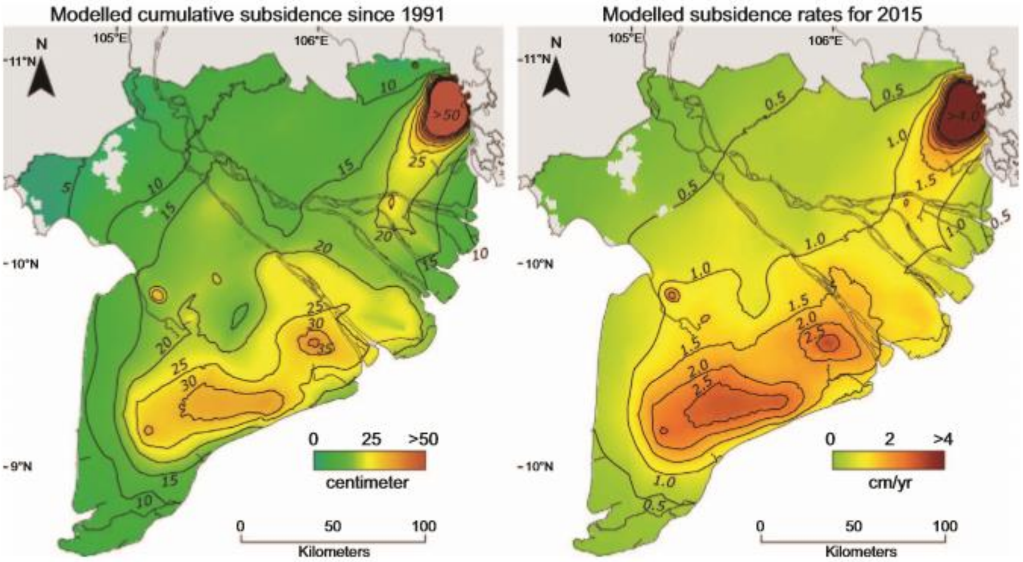


Figure 2: (***a***) modelled cumulative subsidence due to groundwater extraction from 1991 to 2016 (***b***) modelled subsidence rates induced by groundwater extraction for 2015 (Minderhoud et al., 2017)

Groundwater extraction has strongly increased in the last decades, following the continuing economic growth after Vietnam's transition to a market economy in 1986. This transition resulted in a huge increase in cultivation, urbanisation and industrialisation in the VMD. Groundwater is the main source to meet the increasing freshwater demand in the delta, since surface water is often polluted or saline (Minderhoud et al., 2017). Although groundwater resources provide numerous socio-economic benefits (e.g. people rely on groundwater resources for food and energy production, health and recreation), sustainability of the resource is threatened as groundwater quality and groundwater levels are declining (Velis, Conti & Biermann, 2017; IUCN, 2011). An average decline of 26 cm/y was detected (Erban, Gorelick & Zekber, 2014), and reductions are likely to continue unless strategies to reduce groundwater over-extraction are implemented (Ha et al., 2018). Furthermore, groundwater overexploitation induces a variety of hazards, such as saline intrusion and arsenic contamination of groundwater (Erban et al., 2014). Tran and Ross (2009) showed that the safety of drinking water has already become an issue in the delta because of chemical contamination and its adverse impacts on human health. Moreover, according to the study of Erban et al. (2014) the magnitude of pumping-induced subsidence is significantly greater than sea-level rise in the VMD, which is worrisome as the delta is already sensitive to widespread annual flooding. Besides, the majority of the land in the delta is only slightly (<2m) above mean sea level (Wassmann et al., 2004). As a result, "*subsidence acts as a catalyst, increasing vulnerability to flooding and storm surges, saltwater intrusion in the channels and risk of permanent inundation of the delta*" (Minderhoud et al., 2017, p. 1).

The depletion of groundwater resources and associated issues such as land subsidence, in combination with the increasing vulnerability to climate change and sea-level rise make it of utmost importance that strategies are developed to deal with groundwater over-extraction. It is also emphasized by various studies (e.g. Minderhoud et al., 2017; IUCN, 2011.; Shrestha, Bach & Pandey., 2016) that strategies need to be developed and implemented which focus on the sustainable use of groundwater in the VMD. IUCN (2011, p. 8) argues that "*it is vital that policy makers recognize the services provided by a healthy groundwater system and intervene to manage both the supply and demand aspects of groundwater in the delta"*. This research therefore focuses on assessing the feasibility of potential strategies that can reduce the pressure on groundwater use.

1.2 Previous research: towards an integrated approach

Groundwater has immense social, economic and environmental importance, however not much attention is given to using groundwater wisely and managing and protecting it in an effective manner (FAO, 2016a). Due to the character of groundwater as a common pool resource, including attributes of subtractability and excludability (Ostrom, Gardner & Walker, 1994), it is vulnerable to the so-called 'tragedy of the commons' (Hardin, 1968) in which stakeholders act merely in their own short-term self-interest rather than taking long-term shared interests into account (Foster et al., 2009). This makes the protection of groundwater resources and the effectiveness of management even more difficult. Subtractability means that groundwater resources have a limited capacity, whereby consumption of groundwater by one subtracts groundwater available to others. Excludability refers to the issue that it is difficult to prevent water users from pumping groundwater. The challenges ascending from groundwater over-extraction are diverse and require location-specific approaches (Knüppe & Pahl-Wostl, 2011).

The traditional fragmented approach to groundwater management was no longer deemed viable to deal with the diverse challenges ascending from groundwater overexploitation. This resulted in the development of a more holistic approach to groundwater management, namely the Integrated Groundwater Management (IGM) approach. This framework promotes the "*coordinated management of groundwater and related resources […] taking into account non-groundwater policy interactions, in order to achieve balanced economic, social welfare and ecosystem outcomes over space and time"* (Jakeman et al., 2016, p. 6). Managing groundwater concerns multiple stakeholders and decision-makers with competing objectives and interests (consisting of interactive social, economic and ecological components) which are complex and continuously changing. Given the complexity of groundwater systems and the increasing importance of groundwater as a source to meet freshwater demands, an effective integrated approach to groundwater management is crucial. The main drivers of poor groundwater management have included limited scientific understanding of groundwater systems, the resource being undervalued or under-priced, poor governance, and short prospects of management (Jakeman et al., 2016).

In recent years, terms as '*sinking cities*' and '*sinking deltas*' have received widespread attention, and multiple studies have been published on land subsidence (e.g. Erkens et al., 2015; Sahu & Sikdar, 2011; Carbognin, Pietro & Luigi, 2005; Erban et al., 2014; Chaussard et al., 2013). Although there is an increasing awareness of the threat of land subsidence, and literature also provides strategies to address the issue (e.g. by raising dykes), it is not known which strategies are most feasible for the specific case of the VMD. According to Deltares (2013, p. 8) if attention is paid to *"developing the required technical, administrative, and institutional capabilities, the negative impacts of land subsidence can be mitigated and the process largely stopped"*. An important and comprehensive document for the specific case of the VMD is the Mekong Delta Plan (MDP), which was published in 2013. The plan was prepared under the Strategic Partnership Arrangement on Climate Change Adaptation and Water Management between the Kingdom of the Netherlands and the Socialist Republic of Vietnam. This report discusses several challenges that influence the management of the delta, such as climate change but also land subsidence. To address the issue of subsidence, the MDP proposes to radically shift from groundwater supply to supply from surface water. Moreover, it is proposed that mechanisms (financial and political) should be put in place *"to come to an effective coordination and integration of planning across sectors, and across governance domains, at national and provincial level, to come to a congruent planning and implementation in the future"* (Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013, p. 85).

1.3 Research objective and questions

This research aims to contribute to the more sustainable management of groundwater resources in the delta. As mentioned previously, this study focuses on assessing the feasibility of potential strategies that can reduce groundwater over-extraction in the VMD. The feasibility will be assessed on the presence of a set of conditions, which are required for a successful development of the strategies. Based on the analysis of the assessment results, recommendations are provided on feasible strategies to implement in the delta to deal with the urgent threat of groundwater over-extraction and accompanied issues such as land subsidence. Deriving from the research problem and objective, the following research question is formulated:

"To what degree are required conditions for implementing strategies that reduce groundwater over-extraction present in the Vietnamese Mekong Delta?"

The research question provides the framework for guiding the research, illustrated below in Figure 3.

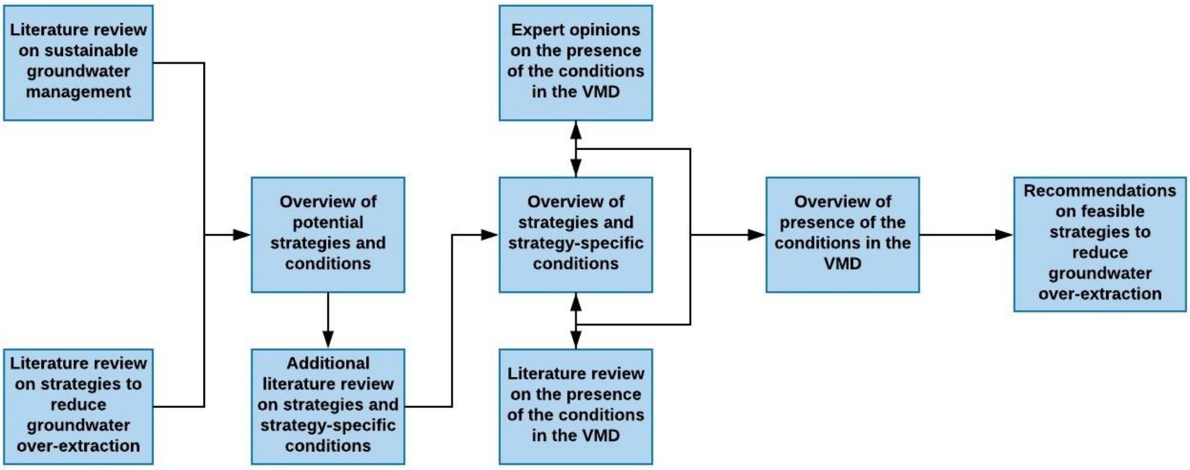


***Figure 3**: Research Framework*

Figure 3 shows the steps taken to answer the main research question. Reading from left to right, the first phase consists of a literature review on the sustainable management of groundwater and on strategies to reduce groundwater over-extraction. The outcome of this literature review is an overview of potential strategies and conditions. An additional literature review is conducted on the strategies and on the strategy-specific conditions. Subsequently, these strategy-specific conditions guide the interviews with experts and in turn the experts make an estimation whether these conditions are present or not in the delta. Furthermore, a literature review is conducted on the presence of the conditions in the VMD. The outcomes of this literature review and expert opinions then lead to an overview of the presence of all conditions in the delta. From these results, recommendations are provided on feasible strategies to reduce groundwater over-extraction.

These steps lead to the following sub-questions:

1. Under which conditions is sustainable groundwater management possible?
2. Which strategies for addressing groundwater over-extraction are proposed in literature?
3. What are the required conditions for implementing these strategies?
4. Which of the required conditions are present in the VMD?

1.4 Outline of thesis

The thesis report is structured as follows. After having presented the objective of this thesis , the next chapter outlines the potential strategies to reduce groundwater-overextraction, and existing theory on sustainable groundwater management. This leads to three lists of conditions that are in general required for sustainable groundwater management. Chapter 3 describes more specifically how the research is conducted to answer the research questions. The following chapters consist of the assessment on the feasibility of potential strategies to reduce groundwater over-extraction. These strategies include: rainwater harvesting (Chapter 4), surface water use (Chapter 5), wastewater reuse (Chapter 6), seawater desalination (Chapter 7) and managed aquifer recharge (Chapter 8). The thesis will be ended with Chapter 9, that consists of a conclusion where the main research question is answered, a discussion on the limitations of the research and finally recommendations are provided on feasible strategies to reduce the pressure on groundwater use in the delta.

Chapter 2

Required conditions for sustainable groundwater management

This chapter elaborates on theories that deal with sustainable groundwater management. Furthermore, strategies to reduce groundwater overexploitation which have been found in literature, are presented. This provides the foundation of what is included in the assessment framework, as it leads to conditions that are in general required for sustainable groundwater management. The framework consists of a set of physical and technical, economic, and governance conditions. In the next sections two sub-questions are addressed, namely: (1) Under which conditions is sustainable groundwater management possible and; (2) Which strategies for addressing groundwater over-extraction are proposed in literature.

2.1 Integrated groundwater management

Groundwater is the largest accessible freshwater resource and accounts for approximately one-third of freshwater withdrawals worldwide (Gorelick & Zheng, 2015). Although essential, continuing groundwater overexploitation is unsustainable. Strong efforts are needed that are geared towards minimizing the pressure on groundwater use and restoring delta sustainability (Anthony et al., 2015). To deal with the diverse challenges ascending from groundwater overexploitation, a holistic framework is presented in literature, namely the Integrated Groundwater Management approach. This framework can be seen as a part of the Integrated Water Resources Management (IWRM) approach, however it focuses solely on the management of groundwater. The IGM approach emphasizes that many issues are interrelated and can thus not be solved in isolation. For instance, policy interventions that are initially developed to reduce the pressure on groundwater use may positively or negatively affect other policies. An example of this could be that pumping restrictions are enforced in a stringent way to ensure the sustainable use of the resource, however this could lead to drastic changes in the domestic drinking water supply. This implies that groundwater related issues should be treated holistically, and competing interests of stakeholders should be considered (Jakeman et al., 2016).

An important component of IGM is the governance of groundwater. In general, governance is a vast concept, encompassing a set of principles, ideas, theories, contexts, objectives, and practices (Varady et al., 2013). In literature (e.g. Weiss, 2000; Rhodes, 2007; Kooiman, 2003; Provan & Kenis, 2007), various definitions of the concept 'governance' and of more specific fields such as 'environmental governance' are provided. Groundwater governance is defined as "*the exercise of appropriate authority and promotion of responsible collective action to ensure sustainable and efficient utilization of groundwater resources for the benefit of humankind and dependent ecosystems*" (Foster et al., 2009, p. 1). According to the Food and Agriculture Organization of the United Nations (FAO, 2016b), effective and sustainable groundwater governance consists of the following components:

1. An institutional framework, which is characterized by leadership, stakeholder engagement, sound organizations with sufficient capacity, and mechanisms to coordinate between groundwater and other sectors;
2. An effective and coherent legal and regulatory framework;
3. Policies, plans, finances and incentive structures which are adjusted to the objectives of society;
4. Widely-shared and accurate knowledge of the groundwater systems and awareness of the sustainability challenges such as issues related to groundwater over-extraction (FAO, 2016b, p. 4).

It is increasingly recognized in literature (e.g. Conallin et al., 2017; Jakeman et al. 2016) that stakeholder engagement is of essential importance for sustainable groundwater management. Stakeholder engagement is defined as: "*a framework of policies, principles, and techniques which ensure that citizens and communities, individuals, groups, and organizations have the opportunity to be engaged in a meaningful way in the process of decision-making that will affect them, or in which they have an interest*" (Conallin et al., 2017, p. 132). The stakeholder engagement process is particularly important for effective IGM as it ensures that a wide range of interests, knowledge, and perspectives are considered, shared and understood. Furthermore, the process of stakeholder engagement can help to reduce conflicts and build trust among stakeholders. It can also promote mutual learning between stakeholders in different fields. Thus, stakeholder engagement can be considered as a required condition to gain acceptance of proposed management strategies (Jakeman et al., 2016). It also embodies a shift away from top-down centralized governance towards bottom-up collaborative approaches to water management (Conallin et al., 2017).

2.2 Potential strategies

As the sustainable management of groundwater is a challenge in many parts of the world, a variety of responses to address groundwater over-extraction are presented in literature. It is first however important to define the term '*strategy*'. A strategy is a plan of action that is designed to achieve a long-term objective (Dimitrios, Sakas & Vlachos, 2013). In this study a strategy aims to reduce groundwater over-extraction and consists of three components: (1) an alternative water source; (2) technical measures; and (3) governance measures.

The first component of a strategy is the alternative water resource. Groundwater in the VMD supplies water for domestic use, urban water supply, irrigation, aquaculture, and industrial sites (IUCN, 2011). This implies that alternatives to groundwater are needed. As mentioned previously, in the MDP it was proposed to radically shift from groundwater supply to supply from surface water (Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013). Besides surface water, other alternatives are available. These include rainwater, seawater and (treated) wastewater.

Secondly, a strategy consists of technical measures. These measures can be divided into the following three groups (Bau et al., 2005)

- Measures that lead to better usage of available water resources. A technical measure could be to store excess rainwater, so that is can be used in dry seasons;
- Measures that lead to an increase of available water resources. In the case of the VMD, groundwater use stems among other things from the deteriorating quality of surface water, not the quantity (Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013). Therefore, when surface water is treated or seawater is desalinated, the quantity of available water resources increases. Another technical measure is to introduce managed aquifer recharge technology, which is seen as an important measure as it can restore declined groundwater levels and decrease the rate of land subsidence (Shi et al., 2016);
- Measures that lead to a reduction of groundwater consumption. A technical measure that is proposed in literature is the reuse of wastewater. This could eventually lead to a reduction in groundwater use (Bau et al., 2005).

Lastly, a strategy consists of governance measures. As mentioned previously, to ensure sustainable groundwater governance it is important to engage with stakeholders. Thus, an example of a governance measure could be to educate stakeholders about groundwater issues, or to create more awareness among users about the negative impacts of groundwater use. Besides, governance measures include the creation of appropriate laws and regulatory mechanisms that could reduce the pressure on groundwater use (Shah et al., 2000). It can include a mix of policy instruments, such as the following five types (Jakeman et al., 2016):

- Command and control instruments, including regulatory standards, licenses and management zones. These instruments can influence the behaviour of groundwater users;
- Economic instruments, such as taxes and subsidies, which can stimulate desired behaviour by influencing the costs and benefits of possible actions;
- Collaborative agreements, which have the intent to strengthen cooperative behaviour between groundwater users, by augmenting non-economic motivations (e.g. altruism and reciprocity);
- Infrastructure instruments, which include public sector investments aimed at improving groundwater management;
- Communication and diffusion instruments, which aim to influence the knowledge, attitudes and/or motivations of individuals and their choices (Jakeman et al., 2016).

Jakeman et al. (2016, p. 9) argue that ideally "*decision makers should develop strategies and institutions that effectively combine these instruments to deliver acceptable environmental and socio-economic outcomes, and are also robust under potential changes to the natural and human settings*". One of the main problems is to ensure consistency of strategies, and that one instrument does not influence the effectiveness of other instruments.

The combination of these alternative water sources, technical and governance measures lead to a strategy. The following strategies are included in this research. It is important to note that other combinations are possible as well, as for instance taxes can also be used when developing rainwater harvesting systems. To avoid repetition, the combinations that were most commonly found in literature are used.

The first strategy is rainwater harvesting (RWH), which is a water supply technology that has been used for centuries. It is a method for collecting, storing and conserving rainwater for domestic use, agricultural use and for other purposes (Rahman, 2017). Subsidies can be implemented to advocate and expand RWH technologies (Amos, Rahman & Gathenya, 2016).

The second strategy is surface water use. Surface water is often contaminated and needs to be treated before it has the required quality. Treatment plants can be introduced that can improve the quality of surface water (Delpla et al., 2009). To discourage groundwater extraction, tax instruments can be introduced that penalize the use of groundwater or the decrease in the water table level (Esteban & Dinar, 2013).

The third strategy is the desalination of seawater. In order to use this abundant resource for drinking water or for other purposes, it should first be purified. Seawater desalination offers a supposedly unlimited and steady supply of high-quality water without harming natural freshwater ecosystems (Elimelech & Phillip, 2011). To ensure a successful development of desalination systems, incentives should be in place that encourage the use seawater instead of groundwater. An example of a regulatory instrument is the prohibition of groundwater resources, altogether or for certain purposes (Duch, 2018).

The fourth strategy is the reuse of wastewater, which is becoming more common around the world. Reuse of wastewater can improve the environmental status by substituting abstraction and also by minimizing the discharge of wastewater to sensitive areas. It is considered a reliable water supply, which is rather independent from weather variability (EC, 2017). It is important that stakeholders are educated about the treatment of wastewater and awareness is created about the negative effects of groundwater over-extraction (Hanjra et al., 2012).

The last strategy is managed aquifer recharge (MAR), which is the purposeful recharge of water to suitable aquifers for subsequent recovery or to achieve environmental benefits. MAR can be used for multiple reasons, including securing and enhancing groundwater supplies, improving groundwater quality and preventing salt water intrusion into the aquifers (Dillon et al., 2009). To ensure that aquifers are replenished in an effective way, the government can introduce groundwater protection zones and educate users so that they can recognize risks of groundwater overexploitation (Nel et al., 2009).

2.3 Assessment framework

To examine whether the potential strategies identified during the literature review are feasible, an assessment framework is developed. The assessment framework consists of general conditions that are required to be present in the VMD for sustainable groundwater management (see Tables 1, 2 and 3). These conditions are retrieved from the previously discussed theories and an extensive literature review on potential strategies. The conditions are assessed based on the following values: (1) absent [-], (2) partially present [+/-], and [+] fully present. In the assessment chapters (see Chapters 4, 5, 6, 7 and 8) the conditions are further specified for each strategy.

***Table 1**: Physical and technical conditions required to be present in the delta for sustainable groundwater management*

Physical and technical conditions		
Variables	Conditions	Sources
Availability of water	Alternative water resources are sufficient and reliable in terms of quantity and quality	Abdulla & Al-Shareef, 2009; Gale et al., 2002; Jakeman et al., 2016
Availability of land	Land is available for the development of technical measures	Chew et al., 2016; Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013
Degree of knowledge and skills	Expert knowledge is available for the development of technical measures	Jakeman et al., 2016; Knüppe, 2011
	Management and maintenance skills are available for the development of technical measures	Jakeman et al., 2016; Knüppe, 2011
	Knowledge is available on the sustainable management of groundwater resources	FAO, 2016b; Jakeman et al., 2016; Knüppe, 2011
Required equipment	Equipment is available for the development of technical measures	Jakeman et al., 2016; Zhou & Tol, 2005

Table 2: Governance conditions required to be present in the delta for sustainable groundwater management

Governance conditions		
Variables	**Conditions**	**Sources**
Stakeholder engagement	Stakeholders are involved in groundwater management efforts and policy interventions that could potentially affect them	Conallin et al., 2017; FAO, 2016b; Jakeman et al., 2016
	Information about groundwater issues is actively communicated to non-state actors	Conallin et al., 2017; FAO, 2016b; Jakeman et al., 2016;
	Stakeholders accept new and innovative means to sustainably manage groundwater resources	Hanjra et al., 2012; Po et al., 2005
Institutional capacity	There are no regulatory constraints for the development of strategies to sustainably manage groundwater resources	Jakeman et al., 2016
	Groundwater regulations are coordinated with other sectors	FAO, 2016b; Jakeman et al. 2016; Kingdom of the Netherlands and the Socialist Republic of Vietnam; 2013
	An articulate legal and regulatory framework for sustainable groundwater management is available	FAO, 2016b; Jakeman et al., 2016; Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013
	Leadership is present that stimulates the sustainable management of groundwater resources	FAO, 2016b; Jakeman et al., 2016

Table 3: Economic conditions required to be present in the delta for sustainable groundwater management

Economic conditions		
Variables	**Conditions**	**Sources**
Financial capacity	Capital is available for the initial investments of certain measures	Badiuzzaman, McLaughlin & McCauley, 2017; Kingdom of the Netherlands and the

		Socialist Republic of Vietnam, 2013
	Capital is available for the continuous monitoring of certain measures	Badiuzzaman et al., 2017; Kingdom of the Netherlands and the Socialist Republic of Vietnam, 2013
	Costs are allocated in an equitable way between the stakeholders	Jakeman et al., 2016

2.4 Conclusion

This prior section provided an overview of potential strategies and conditions for sustainable groundwater management. In order to assess the feasibility of the strategies, the conditions will be further specified for each strategy. The following chapter will describe the methods used to determine the strategy-specific conditions and the presence of these conditions in the delta.

Chapter 3
Methodology

This chapter addresses the methodology used to conduct the assessment on the feasibility of strategies to reduce groundwater over-extraction. The characteristics of the research area and the selection of research methods and data analysis are elaborated.

3.1 Research area

The Mekong River Basin is shared among six countries, namely China, Laos, Thailand, Cambodia and Vietnam. The Mekong River is among the ten largest rivers worldwide, because of its flow discharge and sediment load (Kondolf et al., 2018). Besides, the river ranks second in overall biodiversity (Anthony et al., 2015). In terms of fish species, the delta is reported to be the most biodiverse region of the Mekong River, with 1,300 species of fishes (Deltares, 2011a). Like other deltas, the VMD is the result of sediment load transported down the river and deposited where the river meets the sea (Kondolf et al., 2018). The delta begins in Phnom Penh in Cambodia, where the Mekong River divides into its two main distributaries, the Tien River and the Hau River. The Tien River then divides into six main channels, and the Hau River into three channels, which form together the 'Cuu Long' meaning the 'Nine Dragons' of the outer delta in Vietnam (Deltares, 2011a).The VMD consists of thirteen provinces, namely Kien Giang, An Giang, Dong Thap, Long An, Tien Giang, Can Tho, Hau Giang, Vinh Long, Ca Mau, Bac Lieu, Soc Trang, Ben Tre, and Tra Vinh (see Figure 4).

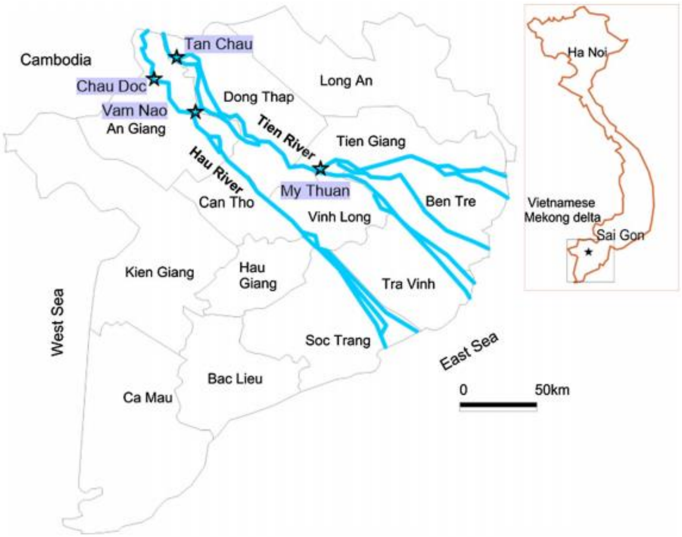


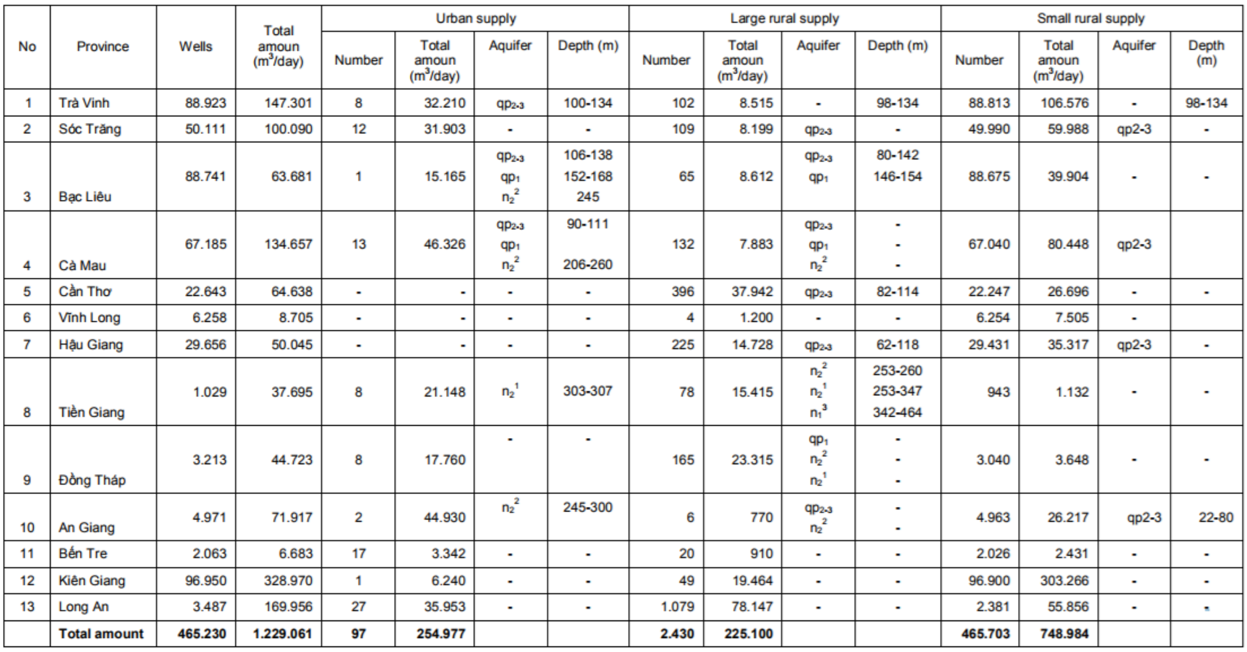
Figure 4: Vietnamese Mekong Delta (Tran & Nguyen, 2015)

3.1.1 Physical characteristics

The VMD is located in the tropical monsoon climate with two distinct seasons in a year. The dry season lasts from November to April, and generally coincides with the North-East monsoon. During this season, the weather is characterized by little rain and dry heat. Whereas the wet season lasts from May to October, and coincides with the South-West monsoon. In this season there is a high temperature, high humidity and rainfall (Deltares, 2011b). The yearly average rainfall in the delta is 1733 mm (Deltares, 2011a), whereby the total water volume during the wet season accounts for 80-83% of the annual rainfall (Renaud & Kuenzer, 2012). It is expected that climate change will have a major impact on the VMD, even though Vietnam has only produced 0.35% of the world´s greenhouse gases (Adam, 2008). It will create a significant threat to the delta as for instance temperature increases and sea-level rises, causing additional flooding and salt water intrusion. The Ministry of Natural Resources and Environment studied potential climate change and sea-level rise scenarios for Vietnam as a whole. Under these scenarios, in the late 21st century the average temperatures in Vietnam could increase by 2.3°C, the total annual rainfall and wet season rainfall could also increase while dry season rainfall decreases. A sea-level rise is expected of approximately 75 cm (Deltares, 2011b). Especially, sea-level rise will have a major impact on Vietnam as almost half of the delta's land surface is <2 m above mean sea level (Kondolf et al., 2018). The terrain in the delta is mainly flat, with an average elevation of approximately 0.8 m above sea level, except for some hills in the Northern province of An Giang (Deltares, 2011a; Deltares, 2011b).

In the VMD, groundwater is an important water resource. There are approximately 200 large wells for urban water supply and over 25,000 small-scale wells for rural water supply (Deltares, 2011a). In the Eastern region of the delta, groundwater is fresh and recharged by rainfall. Whereas, in the Western region, fresh groundwater is limited (Deltares, 2011b). The aquifers have depths ranging from 15 to 75 metres and from 275 to 400 metres. Currently, the total exploited groundwater is about 48,000 m^3/day (see Table 4 for an overview per province) and groundwater is abstracted primarily from the Upper-Middle Pleistocene and Middle Pliocene aquifers. Groundwater is exploited mainly for domestic use (42%), agricultural activities (40%), and industrial (18%) use (Lee et al., 2017). Groundwater over-extraction has resulted in continuous decreases in groundwater level (IUCN, 2011). Since the water in the lower aquifers is 20,000 to 30,000 years old and not recharged by local rainfall, a further decrease in groundwater level is expected (Nesbitt, 2005).

Table 4: Groundwater utilization in the Mekong Delta (Deltares, 2011b)



No	Province	Wells	Total amoun (m^3/day)	Urban supply				Large rural supply				Small rural supply			
				Number	Total amoun (m^3/day)	Aquifer	Depth (m)	Number	Total amoun (m^3/day)	Aquifer	Depth (m)	Number	Total amoun (m^3/day)	Aquifer	Depth (m)
1	Trà Vinh	88.923	147.301	8	32.210	qp_{2-3}	100-134	102	8.515	-	98-134	88.813	106.576	-	98-134
2	Sóc Trăng	50.111	100.090	12	31.903	-	-	109	8.199	qp_{2-3}	-	49.990	59.988	qp2-3	-
3	Bạc Liêu	88.741	63.681	1	15.165	qp_{2-3} qp_1 n_2^2	106-138 152-168 245	65	8.612	qp_{2-3} qp_1	80-142 146-154	88.675	39.904	-	-
4	Cà Mau	67.185	134.657	13	46.326	qp_{2-3} qp_1 n_2^2	90-111 206-260	132	7.883	qp_{2-3} qp_1 n_2^2	- - -	67.040	80.448	qp2-3	
5	Cần Thơ	22.643	64.638	-	-	-	-	396	37.942	qp_{2-3}	82-114	22.247	26.696	-	-
6	Vĩnh Long	6.258	8.705	-	-	-	-	4	1.200	-	-	6.254	7.505	-	
7	Hậu Giang	29.656	50.045	-	-	-	-	225	14.728	qp_{2-3}	62-118	29.431	35.317	qp2-3	-
8	Tiền Giang	1.029	37.695	8	21.148	n_2^1	303-307	78	15.415	n_2^2 n_2^1 n_1^3	253-260 253-347 342-464	943	1.132	-	-
9	Đồng Tháp	3.213	44.723	8	17.760	-	-	165	23.315	qp_1 n_2^2 n_2^1	- - -	3.040	3.648	-	-
10	An Giang	4.971	71.917	2	44.930	n_2^2	245-300	6	770	qp_{2-3} n_2^2	- -	4.963	26.217	qp2-3	22-80
11	Bến Tre	2.063	6.683	17	3.342	-	-	20	910	-	-	2.026	2.431	-	-
12	Kiên Giang	96.950	328.970	1	6.240	-	-	49	19.464	-	-	96.900	303.266	-	-
13	Long An	3.487	169.956	27	35.953	-	-	1.079	78.147	-	-	2.381	55.856	-	-
	Total amount	**465.230**	**1.229.061**	**97**	**254.977**			**2.430**	**225.100**			**465.703**	**748.984**		

3.1.2 Socio-economic characteristics

The VMD is home to nearly 18 million people, which is 22% of the Vietnamese population. Nearly 85% of the inhabitants of the delta live in rural areas. The delta is one of the most productive areas, large parts are used for rice cultivation, shrimp farms, orchards and vegetable crops (Deltares, 2011a). The VMD is often referred to as the 'rice bowl', as it is the second largest rice exporter in the world. Moreover, it produces half of Vietnam's annual rice production, and it is therefore of importance to Vietnam's national food security (Cosslett & Cosslett, 2014). Even though the delta is of economic importance for Vietnam as a whole, the VMD remains one of the poorest regions. The per capita income in the VMD averaged in 2008 around 730 US$ (Deltares, 2011a). This lags behind the high expectations that were shaped after the implementation of the Renovation Policy (*Doi Moi),* which aimed to shift from central planning towards a market-based economy. It is however similar to development trajectories of other countries, especially in South East Asia. This is because it is difficult to keep up the pace with the industry and service sectors. Furthermore, the delta is lagging behind Vietnam's other regions in essential socio-economic aspects, such as education and poverty reduction. The low education level poses a challenge for the delta, as it is difficult to find qualified employees. This is also related to the increasing trend in the VMD towards urbanization and outmigration. In other regions or cities, there are more opportunities for income that is not generated on a farm, and higher living standards (Renaud & Kuenzer, 2012).

3.1.3 Institutional characteristics

In 1986, the government of Vietnam introduced the *Doi Moi*, with the objective to shift towards a market-based economy. The reforms included economic liberalisation, decentralisation, socialisation and changes to state management institutions. This also had a major impact on the policies for water resources management. For instance, water control and supply services were partly privatised and private businesses evolved offering pumping and drainage services. Traditionally, water resources management focused on flood control and the provision of freshwater for agricultural production. Technical water engineering was the dominant approach in the sector. In contrast, water resource protection was long ignored although water pollution increasingly occurred. In 1998, the Law on Water Resources was enacted which led to the issuance of more than 300 water-related regulations on guidance and implementation of the law. Vietnam's legislation on water resources is complex, as legal documents are ordered in various levels and adopted by different authorities. Vietnamese policies are based on 10-, 5-year and annual plans, that are developed by the central government. Local authorities gather and submit data to higher authorities. On basis of this information, provincial and central governments develop planning targets. In turn, when the targets are set, local administrative agencies implement the plans (Renaud & Kuenzer, 2012).

Water management in Vietnam involves various ministries and agencies (see Figure 5), which are divided into four vertical levels (central, province, district and commune). At the national level, Ministry of Natural Resources and Environment (MONRE) is in charge of the overall planning and management of water resources and is solely responsible for managing groundwater. Ministry of Agriculture and Rural Development (MARD) is in charge of the overall planning, implementation, and management of structures for irrigation, flood control and salinity intrusion prevention (Ha et al., 2018). Moreover, a number of other ministries, such as the Ministry of Health and the Ministry of Construction, have a stake in water resources management. This illustrates the institutional fragmentation present in Vietnam. Furthermore, a few agencies such as the National Water Resources Council (NWRC), have been set up to include different perspectives and concerns, however their role remains an advisory one. Even though one of the reforms of the *Doi Moi* included decentralisation programmes, national policies are developed at the central level and have to be implemented by the local governments (Waibel, 2010). At the provincial, district and communal level, People Committees are established. These committees are local administrative agencies that have responsibility for the implementation of laws and other policy documents that are introduced by higher authorities. At the provincial level, MONRE and MARD have subsidiary agencies (DONRE and DARD). These agencies assist the committees in implementing state management tasks on for instance water resources protection (Ha et al., 2018).

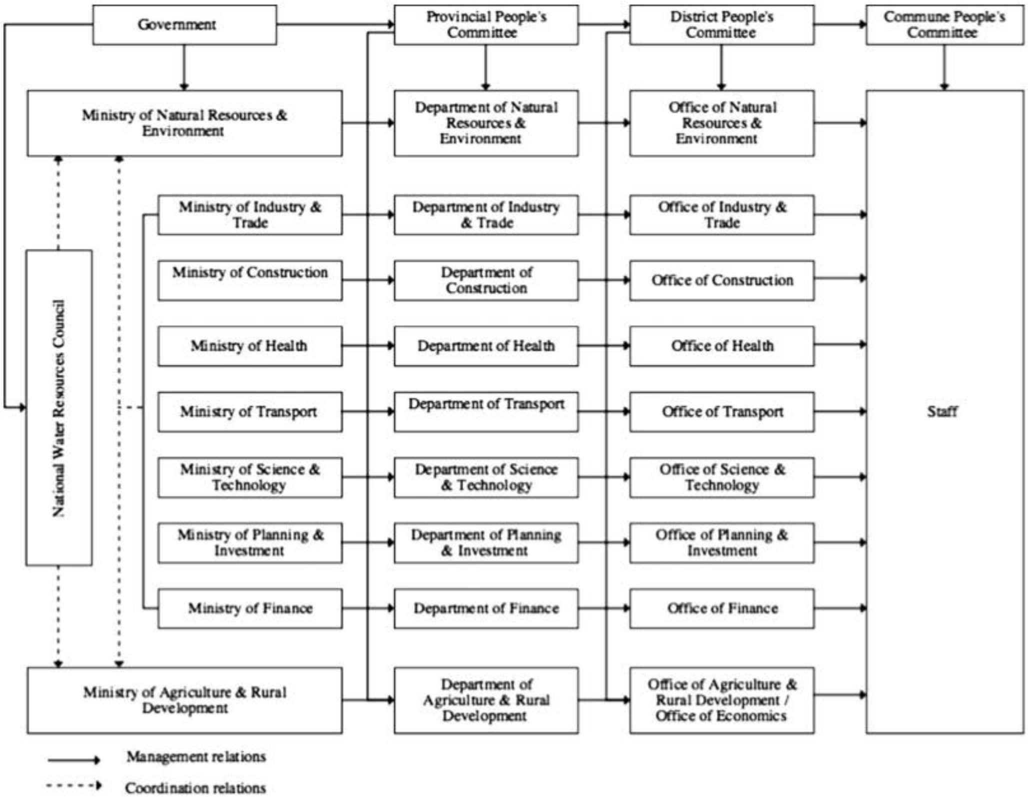


***Figure 5**: The institutional structure for water management in Vietnam (Ha et al., 2018)*

3.2 Data collection

Multiple methods have been used to collect data required for this research, including desk research, a workshop and semi-structured interviews.

The research started with an extensive literature review of sustainable groundwater management and potential strategies to reduce groundwater over-extraction. From this literature review, general conditions were identified that are required for sustainable groundwater management, which were presented in Chapter 2. Secondary data was collected using scientific search engines such as Scopus and Google Scholar, but literature was also collected from the online catalogue of Utrecht University library. The main keywords that were used are "*groundwater overextraction", "groundwater strategies", "integrated groundwater management", "alternatives groundwater", "Vietnamese Mekong Delta",* and so on. To assess whether a strategy is feasible it was necessary to further specify the conditions for each strategy. Therefore, additional literature was studied which led to strategy-specific conditions. The search for information was thus continued via Scopus, Google Scholar and the online catalogue, with keywords such as *“rainwater harvesting”, “desalination”, “managed aquifer recharge”, “treatment plants”, “wastewater reuse” and “water recycling”.* To further narrow down the search results, the functions ‘most cited’ and ‘most recent’ have been used. Lastly, during the desk research also policy documents and reports were analysed. These were obtained through internet search or through the internship position. The following two steps were conducted to obtain primary data.

The first step consisted of a workshop that was organised together with the supervisors from Deltares and Utrecht University. The aim was to get a first impression of the feasibility of potential strategies, and to get more insight into the opinions of experts on these strategies. This workshop included experts that are researchers within the Rise and Fall project, which this thesis is part of. This project is a Netherlands Organisation for Scientific Research (NWO) granted research that started in 2014 and will last until 2019. It aims to *“enhance the capabilities of individuals and organisations to develop sustainable strategies for dealing with groundwater extraction, land subsidence and saltwater intrusion in the increasingly urbanising Mekong Delta (Vietnam)”* (NWO, n.d.). See Table 5 for the participants of the workshop.

The workshop has been recorded and transcribed. The results are incorporated in Chapter 2. See Appendix I for a summary of the workshop.

Table 5: _Experts of the Rise and Fall project present at the workshop *Supervisor from Utrecht University_

Number	Institution(s)	Function(s)
W1	Utrecht University	Associate Professor
W2	Utrecht University*	Assistant Professor
W3	Deltares	PhD Researcher
	Utrecht University	
W4	Deltares	Senior Geologist
	Utrecht University	Researcher
W5	Deltares	Senior Specialist Hydrogeology
	Utrecht University	Associate Professor
W6	Deltares	Head of the department Urban Water and Subsurface Management

The second step consisted of eleven semi-structured interviews with experts with knowledge of water management in Vietnam. Expert opinions were necessary to make an estimation of the presence of required conditions in the delta. The experts thus supplied information through their experience or expertise in the research subject. It was first important to identify the experts in the field. This was done by asking both of the supervisors at Deltares and Utrecht University, but also by searching on the internet. This search was mainly aimed at identifying research projects within the Netherlands, that focus on water management in the delta. This led to the identification of nineteen experts, from various institutions. All of these experts were contacted by e-mail. In this e-mail, the research project was shortly introduced and in some cases the questions were send in advance of the interview (e.g. when the interview was conducted through Skype). However, it was difficult to reach all of the experts, because some did not respond. In total ten experts did not respond after the first invitation for an interview. Therefore, a reminder was send after approximately two weeks. After this reminder, two additional experts responded positively and an interview was planned. Another two of the experts did respond, but due to unavailability an interview could not be arranged. The other six experts did not respond at all. The list of interviewed experts from different institutions are listed below in Table 6.

Table 6: Overview of the interviewed experts, including their workplace and function

Number	Institution(s)	Function(s)
[E1]	IHE Delft Institute for Water Education	Senior lecturer in Hydrogeology and Groundwater Resources
[E2]	Deltares	Specialist Coastal Management and Flood Risk Management
[E3]	Delft University of Technology	Postdoctoral Researcher *(project: Strengthening Strategic Delta Planning in Bangladesh, Netherlands, Vietnam and beyond)*
[E4]	Wageningen University & Research	Project Manager, Aquaculture and Fisheries group
[E5]	Vitens Evides International	Resident Project Manager, Water Supply Expert
[E6]	Waterland Experts	Expert on Land and Water Management in Vietnam
[E7]	IUCN Vietnam	Mekong Delta Programme Manager
[E8]	Can Tho University, Vietnam	Associate Professor in Water Resources Management and Modelling
		Vice Dean of the College of Environment and Natural Resources
[E9]	Deltares	Senior Geologist
	Utrecht University	Researcher
[E10]	HZ University of Applied Sciences (Dutch Delta Academy)	Senior Lecturer and Researcher
[E11]	Deltares	PhD Researcher *(project: Rise and Fall)*
	Utrecht University	

Seven of the interviews were conducted face-to-face, and four interviews were conducted through Skype. This is because some of the respondents work abroad, mainly in Vietnam. The timeframe for each expert interview was approximately 45 minutes to 1 hours. All interviews had a similar structure, as the questions were based on the identified conditions from the literature study (see Appendix II for the list of questions and detailed information on the interviews). The experts were questioned via a semi-structured interview, which helped to steer the interview towards relevant answers but also gave experts the opportunity to elaborate on the perceived feasibility of strategies. All interviews started by giving a general introduction about the research and the aim of the interview was explained. Furthermore, respondents were asked if they give permission for the audio-recording of the interview. After this introduction, the researcher asked if the respondent also could elaborate on prior research or work experience in Vietnam. Subsequently, questions were posed about the presence of conditions in the delta.

3.3 Data analysis

To analyse the primary data, interviews were recorded and transcribed. The respondents gave permission to record the conversations. The interviews were conducted both in Dutch and English. To guarantee that the conversations were translated well, the Dutch interviews have first been transcribed in Dutch and later in English. The transcripts were subsequently uploaded into the qualitative data analysis software *NVivo.* This is a software that helps in organising, categorising and analysing qualitative data, and is therefore very suitable for this research. In *NVivo* the interviews were coded, by creating nodes and sub-nodes that have a similar structure to the assessment framework. The nodes are the strategies, the sub-nodes are the conditions which are assigned within these nodes. All of the transcripts were analysed, and the information belonging to a certain sub-node was marked and placed within the sub-node. While coding the interview responses, additional nodes were created to reflect responses that did not fit in the set of codes based on the assessment framework, such as *"alternative strategies"*. The structure of the coding in *NVivo* can be found in Appendix III. The coding led to the interpretation of the interviews and to information that is used in the following chapters. As can be seen in Table 6, each expert has its own number. For instance, expert 1 has the number [E1] and expert 2 has the number [E2], and so on. In the results chapters these numbers are used to make clear which expert said what.

3.4 Conclusion

This chapter provided a detailed explanation of the research area and the research methods used in this thesis to explain how the following results were gathered. In the next chapters, the results of the expert interviews are presented and in each chapter an overview is provided of the presence of the conditions in the delta.

Chapter 4
Feasibility of Rainwater Harvesting

In this chapter it is assessed whether rainwater harvesting is a feasible strategy to reduce groundwater over-extraction in the Vietnamese Mekong Delta. First, the strategy will be elaborated in-depth, including its characteristics. Subsequently, based on the presence of the physical and technical, governance and economic conditions it will be assessed whether RWH is a feasible strategy for development in the VMD.

4.1 Rainwater harvesting system

Precipitation is the source of all renewable freshwater on earth. When rain reaches the ground, part of it becomes runoff or infiltrates into the soil, and part of it evaporates. Rainwater can be utilized through direct use or use of land moisture that is formed from rain (Zhu et al., 2015). It is used as a drinking water source worldwide, as it is considered a safe source due to its positively characterized features such as colour, taste and smell (Wilbers et al., 2013). A specific kind of rainwater utilization is rainwater harvesting. This water supply technology has been used for centuries, and includes all approaches of inducing, collecting and storing rainwater for domestic use, agricultural use or for other purposes (Rahman, 2017). It is promoted and encouraged in countries across the globe, including China, India, Australia and Brazil (Aladenola & Adeboye, 2010). Rainwater is either collected from impervious surfaces, such as rooftops and roads, or from natural land surfaces (Rahman, 2017). Subsequently, the water is stored in for instance tanks and ponds. Especially in rural areas, RWH can contribute towards meeting goal six of the Sustainable Development Goals: "*Ensure access to water and sanitation for all*" (UNDESA, n.d.). In these areas, RWH systems can provide a cost-efficient and resilient way of enhancing water security in comparison to public water supply systems. Nowadays, the people that use rainwater around the globe can be divided into two groups: those that use rainwater as a supplement to already existing water supply systems and those that use rainwater as a basic supply (Rahman, 2017).

RWH is an integrated system, consisting of three subsystems: rainwater collection, rainwater storage and the water supply (see Figure 6).

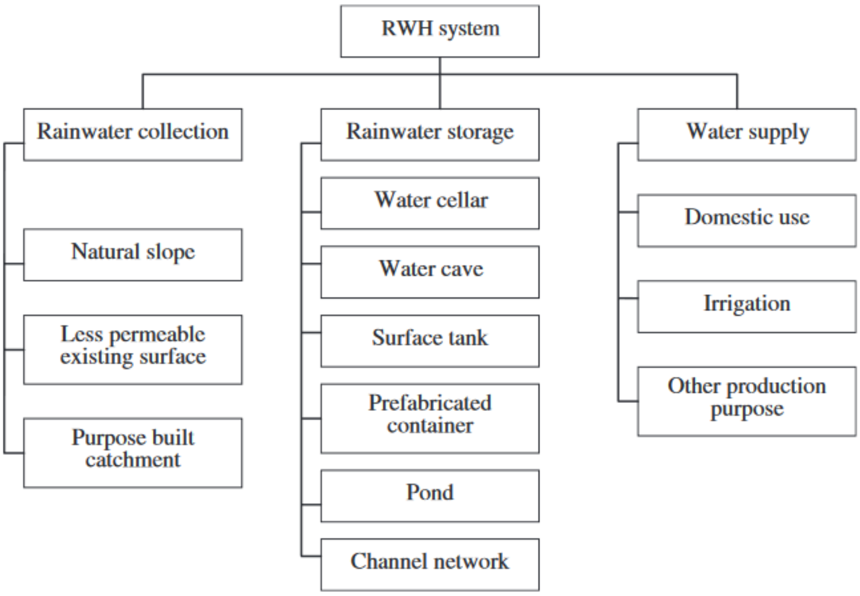


Figure 6: *RWH system (Zhu et al., 2015)*

4.1.1 Rainwater collection subsystem

The rainwater collection subsystem includes the collection surface (catchment) as well as interception, collection and conveyance ditches. In general, rainwater catchments can be divided into three types, namely natural surface, less permeable surface of existing structure and the purpose-built catchment (Zhu et al., 2015). The catchment should be impervious to get high rainwater collection efficiency (RCE). RCE can be improved by both treating the catchment and enlarging its area. In terms of affordability, first less permeable surface of existing structure should be considered (e.g. roofs, courtyards and road surfaces). In humid and semi-humid areas, natural slopes are mostly used as catchment areas because of low infiltration. Whereas in dry regions, it is sometimes necessary to construct a purpose-built catchment in order to collect sufficient water that meets the demand. Surfaces are then paved with impermeable materials such as cement concrete or plastic coverage. Thus, local (climatic) conditions influence the type of catchment used for the collection of rainwater. The most used rain catchments identified in literature are as follows (Zhu et al., 2015).

First, roofs are the most commonly used surface for the collection of rainwater. However, the suitability of a roof as a catchment area is dependent on the material of the roof. For instance, Wilbers et al. (2013) found that thatched roofs caused higher contamination in comparison with asbestos and concrete tiles and galvanized metal roofs. Second, courtyards are also used frequently as they are easily cleaned and therefore relatively clean water is obtained. Third, concrete or asphalt roads can be used as rainwater collection surfaces. These roads are cost-effective catchments when they are already existent just like the prior collection areas. In order to collect water, a drainage ditch can be used by the side of the road. Fourth, natural slopes are mostly used in (semi-) humid areas where rain is frequent and the soil is moist. Lastly, purpose-built catchments are used in dry areas where runoff is small. In this case, the surface can be paved with concrete, cement soil or covered with plastic film. An interception ditch is used to capture the rainwater runoff, and another ditch collects water from these interception ditches. In turn, the water is transported to the storage (e.g. a tank) through a conveyance ditch (Zhu et al., 2015).

Rainwater is usually free from physical and chemical contaminants, such as pesticides and suspended materials. However local circumstances and environmental factors are critical to the quality of rainwater, such as the degree of atmospheric pollution, type of construction materials and level of maintenance of the rainwater collection system. In industrialized urban areas, atmospheric pollution often makes rainwater unsafe to drink. Heavy metals such as lead are potential hazards especially in areas of high traffic density. Despite the numerous sources of atmospheric pollution, in most parts of the world, levels of contamination of rainfall are low (Zhu et al., 2015). The quality of harvested rainwater mainly depends on the surrounding environment, the tank material and maintenance of the RWH system. If rainwater is harvested from roofs, it could contain heavy metals and nutrients. Regular maintenance can significantly improve the harvested water quality, for instance washing of roof surfaces, gutters, tank, and inspecting for points of entry for mosquitos and vermin (Rahman, 2017). Furthermore, users should be encouraged to collect and dispose the first flush of rainwater from roofs. The first flush picks up most of the contaminants (Abdulla & Al-Shareef, 2009) and therefore needs to be flushed off before it enters the storage subsystem (Pushard, n.d.). The quality of rainwater is directly related to the hygiene of catchments, gutters, and storage tanks. For instance rooftop catchments collect dust, organic matter and bird and animal droppings, which can contaminate the harvested rainwater and cause sediment build-up in the storage system. Furthermore, the breeding of mosquitos in storage systems is a significant health risk as they can be a vector for viruses such as malaria. Therefore, it is of essential importance that sanitary inspections are conducted. These inspections should at least include checking the hygiene of the catchment area and storage and the physical quality of rainwater (WHO, n.d.).

4.1.2 Rainwater storage subsystem

In the water storage subsystem rainwater is stored in the wet season to meet the water demand of users in the dry season. These storage systems can be underground or above the ground. Surface storage systems are commonly surface tanks. These tanks are popular in humid and sub-humid areas, where precipitation is high and evaporation is low. These tanks can be round or rectangular and usually have diameters up to 10 m or more (Zhu et al., 2015). Surface storage tanks are relatively inexpensive storage systems, both in procurement costs and installation costs. Moreover, they require little or no excavation and can be developed within almost any climate. However, it should be ensured that the quality of stored water is not affected by temperatures for instance by insulating the tank (CT, 2012). In the humid areas of Southwest China, surface tanks are also used for paddy irrigation. According to the experiences of Guizhou Province and Guangxi Zhuang Autonomous Region, the tank with a volume of 50 m^3 can irrigate 1/15 ha of paddy field. Another type of a surface storage system is a pond. A problem related to ponds is that of seepage loss, this can however be avoided by sealing or lining the pond with impervious material (Zhu et al., 2015).

Secondly, underground storage systems include different types, namely water cellars and water caves. Water cellars are underground tanks and commonly used for domestic water supply. The water cave is also an underground tank, but has the advantage of not occupying land as they are constructed in cliff sides (Zhu et al., 2015). Underground tanks are invisible and provide a cool and dark environment ensuring less microbial growth and algea. Therefore, underground storage systems can be preferential in comparison to surface storage systems when the water is used for domestic purposes. However, underground storage is about two to three times more expensive than surface storage and involves significant excavation (CT, 2012).

The most suitable choice of a storage system depends on local conditions. Environmental factors may exclude certain types of storage systems. For instance, metal tanks are not suitable in coastal areas. Several factors influence the choice for a specific storage system, including (Zhu et al., 2015):

1. The required amount of water storage;
2. Size and type of catchment area;
3. Rainfall amount and distribution;
4. Soil type and permeability;
5. Availability and cost of construction materials;
6. Availability and cost of storage designs;
7. Local skills and experience (failure of RWH systems is not always because of inappropriate use of technology, lack of training or poor management can also influence the level of success);
8. Availability of other water resources (Zhu et al., 2015).

As previously mentioned, to guarantee the quality of harvest rainwater, the storage system requires regular maintenance (WHO, n.d.).

4.1.3 Rainwater supply subsystem

The water supply subsystem can be divided into three categories: domestic water supply, irrigation water supply and water supply for other purposes such as husbandry and small industry use. For domestic use, the most simple way of fetching rainwater from an underground tank is to use a rope and bucket. However, as the bucket is often put on the ground, the harvested rainwater in the tank is easily polluted. To prevent this, an electric pump or hand pump can be used that lifts water from an underground storage system and then through the filtration system. Water delivery for irrigation is done in a similar way to domestic water delivery: by hand or electric pump or by gravity flow through a siphon. The latter is only suitable where the water level in the tank is higher than the area to be irrigated. The hand pump can be used only for small-scale drip or micro-spray system. When large quantities of water are needed for irrigation, an electric pump is required (Zhu et al., 2015).

4.2 Governance incentives for rainwater harvesting

The cost-effectiveness of a rainwater harvesting system will be a product of costs and the water yield delivered over time. The capital costs for RWH systems include the storage tanks, tank installation and fittings, concrete slab or tank stand, household plumbing and a pump. The ongoing operating costs are: energy costs for pumping, and maintenance of the tank and pump. The efficiency of a rainwater harvesting system is influenced by the roof catchment area, tank size, and the amount and regularity of the water demand. However, local rainfall amount and temporal patterns influence the yield from the RWH system. The roof catchment area has the greatest impact on yield, followed by annual rainfall and tank size. This highlights that the cost-effectiveness of a RWH system depends on an optimal configuration of the system that is suited to the local conditions (Sharma, Begbie & Gardner, 2015).

The study of Said (2014) found that the benefits of RWH in New Delhi (India) could be maximised when combined with a program encouraging water use efficiency. Furthermore, Sharma et al. (2015) found that RWH was a feasible option for improved water supply in Dhaka City (Bangladesh) provided there was assistance from the government to reduce the initial costs of investment. Moreover, in Australia researchers have found that RWH is not feasible from an economic perspective without support from the government. Although operation and maintenance costs are usually low, the capital investment costs can be high (Musayev, Burgess & Mellor, 2018). Thus, in order for groundwater users to switch to RWH systems, there should be an incentive for these people to switch to RWH. User reactions in Spain and Kenya and their level of satisfaction towards RWH systems suggest that both regulations and subsidies are good measures to advocate and expand RWH technologies for domestic use (Amos et al., 2016). In comparison to other policy instruments, subsidies are positive incentives for users that will develop a RWH system (Esteban & Dinar, 2013). Subsidies can be paid to an individual user, a business or other stakeholders to achieve certain policy goals. It can come from a national or local government, or from other parties such as non-governmental organisations (NGOs). In water management, subsidies are very common. For the implementation of a subsidy scheme it is necessary to establish a legal framework as a basis, an institutional framework for the implementation of the scheme and a series of administrative procedures to govern the development of the system (Duch & Keller, 2018).

There are many advantages to subsidies. First, participation is usually voluntarily which makes the scheme acceptable (Hellegers & Van Ierland, 2003; Esteban & Dinar, 2013). Furthermore, if the scheme is well targeted it can have a positive effect. There are also barriers to the implementation of subsidies. Subsidies are not economically efficient, and one of the main issues is that subsidy systems often suffer from a lack of clarity regarding objectives and procedures. It is thus very important that there are clearly defined rules to govern the allocation of subsidies (Duch & Keller, 2018).

4.3 Presence of conditions

This section presents the results of the assessment on the feasibility of RWH for development in the VMD, including the required physical and technical, governance and economic conditions. Subsequently, the assessment result is elaborated for each condition.

4.3.1 Physical and technical conditions

The assessment results of the presence of the physical and technical conditions are presented in the table below.

Table 7: Presence of the required physical and technical conditions for a successful development of rainwater harvesting

Variables	Physical and technical conditions	Assessment result
Availability of rainwater	Rainwater is sufficient and reliable in terms of quantity and quality	[+/-]
Availability of land	Land is available for the installation of rainwater storage systems	[+/-]
Degree of knowledge and skills	Expert knowledge is available for capturing and storing rainwater	[+]
	Skilled people are available for the management and maintenance of RWH systems	[+]
Required equipment	RWH system technologies are available in the delta	[+/-]

Availability of rainwater

The analysis of the expert interviews show that experts are questioning rainwater availability in the VMD, in terms of quantity as well as if rainwater is a reliable water resource. The Mekong Delta has a tropical monsoon climate, with a seasonal distribution of dry and wet months. The dry season usually lasts from November to April, which is characterized by little rain. The wet season lasts from May to October, and is characterized by high humidity and rainfall. The yearly average rainfall in the delta is 1733 mm and is mainly concentrated in the wet season (Deltares, 2011a). This is also where the problem lies according to the experts, because although rainwater is available it is not accessible during the whole year. This means that storage capacities should be large enough to store rainwater for the dry season. [E1] states that *"rainwater is abundant in the delta [...] and there is certainly a lot of rain, there is even too much rain in a too short of time which you cannot catch all, that is the difficulty"*. According to [E4], [E8], [E9], and [E10] although rainwater is available, it will not be enough to meet the water demand or that it is not sufficient for all purposes, as [E10] states: "*I myself would think that rainwater is not enough to meet the water demand*".

Moreover, in all climate change scenarios, rainfall tends to decrease in the dry period and to increase in the wet season. Annual precipitation is likely to decrease by 10-20% in the future throughout the delta (Stewart & Coclanis, 2011). According to [E10] it is becoming more clear that rainwater is becoming more irregular. This means that it is very difficult to forecast the weather, as it suddenly starts to rain while it is not expected. Furthermore [E7] also argues that rainwater harvesting is susceptible to climate change impacts, which can be worrisome if people have been relying on rainwater harvesting and suddenly there is an intense drought like the El Niño: *"During the last El Niño in 2015, those households relying on harvesting rainwater ran out of rainwater during the dry season, so rainwater harvesting actually has its limits. So if the climate change projections are less rainfall during periods in the dry season, those rainwater harvesting systems can be vulnerable to those climate change impacts".* In contrast, the study of Musayev et al. (2018) indicates that climate change will have little impact on the ability of RWH systems at household level. Seasonal rainfall variations can limit the amount of water available during dry periods, however it is difficult to maintain a 100% reliability. Nevertheless, the reliability can be increased in all climates by increasing the roof area and tank size.

Thus to conclude, rainwater is available but experts question if rainwater is sufficient for all purposes, and whether in the future it is a reliable resource because of climate change projections. Therefore a [+/-] is given to this condition.

Availability of land

In order to develop rainwater harvesting systems, land needs to be available for the storage systems. However, as [E1] explains it depends on where you want to use the rainwater, if it requires a lot of space. Besides where you want to use it, it also depends on the type of storage system if it requires a lot of space. According to a research conducted by Tran et al. (2010) in three communes in the VMD, rainwater was usually harvested directly from roofs and was mainly stored in 150-250 litre ceramic jars, and occasionally in plastic containers of various sizes. In the research, one of the respondents explained how a lack of containers, often due to financial limitations, restricted their ability to harvest and store enough rainwater for all of their families immediate needs: "*I always use rainwater for cooking and drinking in the rainy season. In the dry season when rainwater has been used up, I pump well water to filter and use. Rarely do I use river water. We also use well water for bathing in the dry season"* (Tran et al., 2010, p. 139). According to [E10] there is not enough room now to catch or store rainwater, because the delta is optimized for everything up to the last centimetre. But on a small-scale it could be possible. Furthermore, [E7] states that some poorer households may not even have the space for storing a large amount of water. So it thus very much depends on (1) the size of the storage system, and (2) the place of the RWH system. The assessment result given is therefore a [+/-], because for each system it should be examined whether enough land is available.

Degree of knowledge and skills

As rainwater harvesting at household level is among the primary sources of drinking water in the VMD (Özdemir et al., 2011), there is knowledge available in the delta about RWH technologies. According to [E4], [E7], and [E8] there is a long history of rainwater use, and that people have knowledge on rainwater harvesting and basic filtering techniques. This is also because ten to fifteen years ago, several NGOs had programs to promote rainwater harvesting in the VMD. Based on these expert opinions, it is concluded that this condition is present in the delta [+].

Required equipment

As mentioned in the previous sections, rainwater harvesting is a common practice in the delta and therefore (basic) equipment is available. However, experts [E4], [E7], [E8] and [E10] mention that there are no large tanks or other storage systems used in the delta to store large quantities of rainwater. This could be a limitation if rainwater needs to be stored for use during the dry season. So therefore it is again dependent on the size of the RWH system if the required equipment is available. Therefore, to conclude a [+/-] is given for this condition.

4.3.2 Governance conditions

The assessment results of the presence of the governance conditions are presented in Table 8.

Table 8: Presence of the required governance conditions for a successful development of rainwater harvesting

Variables	Governance conditions	Assessment result
Stakeholder engagement	Stakeholders are involved in the development of strategies and policy interventions that motivate the use of alternative water sources	[-]
	Information about groundwater issues is actively communicated to non-state actors	[-]
Institutional capacity	There are no regulatory constraints for the use of rainwater in the delta	[+]
	Capacity is available for the development, implementation and enforcement of regulations	[+/-]

Stakeholder engagement

In order to successfully develop RWH systems in the delta, stakeholders should be involved in the development of policy interventions and strategies that could potentially affect their daily water consumption. For instance, if the government decides to subsidize RWH systems, people should be informed about this decision. Respondents [E3], [E6] and [E9] all explained that the government system in Vietnam is top-down. The central government in Hanoi develops policies, regulations and strategies for water management. Local governments and local stakeholders are not involved in this process. However, [E9] argues that top-down governance is a good thing because everything needs to be regulated at the national government, because they can think beyond regional interests and push regulations through. In contrast [E8] argues that although there are quite some policies to support the use of less groundwater, there is no guidance from the government. So the government does not inform how action can be undertaken or involves stakeholders in the process. Therefore, this condition is not met in the delta [-].

Besides, if groundwater extraction should be reduced it is important that users have knowledge about the negative impacts of groundwater use. Thus information should be actively communicated to non-state actors about issues related to groundwater pumping. [E7] argues that there is not enough knowledge about the effects of groundwater pumping in both rural communities as in urban areas. Besides knowledge of the local government could be improved, as this is a very important link between the national government and the citizens [E7]. Furthermore, there is no public education program about the effects of groundwater pumping. To address this, [E7] mentions a simple solution: *"I get a monthly water bill from the water company every month and on the back of the water bill there is some small information system, mainly with contact details for the water company. But there is a lot of unused space, black space on the invoice. I often said to researchers why do they not use that space for a public education system. For example to say, please connect to the government water supply system because* *groundwater pumping has the effect of subsidence that means we are sinking and everybody is going to go underwater in the next twenty years if you pump groundwater".* The expert argues this is a solution, because on every monthly water bill there is a public education system that alerts households to this problem, and moreover it is more affordable in comparison to advertising on tv or radio. Furthermore, he explains "*people say the poor households do not receive the water bill, but the households that are connected to the water supply system is the one that is being educated and they know their neighbour is pumping groundwater [..]. So then me as a neighbour that does not pump groundwater will talk to my neighbour"* [E7]. Also, other experts [E8][E9] emphasize that mainly local actors are not informed about the negative effects of groundwater over-extraction. Education could then be a possible way to increase knowledge amongst these actors. To conclude, information about groundwater issues is not actively communicated to non-state actors, and therefore this condition is not present [-].

Institutional capacity

As rainwater harvesting systems are readily available in the delta, there seem to be no regulatory constraints. Furthermore, according to [E3], the local government also initiates (local) RWH projects. Atkinson, Graetz & Karsch. (2008, p. 33) argue that *"as a result of poor recognition of rainwater as an important resource and its benefits, there are no policies, regulations and guidelines related to rainwater harvesting. […]. At present, the conventional solution to deal with the shortage of water resources in cities is to find additional or alternate resources in remote areas, whereas rainwater harvesting is often viewed as a rural and informal domestic activity. In urban areas, rainwater receives attention, however, only in terms of designing and constructing drainage systems. No government resources are being invested to upscale rainwater harvesting".* This statement implies that there are also no guidelines on the required quality of rainwater for human consumption. Therefore, the regulatory framework could be improved to guarantee safe use of rainwater. However, the condition is present as there are no regulatory constraints [+].

In order to establish regulations for rainwater harvesting systems and a subsidy scheme, it is important that there is capacity for the development, implementation and enforcement of these types of regulations. According to [E3], the government system in Vietnam is top-down. For instance, the MDP was approved by the Prime Minister, but it then takes a long time before it reaches local levels of the government. But according to this expert: "*they want to do something about it. They want and try to find partnerships between different provinces, that it is more bottom-up"*. Other experts also emphasize that the government system is very much top-down, and that all regulations are made by the central government. According to [E2], the activities of MARD and MONRE overlap, as they both have the task to manage water. This means that they are sometimes in each other's way. It is also stressed by this expert that there are many regulations already, so it is important that the rules are clear. Although there is capacity available for the development of regulations, enforcement of regulations is currently poor. [E3] states the following "*They are all just poor farmers and the main goal of the government is also that people can make a living. So therefore, water may not be enforced so well. They do not want to stop or prescribe anything. And the local government may not always have the authority to enforce the rules, and of course not always have the staff to go and check local people and farmers".* Furthermore [E4] and [E6] emphasize that enforcement is poor in Vietnam, and that there are also corrupt officials which makes it even more difficult to enforce regulations. To conclude, this condition is met in a way because there is capacity available for the development and implementation of regulations, but enforcement is poor currently. Therefore, a [+/-] is given to this condition.

4.3.3 Economic conditions

The assessment results of the presence of the economic conditions are presented in Table 9.

Table 9: Presence of the required economic conditions for a successful development of rainwater harvesting

Variable	Economic condition	Assessment result
Financial capacity	Capital is available for the initial investments of rainwater harvesting systems	[-]
	Capital is available for the continuous maintenance of rainwater harvesting systems	[-]
	Capital is available to subsidize rainwater harvesting initiatives	[+]

Financial capacity

The analysis of the results on this condition clearly showed that the lack of financial capacity is one of the main barriers to developing RWH systems in the delta. As Vietnam is still a developing country, this also limits the availability of money to invest in water management technologies. Various experts [E3], [E7], [E9], [E10], [E11] state that finances are a huge barrier or even the biggest problem in Vietnam. [E11] argued that technically everything is possible in the delta, but the main question is where the money comes from and what the return is. However [E9] and [E10] also emphasize that although initial investment costs are high, if people continue using groundwater resources then the costs in the future will be even higher. To conclude, this condition is currently not present in the delta [-].

In order to incentivize the use of rainwater in the delta, the government could subside RWH initiatives. According to [E7] and [E10] the government does indeed have programs in the delta where small subsidies are provided to people with less income. And [E10] emphasizes that although subsidies are expensive, if continued in the same way, it will cost a lot of money too. So it is important to sketch the bigger picture, that people are convinced of the negative effects of groundwater over-extraction. In conclusion, the government has subsidy programs, so capital is available for this purpose. Therefore, this condition is present in the delta [+].

4.4 Conclusion

To conclude, the main barriers to developing rainwater harvesting systems in the delta are the unavailability of capital and the unreliability of the rainwater supply. The experts expressed their concerns about the impact of climate change on the availability of rainwater during the dry season, and also if there are technologies available to capture sufficient rainwater to meet the demand during the whole year. Another barrier is that the government has a top-down approach, and does not involve stakeholders in decision-making processes neither does the government inform non-state actors on groundwater issues. In contrast, there are no regulatory barriers for developing RWH systems and most physical and technical conditions are present in the delta. Furthermore, to incentivize the use of rainwater instead of groundwater, there is capital available for providing subsidies to poorer households. In the next chapter, the feasibility of the surface water use strategy is discussed.

Chapter 5
Feasibility of Surface Water Use

This chapter assesses whether the improvement of surface water quality is a feasible strategy to reduce groundwater over-extraction in the delta. First, the surface water treatment system will be elaborated, including the different treatment methods. Second, based on the presence of the physical and technical, governance and economic conditions it will be assessed whether surface water use is a feasible strategy for development in the VMD.

5.1 Surface water treatment system

Groundwater is an important resource that is used heavily worldwide, since it does not require expensive treatment and is relatively well protected from contamination (Zektser, Loaciga & Wolf, 2005). In contrast, surface water is often contaminated and needs to be treated before it has the required water quality. It typically contains high suspended solid contents, bacteria, algae, organic matter, creating bad taste and odour. In some areas, surface water can be brackish, reaching up to 8000 mg/L of salts (Lenntech, n.d.). To reduce the pressure on groundwater, surface water treatment plants can be introduced to improve surface water quality (Delpla et al., 2009). The treatment plant should be designed in such a way that it takes the water quality being treated into account (Mazille & Spuhler, 2018a). There are different sizes of plants, for instance centralised plants for urban areas that require a distribution system and semi-centralised plants that are adapted to provide drinking water to rural areas at the point of use (Mazille & Spuhler, 2018a). As mentioned previously, it depends on the quality of water how it should be treated. Therefore there is no precise method, because of the various qualities that exist.

One of the oldest and most practiced household water treatment method is boiling of surface water. According to the World Health Organization (WHO, 1997), water needs to be heated until the appearance of the first big bubbles to ensure that it is pathogen free. However, boiling of surface water is quite laborious and uses a lot of energy (Shrestha, Shrestha & Spuhler, 2018). Moreover, boiling of surface water only kills pathogens and does not remove chemical pollution or turbidity from water (Toan et al., 2013). Therefore, water should be purified through the use of surface water treatment plants to ensure it is safe for human consumption.

In general, two processes are used to treat surface water: (1) conventional treatment including clarification (coagulation, flocculation and sedimentation), filtration and disinfection; (2) advanced treatment based on ultrafiltration technology (Lenntech, n.d.). Figure 7 shows the steps of the different methods.

5.1.1 Conventional surface water treatment

The first method is the conventional treatment. Surface water undergoes many processes to make it safe to drink. When water enters a treatment plant, the first step is coagulation. Coagulation is a process where coagulants (e.g. aluminium sulphate) are rapidly mixed into the water to neutralise charges (WEF, n.d.). Subsequently, undesirable particles attract and clump together into larger particles known as flocs.

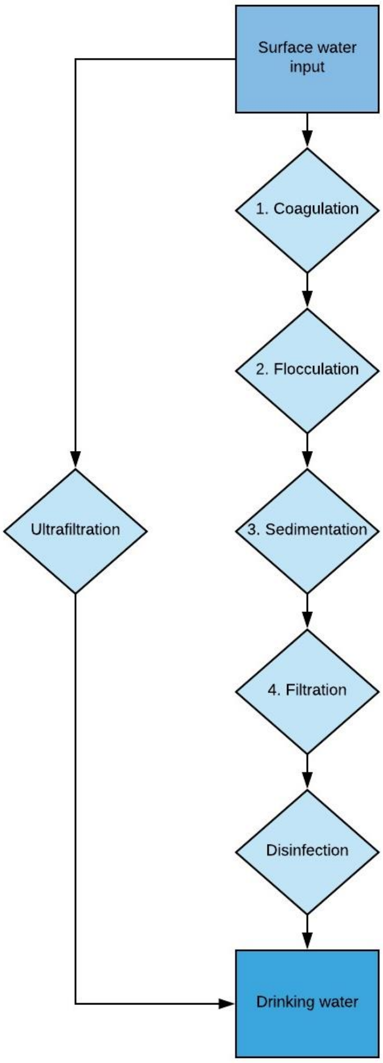


Figure 7: Steps of the conventional and ultrafiltration treatment method

The next step is flocculation. The water is mildly stirred to encourage the particles formed to agglomerate into masses large enough to settle or be filtered from solution. The disadvantages of the abovementioned methods is that the input of chemicals is required and qualified personnel is necessary for design, transfer of chemicals and treating of the sludge (Mazille & Spuhler, 2018a).

In the sedimentation phase, the flocculated water moves through a basin or tank to allow the heavy particles to settle at the bottom so they may be removed (WEF, n.d.). It removes small particulates such as sand, clay and silt, and some biological contaminants (Mazille & Spuhler, 2018a).

At the filtration stage, water is passed through a filter made of sand, coal particles or similar materials that removes particles such as silt, other fine solids and some pathogens that were not removed in the sedimentation processes. Moreover, it reduces turbidity and eventually leads to water that is crystal clear (WEF, n.d.). The most used filters are sand filters and activated carbon filters. Sand filter is a method that is mainly used for the purification of drinking water. However, both construction and operation is cost intensive and is mainly used in developed countries for the treatment of large quantities of water where land is a limiting factor and where material, skilled labour and continuous energy supply are present (Mazille & Spuhler, 2018a). Another method is activated carbon filters; there are many types of activated carbon filters that can be designed for household, community and industry requirements. Although it is relatively easy to install, energy and skilled labour are needed and the regular replacement of filter material can have high costs (Mazille & Spuhler, 2018a).

The last step is disinfection, which adds disinfectants such as chlorine and ozone to water to destroy potentially harmful bacteria or microorganisms that may be in the water (Mazille & Spuhler, 2018a). It should however be noted that some disinfection by-products can harm the environment and human health. Although disinfectants such as ozone, chlorine dioxide and ultra-violet also produce by-products, these are said to be the most environmental friendly solutions. They can still have potential health risks, which leave drinking water suppliers and consumers with a dilemma. For instance the by-products produced by chlorine disinfectants are suspected to cause cancer (WEF, n.d.). The first option is ozonation, which is a chemical water treatment technique based on the infusion of ozone into water, which is one of the most powerful oxidants. The production however requires a lot of energy and is therefore costly. The second option is ultra-violet, which is used in many areas in treatment plants. It is effective, low cost and a simple way for rapid disinfection. However, chemical or physical pollution (e.g. salinity) cannot be treated (Mazille & Spuhler, 2018a). The last option is chlorine dioxide, which can be applied at different stages of treatment (during the clarification process or as disinfection). It is frequently used to remove bad taste, odour and colour (EPA, n.d.).

5.1.2 Ultrafiltration technology

The second method is ultrafiltration (UF), which is one of the most widely used alternative treatment process for surface treatment. It has been one of the most important technology advances in water treatment systems. Compared to the conventional surface water treatment plant, it requires less land. Moreover, the conventional system consists of many steps and each step has to be controlled to get optimal perfomance. In contrast, UF is a less complex system and produces very high quality water regardless of input quality (Chew et al., 2016). Furthermore, ultrafiltration technology does not require the input of chemicals apart from the chemicals used for cleaning the membranes (Clever et al., 2000).

The ultrafiltration method is a filtration technique in which surface water is forced through a semipermeable membrane with very small pore size in order to remove suspended particles, including micro-organisms (RIVM, 2012). According to Chew et al. (2016, p. 3153) an important characteristic of UF is *"its capability to control the permeate quality by careful selection of the membrane material and pore size"*. However, a major drawback of UF systems in large-scale application is membrane fouling (i.e. contamination) which is difficult to control. Membrane fouling can affect the quality of water produced and therefore has to be replaced on regular basis. In Nantong (China), an UF treatment plant is used on industrial scale. Although research showed that the system is capable of producing very stable water quality, the issue of membrane fouling led to extra capital, labour, chemical and energy cost to the industry. Therefore, it is often considered as a more expensive technology compared to the conventional method (Chew et al., 2016).

5.2 Governance incentives for surface water use

Many people use groundwater instead of surface water because it is a relatively cheap resource and of good quality. Thus in order to reduce groundwater over-extraction, measures should be taken to motivate the use of surface water instead of groundwater. An example of a policy intervention is the introduction of taxes on groundwater use. Tax instruments penalize the use of groundwater, or the decrease in the water table level (Esteban & Dinar, 2013). It can be used to discourage users from lowering the groundwater level below a certain threshold. In this case, groundwater is treated as an economic good. The tax price of groundwater can be calculated based on a price index that includes three components: *"a natural resource component that is determined by the zone of abstraction point, the class of water quality, alternative resource availability, and the depth of the aquifer; a recovery and compensation component, which is determined based on abstraction volume and usage; and a raw water price component, which is fixed prices by the cubic metre for deep or shallow groundwater, respectively"* (Takizawa, 2008, p. 229). This is one of the available methods how groundwater taxes can be calculated, which reflects the economic value of groundwater as a natural resource based on social, economic and environmental values

In Bangkok, Thailand, taxes were introduced to reduce groundwater overexploitation and land subsidence. The groundwater tax was first implemented in 1984, where 1.0 Baht/m³ was charged.

Between 2000 and 2004, the taxes gradually increased in the `critical zones´ from 3.5 to 8.5 Baht/m³. Therefore, the total cost of groundwater use in these zones have become relatively high, which has helped in reducing groundwater over-extraction. The critical zones consisted of areas which were associated with land subsidence and groundwater depletion (Taniguchi, 2011). Subsequently, after the year 2000, the groundwater abstraction volume decreased when an increase in the rate of groundwater tax was announced (Takizawa, 2008).

According to Toan et al. (2013), effective water treatment alone will not be enough. Instead, the causes of surface water pollution also need to be addressed. This is a complex issue, as it involves many different stakeholders. Possible measures could include:

1. Reducing the use of agrochemicals, which may be discharged in surface water. Measures could for instance be awareness raising, education, incentives or enforcement of regulations;

2. Reducing the chance that pollutants reach aquatic ecosystems. For instance, through the introduction of buffer zones where possible;

3. Strengthening natural biocontrol mechanisms and thereby allow for a reduction on pesticide use;

4. Enhancing the resilience of ecosystems to deal with pollution issues, by for instance increasing biodiversity or wetlands for bioremediation;

5. Increasing awareness of consumers and promoting environmentally-friendly products on the market;

6. Accelerating programs which can provide access to safe freshwater supplies for rural areas (Toan et al., 2013).

5.3 Presence of conditions

This section presents the results of the assessment on the feasibility of surface water treatment in the VMD, including the physical and technical, governance and economic conditions. Subsequently, for each condition elaboration of the assessment result is provided.

5.3.1 Physical and technical conditions

The assessment results of the presence of the physical and technical conditions are presented in the table below.

Table 10: Presence of the required physical and technical conditions for a successful development of surface water use

Variables	Physical and technical conditions	Assessment result
Availability of surface water	Surface water is sufficient and reliable in terms of quantity	[+/-]
Availability of land	Land is available for treatment plants	[+]
	Land is available for the construction of a water distribution network	[+]
Degree of knowledge and skills	Expert knowledge is available for the treatment of surface water	[+]

	Skilled people are available for the management and maintenance of surface water treatment plants	[+]
Required equipment	Treatment technologies are available in the delta	[+]
	Electricity is available for the water treatment plant	[+]

Availability of surface water

The VMD consists of a dense network of rivers and canals, including its main rivers the Hau River and the Tien River. The rivers are wide and deep, with an average width of about 1000-1500 m and an average depth of 10-20 m. The rivers flow to the sea through nine estuaries: Tieu, Dai, Bai Lai, Ham Luong, Co Chien, Cung Hau, Dinh An, Ba Thac and Tranh De (Deltares, 2011b). The rivers have a mean annual discharge into the East Sea of approximately 475 km^3, or 13.000 m^3/s (FAO, 2011). The fluctuations in discharge are substantial and may vary between 366 and 448 billion m^3 in dry and wet years. According to the experts there is plenty of surface water, as the Mekong River is one of the largest rivers in the world. According to [E9] and [E11], the amount of water is not a problem in the delta, as the entire water demand of the VMD can easily be supplied with surface water in quantities. According to calculations provided by Deltares (2011a), the volume of water resources for the VMD is sufficient, meaning that there is excess water in each month. In an average year, water demand accounts for about 5% of the total water volume. However, [E9] and [E11] emphasize that surface water is in the wrong place in the wrong quality. Meaning that surface water is not available in the whole delta, and that the quality of surface water is degraded. Furthermore, [E10] describes that in Vietnam there was always the idea that there is so much water, because enough is supplied from upstream, *"but with dams this is decreasing too, and with water also all other ecosystem services. There are less fish and less sediment. So that is also a big problem that is going to get bigger and bigger".*

The quality of surface water varies with the seasons, because the content of soluble substances is higher during dry season and lower in the flood season. Since 1999, the Southern Institute for Water Resources Planning is monitoring surface water quality on behalf of MARD. There are 12 stations which are spread over the delta, and samples are taken each month on two moments: during high and low water level. In general, surface water encounters two major issues: high salinity and aluminium contamination. In some parts of the delta, there are systems that prevent saline water to enter the canals through the construction of sluices that can be closed when seawater rises with the tide above river water levels. Another issue is aluminium contamination. This chemical element is significantly present in the delta soils, and during periods of excess rainfall and irrigation it is flushed to the surface waters. This results in contamination of surface water in the VMD (Deltares, 2011a). Furthermore, surface water quality is also affected by wastewater resources from inhabitants that live along rivers and canals, and by emissions from industrial production. Moreover, aquaculture leads to contamination of surface water because of the production of sludge waste and wastewater containing chemicals. Lastly, agricultural activities are a major source of surface water pollution. Annually, 2 million tons of chemical fertilizers and 500,000 tons of pesticides and herbicides are used (Deltares, 2011b). These different sources of pollution all impact the quality of surface water severely in the VMD. According to [E7], communities that live along canals in the delta will no longer use surface water because they *"have seen skin diseases* *of washing and bathing in the water and that is because it is full with pesticides and chemicals from large scale use of pesticides in agriculture. So it is literally quite dangerous to use surface water almost universally throughout the delta but particularly in the rice-growing areas".*

Although the purpose of the treatment plant is to improve the surface water quality, in some places it can be difficult because of saline intrusion [E3][E5]. One of the experts worked on a project which developed a surface water treatment plant in a province in the Mekong Delta, Soc Trang, but in the dry season the plant had issues with treating surface water because of the salinity. The expert [E5] explains that "*if you look in the long term, you should go much further inland to get water. There has been a plan to get water from the Hau river, then pump that water through pipelines towards the delta. The problem is in the dry season, when the runoff of the Mekong River is limited and it could be more limited because of the construction of many dams and the increasing intrusion in the river. So you can now say that you have sufficient freshwater […] but if that is still the case in 20-50 years is the question".*

Concluding, there is currently a sufficient amount of surface water in the VMD. There are however some difficulties, including saline intrusion and water availability throughout the delta. This means that it is a location-specific strategy, or infrastructure needs to be developed to transfer the water to other areas in the delta. Therefore, the condition is not fully present as surface water is not sufficient throughout the whole delta [+/-].

Availability of land

The amount of land required for a treatment plant is dependent on the treatment method. According to [E5] and [E6] it is in terms of space possible, especially if there is a central facility that can be used by different companies. According to [E6], the construction of a treatment plant and pipe lines to transfer the water to other areas in the delta was also feasible. However, because of costs this plan was never implemented. In conclusion, land is available and therefore this condition is present [+].

Degree of knowledge and skills

The experts agree that there is a lot of expert knowledge, especially on the regional and national level. According to [E3] there are quite a lot of people that have technical knowledge, and that in Vietnam they have the same kind of specialist knowledge as in developed countries such as the Netherlands. This condition is thus present in the delta [+].

Required equipment

According to [E6] the government often installs the basic infrastructure for industries, such as an industrial park, access roads, sewage system and electric supply. Thus the required equipment is available. Moreover, costs have been reduced for treatment systems because the equipment is increasingly produced locally in Vietnam. So, ten or fifteen years ago the whole system needed to be imported but now only membrane needs to be imported. Thus, the costs of the technology can be even further reduced if membrane is produced locally [E7]. Besides the costs of electricity have also decreased because of technological innovations. According to [E10] there are also renewable energy sources available in the delta, such as wind farms. Therefore, this condition is present in the delta [+].

5.3.2 Governance conditions

The assessment results of the presence of the governance conditions are presented in Table 11.

Table 11: Presence of the required governance conditions for a successful development of surface water use

Variables	Governance conditions	Assessment result
Stakeholder engagement	Stakeholders are involved in the development of strategies and policy interventions that motivate the use of alternative water resources	[-]
	Information about groundwater issues is actively communicated to non-state actors	[-]
Institutional capacity	There are no regulatory constraints for the use of surface water in the delta	[+]
	Capacity is available for the development, implementation and enforcement of regulations	[+/-]

Stakeholder engagement

As mentioned in the previous chapter, stakeholders are not involved in the development of strategies and policies, and are also not informed about groundwater issues [E3][E6][E9]. Thus, the condition is currently not present in the delta [-].

Institutional capacity

Although there are no regulatory constraints for the use of surface water in the delta, in a report from the Department of Construction a decision is made that the plan of treating surface water and transferring it through pipes had not been developed further because stakeholders did not agree with the plan. This means that there was no institutional support for the development of this strategy. This also had to with finances, because the provinces in the South could not afford the pipelines, however upstream areas did not want to invest in the plan because they have plenty of surface water available [E5]. Also, [E11] emphasizes that a piped water system runs up against governance problems. In conclusion the condition is present since there are no regulatory constraints in the delta for the use of surface water [+].

There is capacity available for the development and implementation of regulations. However, the level of enforcement is currently not good [E3], [E4], [E6]. Furthermore, experts mention that the collaboration between the North and South of Vietnam is not very good. The central government is located in Hanoi in the Northern part of Vietnam. [E11] argues that the North and South Vietnamese history is underlying, as they were separated in the past. According to [E11] it is also because the delta is literally far away from Hanoi: "*On the one hand it gives an advantage because they can do things themselves, so a bit freer than in the Northern part in terms of socialism*. *But we also have the idea that there is more attention for the North [..] then to the South*". To conclude, there is capacity available for the development of regulations, but because the collaboration between the central and local government is not very well, this condition is not fully present [+/-].

5.3.3 Economic conditions

The assessment results of the presence of the economic conditions for the development of the surface water use strategy are presented in Table 12.

Table 12: Presence of the required economic conditions for a successful development of surface water use

Variable	Economic condition	Assessment result
Financial capacity	Capital is available for the initial investments of treatment plants for the surface water treatment plants	[-]
	Capital is available for the continuous maintenance of surface water treatment plants	[-]

Financial capacity

The analysis of the results on this condition show that the greatest barrier to the development of surface water treatment systems are the costs [-]. Since surface water is degraded, more expensive treatment systems or more sophisticated treatment systems are required. According to [E7] this is the cost-benefit that the government does that leads them to invest money on a pumping station that pumps groundwater instead on a surface water treatment plant. However, treatment systems are becoming more competitive as the equipment is largely produced in Vietnam nowadays, meaning that systems are less expensive and thus more feasible. Furthermore costs can be decreased if the treatment plant is shared among companies, which all can benefit from the treatment plant [E6].

5.4 Conclusion

The assessment results show that except one condition that is not fully met yet, all physical and technical conditions are present in the delta. This implies that technically it is feasible to develop surface water treatment systems in the delta. However, a major barrier is that surface water is not accessible throughout the whole delta, and that saline intrusion makes it more difficult and expensive to treat surface water. Thus, surface water treatment is a location-specific strategy as local conditions influence the level of success. Furthermore, the government does not involve or inform stakeholders in any way and the level of enforcement of regulations in the delta is poor. However according to the experts, the lack of financial capacity is the largest barrier for developing treatment systems in the VMD. In the next chapter, the feasibility of the wastewater reuse strategy is assessed.

Chapter 6
Feasibility of Wastewater Reuse

In this chapter it is assessed whether wastewater reuse is a feasible strategy to reduce groundwater over-extraction in the delta. First, the characteristics of wastewater reuse systems are extensively elaborated. Then, the feasibility of reuse systems is assessed based on the presence of physical and technical, governance and economic conditions required for a successful development in the VMD.

6.1 Wastewater reuse systems

It is becoming more common to reuse wastewater in the world (Shuval & Dweik, 2007). Various countries have included wastewater reuse in their water management plan, such as Australia and the USA where wastewater is used for irrigation (FAO, 1992). However, two-thirds of urban wastewater generated in the world is not treated before discharge to a receiving water body and this is particularly an issue in developing countries. A study by Satoa et al. (2013) estimated that high-income countries on average treat 70% of the generated wastewater, followed by upper-middle-income countries (38%), lower-middle-income countries (28%) and low-income countries, where only 8% of the wastewater generated is treated. The main reason for these low rates of wastewater treatment is the high cost of conventional treatment facilities. Treated wastewater can be considered as a ‘new’ water resource, which can be added to the general water balance of a country. It can substitute potable water used for irrigation or for other purposes that do not require water of drinking water quality, while releasing pressure on groundwater use (Friedler, 2001). Reuse of wastewater can provide significant environmental, social and economic benefits. It can improve the environmental status by substituting abstraction and also by minimizing the discharge of wastewater to sensitive areas. Besides, when compared to alternative sources of water supply (e.g. desalination methods), water reuse requires less investment costs and energy (EC, 2017).

One of the most important characteristics of treated wastewater is that it is a reliable resource, because it is relatively constant during the year. Urban wastewater can be one or the combination of (1) domestic effluent consisting of blackwater (excreta, urine and associated sludge) and greywater (kitchen and bathroom wastewater); (2) water from commercial organisations and institutions; (3) industrial effluent and; (4) storm water and other urban runoff. Normal municipal wastewater consists for 99% of water with only 1% of dissolved solids (Kurian & Ardakanian, 2015). Without proper treatment wastewater is however unsuitable for utilization. If wastewater is released into the environment, it is important that it is treated in such a way that the concentration in the effluents is as low as possible. Whereas, if the purpose of wastewater reuse is for agricultural practices then a certain level of nutrients is preferable because then it removes the need for fertilizers. For other domestic purposes, such as for sanitation, the pathogens (viruses, bacteria and parasites) should be removed from the wastewater. Thus it depends on the purpose of wastewater reuse to what extent water should be treated. One of the main concerns related to reuse is the potential transmission of diseases. However, with proper treatment wastewater reuse does not jeopardise public health (FAO, 1992).

6.1.1 Wastewater treatment

To reuse wastewater it is important that raw wastewater is treated, in order to protect public health and the environment. Wastewater treatment processes can be categorized into the following three:

- *Physical processes:* impurities are removed physically by for instance sedimentation, filtration or absorption;
- *Chemical processes:* impurities are removed chemically through processes such as coagulation, absorption or disinfection;
- *Biological processes:* pollutants are removed using biological mechanisms, such as aerobic treatment (Eslamian, 2016).

In general there are three steps in the treatment process, and if the water is used for domestic use or irrigation for food crops it should be disinfected as well (FAO, 1992). The treatment process is in general designed as follows:

1. *Primary treatment:* during this process the (in)organic solids are removed by sedimentation. Primary treatment is the minimum level of pre-treatment required for wastewater. If the wastewater is used to irrigate crops that are not consumed by humans, it may be considered sufficient treatment. The primary treatment tanks are round or rectangular basins and are typically 3 to 5 m deep;
2. *Secondary treatment:* the effluent is in this process further treated, to remove residual organics and suspended solids;
3. *Tertiary treatment:* this type of treatment is used when specific wastewater elements are not removed by secondary treatment, for instance the removal of nitrogen and phosphorus. Tertiary treatment can however also be combined with primary and secondary treatment;
4. *Disinfection:* if the wastewater will be used by humans, it should be disinfected. Usually, a chlorine solution is injected (FAO, 1992).

After the wastewater is treated, it can be used for multiple purposes. Reuse however means that infrastructure is needed, such as pumps, pipes, reservoirs, and so on. Thus, wastewater reuse systems may have high initial costs, especially when treatment systems are not present yet. Treated wastewater can be reused for domestic purposes, such as for toilet flushing and laundry. Furthermore, it is widely used in agriculture, because it can provide additional water for crop production and is also a rich source of nutrients for crop growth. According to Hanjra et al. (2012) most crops give higher yield with wastewater irrigation, and reduce the need for chemical fertilizer resulting in net income gains to farmers. Besides agriculture, in some countries fish and aquaculture is also an important source of food and livelihood. Wastewater can pose risks to public health if fish are consumed directly after catch. Potential health effects can be avoided if wastewater is adequately treated before use for aquaculture. A study in Suez, Egypt showed that wastewater treatment stabilization ponds can be used for growing fish with average yield as high as 5-7 metric tonnes/ha/year (Hanjra et al., 2012).

6.2 Governance incentives for wastewater reuse

According to the United Nations Environment Programme (2005), successful wastewater reuse projects are designed to reflect specific local conditions such as water demand, urban growth, socio-economic characteristics, and cultural preference as well as the institutional and policy framework. According to Po et al. (2005) public acceptance of wastewater reuse is crucial for a successful development of wastewater reuse systems. For instance, Saudi Arabia imposed a ban on the import of some Jordanian fruits and vegetables during the early 1990s based on concerns about the use of reclaimed water for irrigation (Hanjra et al., 2012). Researchers found that there was a psychological barrier when it came to using recycled water, as people found it a disgusting idea to reuse it. Another important factor influencing public acceptance is the perceived risk of using recycled water, related to public health issues when using the water. However, public acceptance is also determined by the amount of water available. In areas with water shortages, people were reported to easily accept water reuse because of the awareness of the need to conserve water (Po et al., 2005). Thus, it is important that pubic concerns are addressed through public education and awareness programs (Hanjra et al., 2012). However these educational programs should also focus on the issues related to groundwater over-extraction. If people have more knowledge about this issue, it could be that they more readily accept wastewater reuse systems.

6.3 Presence of conditions

This section presents the results of the assessment on the feasibility of wastewater reuse in the delta, including the physical and technical, governance and economic conditions. Subsequently, for each condition elaboration of the assessment result is provided.

6.3.1 Physical and technical conditions

The assessment results of the presence of the physical and technical conditions are presented in the table below.

Table 13: Presence of the required physical and technical conditions for a successful development of wastewater reuse

Variables	Physical and technical conditions	Assessment result
Availability of land	Land is available for treatment plants	[+]
	Land is available for the construction of a water distribution network	[+]
Degree of knowledge and skills	Expert knowledge is available for treating wastewater	[-]
	Skilled people are available for the management and maintenance of wastewater treatment systems	[-]
Required equipment	Treatment technologies are available in the delta	[-]
	Sewage infrastructure is available in the delta	[-]

Availability of land

According to [E5] and [E6] there is enough land available for the construction of treatment systems and for the construction of a water distribution network [+].

Degree of knowledge and skills

The results of the analysis on this condition show that knowledge and skills about wastewater treatment and reuse are not present yet. According to [E6], knowledge can be increased with education or awareness campaigns. Furthermore, this expert mentions that government officials and environmental agencies should be more attentive when wastewater is discharged in an environmental-unfriendly manner. Large industries, but also local farmers should be educated on the negative impacts untreated wastewater can have on the environment and public health. Thus, knowledge and skills are not present in the delta regarding wastewater reuse systems [-]. [E10] argues that on a small scale education and awareness programs make sense, which have a bottom-up approach, but you should ensure that it is a system that maintains itself.

Required equipment

With the current rate of economic development in Vietnam, many industrial and processing zones have been established. Very few of the factories have, as yet, local wastewater treatment systems and all wastewater is discharged to the sewage system or directly discharged into the canals or rivers. In spite of the Environmental Protection Law in Vietnam, wastewater treatment let alone reuse have not received much attention (Raschid-Sally, Hoek & Ranawaka, 2001). According to [E2], [E8], [E9] and [E10], wastewater treatment is hardly done. [E2] emphasized this by saying "*wastewater reuse is not done in Vietnam, wastewater treatment is even hardly done. This is a problem, because in some areas the water quality is very poor. Therefore, before water can be reused, it should first be treated*". There are strategies for wastewater reuse for agricultural purposes but they are not well applied in the delta. The wastewater from the urban area at the moment is just discharged untreated into the river or canals of the city. Moreover sewerage systems are also not working fully yet, so not all wastewater is collected which limits proper treatment and reuse. However, according to [E5] and [E6], there are more and more treatment facilities in the delta. Concluding, the required equipment for wastewater treatment and reuse are currently not present in the VMD [-].

6.3.2 Governance conditions

The assessment results of the presence of the governance conditions are shown in Table 14.

Table 14: Presence of the required governance conditions for a successful development of wastewater reuse

Variables	Conditions	Assessment result
Stakeholder engagement	Stakeholders are involved in the development of strategies and policy interventions that motivate the use of alternative water resources	[-]
	Information about groundwater issues is actively communicated to non-state actors	[-]
Institutional capacity	There are no regulatory constraints for the use of wastewater water in the delta	[+]
	Capacity is available for the development, implementation and enforcement of regulations	[+/-]

Stakeholder engagement

Stakeholders are not involved in decision-making processes, instead the government system has a top-down approach [-]. Furthermore, the government could inform stakeholders more about the issues related to untreated wastewater. [E1] mentioned that wastewater treatment is a social problem, because Vietnamese people think they still have enough water. Therefore, little is done regarding wastewater treatment. As mentioned in previous chapters about RWH and surface water use, non-state actors are not actively informed about groundwater issues [-].

Institutional capacity

There are no regulatory constraints for the use wastewater in the delta [+], but there are legal documents in Vietnam that include standards on domestic, livestock and industrial wastewater quality. Furthermore, there is capacity for the development of regulations concerning wastewater reuse as there are strategies implemented for better treatment of wastewater. The Prime Minister of Vietnam has issued the '*Orientation for Development of Water Sewage and Drainage Systems in Vietnam's Urban Centres and Industrial Parks Leading to 2025, and Vision for 2050'.* This plan includes that by 2025 in all urban areas in the delta, 70 till 80 percent of municipal wastewater will be collected and treated properly. Furthermore, all small villages will have centralized or decentralized wastewater treatment facilities. The Vietnamese government is thus investing in developing wastewater treatment systems (FIA, 2011) However, [E8] stated that although there are strategies concerning wastewater treatment, *"the strategy is not well applied in the delta. And then the use of wastewater from the urban area at the moment is just dumped into the river and canals in the city, and that is it. So it is not very well collected and treated and reused".* To conclude, there is a legal and regulatory framework available, however this framework is up till now not fully implemented and enforced. Therefore, a result of [+/-] is given for the presence of this condition.

6.3.3 Economic conditions

The assessment results of the presence of the economic conditions are presented in Table 15.

Table 15: Presence of the required economic conditions for a successful development of wastewater reuse

Variable	Economic conditions	Assessment result
Financial capacity	Capital is available for the initial investments of wastewater treatment systems	[-]
	Capital is available for the continuous maintenance of treatment systems	[-]

Financial capacity

The prior conditions showed that sewage systems are not reliable or readily available in the delta, nor are treatment systems available. Therefore, before wastewater can be reused, treatment facilities should be available. This means that the initial investment costs of this strategy are high. As mentioned previously, Vietnam is a developing country with limited capital available for the initial investment costs and continuous maintenance costs of the treatment systems [-]. [E10] explained this by stating: *"the big problem is the costs in Vietnam, you also see that for waste collection, for example, that is not going well at all. If you say that they are one of the biggest polluters of plastic in the sea, so they also have to take* *it out of the rivers, they begin to sigh deeply that they do not even get it organized on land, let alone to get it out of the water. So now they have the idea: go with the flow, then it is not my problem anymore because it flows away".*

6.4 Conclusion

The assessment results show that many conditions required for a successful development of wastewater reuse in the VMD, are not present currently. The main barriers identified are the unavailability of capital, and also the unavailability of sewage infrastructure and treatment systems. In the next chapter, it is assessed whether seawater desalination is a feasible strategy to develop in the delta.

Chapter 7
Feasibility of Seawater Desalination

In this chapter it is assessed whether the desalination of seawater is a feasible strategy to reduce groundwater overexploitation in the delta. First, the desalination system will be elaborated in-depth. Subsequently, based on the presence of the physical and technical, governance and economic conditions it will be assessed whether seawater desalination is a feasible strategy for development in the VMD.

7.1 Seawater desalination systems

A potential alternative to the use of groundwater is seawater. The concentration of salt in seawater varies from 500 parts per million (ppm) to 35,000 ppm. In order to use this abundant resource for drinking water or other purposes, it should first be purified. This process is also called desalination (Manju & Sagar, 2017). Seawater desalination offers a supposedly unlimited and steady supply of high-quality water without harming natural freshwater ecosystems. Therefore, it could be a suitable alternative to groundwater. In the past decade, seawater desalination facilities have expanded rapidly worldwide, as a consequence of decreasing water supplies and growing demands for water (Elimelech & Phillip, 2011). Almost 150 countries in the world use desalination technologies to produce freshwater, including for instance Saudi Arabia, Spain, Greece, China, Japan and Australia. Especially in the Middle East, desalination plants are used widely, with a desalination capability of 31.29 million m^3/day. With this large capability it leaves American and European countries behind. This is mainly because the local government in Middle East countries encourage using desalination technology, because they have abundant (conventional) energy resources which are needed to desalinate seawater (Manju & Sagar, 2017).

Many efforts have been made to develop feasible and inexpensive desalination technologies for converting salt water to freshwater. The available desalination technologies are primarily thermal and membrane processes, which will be discussed below.

7.1.1 Desalination processes

The first method is thus converting salt water to freshwater using thermal processes. During the thermal process, seawater is heated which in turn produces water vapour. This vapour eventually condenses to form distilled water. The energy used for this method can come from nuclear energy, conventional or non-conventional energy sources. There are multiple desalination processes based on thermal energy, namely multi stage flash (MSF) distillation, multiple effect distillation (MED), vapour compression (VC) (Manju & Sagar, 2017), and solar distillation (SD) (Mazille & Spuhler, 2018b).

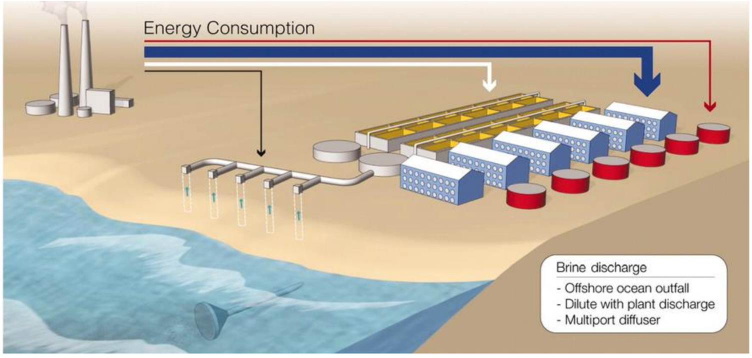


Figure 8: Illustration of a seawater desalination facility (Elimelech & Phillip, 2011)

The first technology is MSF, which is a process that sends seawater through multiple compartments, through which the water is heated and compressed to a high temperature and pressure. When the water passes through the compartments, the pressure is reduced which results in boiling of the water.

This in turn causes vapour to be produced in each compartment. This vapour is composed of freshwater and is then condensed and collected (Manju & Sagar, 2017). Of all the thermal processes, MSF is used mostly in desalination set-ups. The second method is MED, which is similar to the prior method. However, instead of using a single vessel, multiple vessels are used which makes it more efficient. The third technology is VC, which can function independently or can be used in combination with other thermal processes. VC distillation uses heat from the compression of vapour to evaporate the seawater. This technology is mostly used in small and medium-scale desalination plants. The last technology is solar desalination, which is usually used in small-scale operations in arid areas. The design of this technology varies, however the general condition is that sun provides energy to evaporate freshwater from seawater (Mazille & Spuhler, 2018b).

The membrane processes consist of Reverse Osmosis (RO), Electrodialysis (ED) and Nanofiltration (NF). MSF (discussed above) and RO are mainly used for seawater desalination, sharing about 88% of the total installed desalination capacity (Mazille & Spuhler, 2018b).

The first technology is ED, which removes salts from the water using membranes that allow the passage of either negatively or positively charged ions. The second technology is NF, which is the most recent developed pressure-driven membrane process. In this process, seawater is heated to increase its vapour pressure. The hot water vapour passes through the pores of the membranes, which is subsequently condensed on a cooler surface to produce fresh water. The last and most used method is the RO, which is a process (see Figure 9) which uses a pressure gradient as the driving force to move high-pressure sea water through a membrane that prevents the salt from passing (Mazille & Spuhler, 2018b; PIW, n.d.).

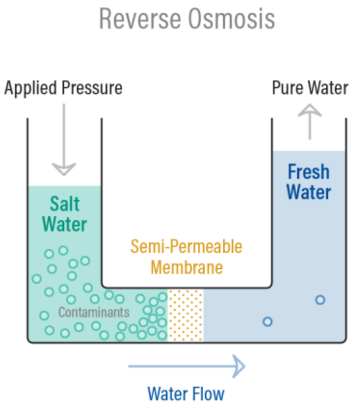


Figure 9: The process of reverse osmosis which transforms salt water to freshwater using a semi-permeable membrane (PIW, n.d.)

7.2 Governance incentives for desalinating seawater

The costs of desalinated water have decreased considerably over the years, as a result of reductions in cost of equipment, reductions in energy consumption and advances in system design and operation. The main costs of desalination facilities are capital costs (e.g. purchase cost of equipment, land, construction, management overheads and contingency costs) and annual operation costs. However, the costs vary depending on the size and type of desalination plant, the source and quality of incoming saline water, the plant location, site conditions, qualified labour, energy costs and plant lifetime. Although the costs have dropped, it is important to note that the costs of desalination techniques still remain higher than other alternatives in most regions of the world (Zhou & Tol, 2005).

Moreover, desalination processes are accompanied by negative impacts on the environment. Desalination plants require energy; one of the sources is thermoelectric energy. This energy source leads to the emission of air pollutants and greenhouse gases that further aggravate climate change. The carbon footprint of desalination plants can thus be substantial, especially concerning large-scale facilities. In order to minimize greenhouse gas emissions, renewable energy sources could be used if present. The desalination facilities can also have a negative impact on marine systems. For instance, seawater intake could lead to the impingement and entrainment of juvenile fish. However, this is not clear given the naturally high mortality of larval organisms. Open surface intake can reduce impingement, and entrainment can be minimized or eliminated by taking the seawater in far from biologically productive areas (e.g. in deeper water and further offshore) (Elimelech & Philip, 2011). Another impact of the desalination facility is the output it generates, which is also referred to as the by-product called brine. The brine waste is a concentrate salt solution which has a high salinity level (Mazille & Spuhler, 2018b). The brine waste is about twice as much saline than seawater and the chemicals used pose environmental risks to organisms when discharged into the marine system (Elimelech & Philip, 2011). Therefore, when considering options for massive implementation of desalination facilities, environmental impacts will have to be internalized and to be minimized for instance by planning (Zhou & Tol, 2005).

Thus, it is important that there are regulations available that minimize the negative impacts of desalination systems on the environment. Furthermore, in order for desalination facilities to be competitive to groundwater, it is important that there is awareness of the issues related to groundwater over-extraction and that there are governance incentives to use seawater instead of groundwater. The government can for instance invest in the desalination facilities and at the same time prohibit the use of groundwater all together or for certain purposes. Prohibitions are top-down instruments that can be used to achieve more sustainable groundwater use. For instance, in Tokyo, regulations were introduced that restrict groundwater use. The laws ban both new and existing wells that fail to meet certain requirements, and are thus mainly aimed at the structural design of pumping facilities. As pump performance improved over the years, a growing number of small pumping facilities became exempt from the law or decree on pumping groundwater (Sato, Haga & Nishino, 2006). The implementation and enforcement of a regulation that prohibits the use of groundwater can be troublesome in many respects. First, it is necessary that the compliance with restrictions can be monitored, and non-compliance can be sanctioned. Thus, prohibitions demand human and financial resources to control the compliance. This means that legislation must be clear, so that authorities can control the forced restrictions, and also that it is clear what the sanctions will be for the people that do not comply. Water prohibition can be combined with other measures such as awareness raising, training and education, and the implementation of water-saving technologies at different user levels (Duch, 2018).

7.3 Presence of conditions

This section presents the results of the assessment on the feasibility of seawater desalination in the delta, including the physical and technical, governance and economic conditions. Subsequently, for each condition elaboration of the assessment result is provided.

7.3.1 Physical and technical conditions

The assessment results of the presence of the physical and technical conditions are presented in the table below.

Table 16: Presence of the required physical and technical conditions for a successful development of seawater desalination

Variables	Physical and technical conditions	Assessment result
Availability of seawater	Seawater water is sufficient and reliable in terms of quantity and quality	[+]
Availability of land	Land is available for desalination systems	[+]

	Land is available for the construction of a water distribution network	[+]
Degree of knowledge and skills	Expert knowledge is available for the desalination of surface water	[+/-]
	Skilled people are available for the management and maintenance of desalination systems	[+/-]
Required equipment	Treatment technologies are available in the delta	[+]

Availability of seawater

There is abundant seawater available in the VMD and it is of constant quality [E5]. The analysis of results on this condition show that desalination facilities are not only appropriate for seawater, but can also be used to desalinate surface water, for instance river water in the delta. Surface water is becoming increasingly saline in the VMD, because of saltwater intrusion [E1], [E3], [E5]. Salt water is mainly available in coastal areas, which makes it difficult for other regions in the delta to access the desalinated water. To solve this issue the water could be transmitted to other areas through pipelines. However, [E3] argues that strategies are always location-specific, as you cannot apply them everywhere. It is thus more useful to do per region. To conclude this condition is present in the delta as there is plenty of seawater and of good quality [+].

Availability of land

The amount of land required is dependent on the size of the desalination facility. According to [E5] and [E6] it is in terms of space possible, especially if there is a central facility. According to [E6], the construction of pipe lines to transfer the water to other areas in the delta is also feasible in terms of land required. This condition is thus also met [+].

Required equipment

According to [E7] the costs have been reduced for desalination systems because the equipment is increasingly produced locally in Vietnam. Furthermore, the costs of electricity have decreased because of technological innovations, "*we are maybe at a point where technology is becoming more affordable, that is the case for renewable energy*". Thus, the required equipment is also available in the delta [+].

Degree of knowledge and skills

According to [E3] there is (technical) knowledge on a regional level, so these people should also be responsible for the development of desalination facilities. However, desalination systems are not common in the delta so there are not many skilled workers available. [E7] states that there is knowledge about simple technologies such as rainwater harvesting, however knowledge is lacking on the more difficult technologies such as desalination systems. Therefore, both conditions have a result of [+/-] because a certain level of knowledge is available, but it can be improved.

7.3.2 Governance conditions

The assessment results of the presence of the governance conditions are presented in Table 17.

Table 17: Presence of the required governance conditions for a successful development of seawater desalination

Variables	Governance condition	Assessment result
Stakeholder engagement	Stakeholders are involved in the development of strategies and policy interventions that motivate the use of alternative water resources	[-]
	Information about groundwater issues is actively communicated to non-state actors	[-]
Institutional capacity	There are no regulatory constraints for the use of seawater in the delta	[+]
	Capacity is available for the development, implementation and enforcement of regulations	[+/-]

Stakeholder engagement

As mentioned previously stakeholders are not informed or involved in decision-making processes [-] that may affect them. In contrast to the technical knowledge, there is not enough knowledge about groundwater issues as this is not actively communicated to non-state actors. The national government does seem to have knowledge about issues related to groundwater over-extraction, because they have recently implemented a new law that prohibits groundwater use in the entire delta. But the knowledge of local people about these issues varies a lot, *"in general I do not think they have this knowledge. This is also because 5/6 years ago it was forbidden for people of the government to talk about land subsidence because it did not exist"* [E11]. Thus, in the past it was forbidden to discuss issues such as land subsidence, meaning that information was not shared with non-state actors. Therefore, this condition is currently not present in the delta [-].

Institutional capacity

There are no regulatory constraints to use seawater in the delta [+]. As mentioned previously, the government has recently developed a regulation that prohibits the use of groundwater in the delta so there is capacity to develop regulations. However, at the same time they do not specify how this regulation should be implemented or enforced [E11]. According to the expert, the national government accepts that groundwater is the main driver of land subsidence. In contrast, the local government in the South are still sceptical, because *"they have a dual role because they also earn money from it. In their network there are many people who use groundwater and if they no longer may pump then they have messed up their own network"* [E11]. Thus, in order to really enforce that groundwater is prohibited, the support from the local government is required. Therefore, this condition is not fully present yet in the delta [+/-].

7.3.3 Economic conditions

The assessment results of the presence of the economic conditions are presented in Table 18.

Table 18: Presence of the required economic conditions for a successful development of seawater desalination

Variable	Economic condition	Assessment result
Financial capacity	Capital is available for the initial investments of desalination systems	[-]
	Capital is available for the continuous maintenance of desalination systems	[-]

Financial capacity

The largest barrier to the development of seawater desalination technologies in the VMD are the high costs for the initial investments as well as for the maintenance of the systems. In the Vietnamese context, this is a very expensive technology [E11]. According to [E6] this kind of technology is only viable for the use of drinking water, because then costs can be recovered because drinking water is paid for. Also, [E11] emphasizes that technically every strategy could be feasible however desalination of seawater is not very valuable from an economic point of view. Therefore, it does not seem to be feasible in terms of costs, because both conditions are not present in the delta [-].

7.4 Conclusion

The assessment results show that technically it is possible to desalinate seawater in the delta, because seawater is abundant and there is land available for the facilities. Seawater is however only available along the coast which makes it a location-specific strategy. It is possible to transfer the water through pipelines, however this will increase the costs of the system significantly. Moreover, skills and knowledge on the implementation and maintenance of the systems are lacking because it is a relatively complicated technology. In comparison to the physical and technical conditions, the governance and economic conditions are less present in the delta. The two main barriers are the lack of financial capacity for the development of desalination facilities and that non-state actors are not involved in the development of regulations and strategies, and informed about groundwater issues. In the next chapter, the feasibility of the managed aquifer recharge strategy is assessed.

Chapter 8
Feasibility of Managed Aquifer Recharge

In this chapter the feasibility of managed aquifer recharge is assessed. First, the strategy will be explained in-depth, including the different water resources that could be used for recharge. Subsequently, based on the presence of the physical and technical, governance and economic conditions it will be assessed whether MAR is a feasible strategy for development in the VMD.

8.1 Managed aquifer recharge systems

Aquifers are replenished naturally as rainwater drenches through the soil to the aquifer below or by infiltration from streams. There are various methods that can be used to recharge an aquifer, three types of human activities that enhance aquifer recharge are identified in literature. First, recharge can be unintentional for instance resulting from leaking water pipes. Second, unmanaged recharge (e.g. through storm water drainage wells). Lastly, aquifer recharge can be managed. The latter is also called 'Managed Aquifer Recharge' (MAR), which includes the purposeful recharge of water to suitable aquifers for subsequent recovery or to achieve environmental benefits. MAR can be used to store water from various sources, such as treated wastewater, water from watercourses, desalinated seawater, rainwater, storm water or groundwater from other aquifers (Dillon et al., 2009). It is used for various reasons, such as for the securing and enhancing of water supplies, improving groundwater quality, reducing or stopping significant land subsidence, and preventing salt water from intruding into coastal aquifers (Rambags et al., 2013).

There are several methods available for MAR in order to meet the diverse local conditions. Thus, the system is adapted to the local situation and is in general dependent on the type of aquifer, topography, land use and intended use of the (recovered) water. In areas where physical attributes are similar, it is common to find comparable recharge systems. Whereas, in other areas different systems are used (Dillon et al., 2009).

The precondition of MAR is that there is a large enough aquifer and water of suitable quality in sufficient quantity, an infiltration area that is of sufficient size and good permeability of the soil. In general, a distinction is made between two types of aquifers. The first type is the confined aquifer with a low permeability layer, which MAR requires injecting water through wells. The second type is the unconfined aquifer that allows water to infiltrate through permeable soils, where recharge can be enhanced by basins and galleries. Figure 10 and 11 show the seven elements that are common to each system: (1) capture zone, (2) pre-treatment, (3) recharge, (4) subsurface storage, (5) recovery, (6) post treatment, and, (7) end use (Dillon et al., 2009).

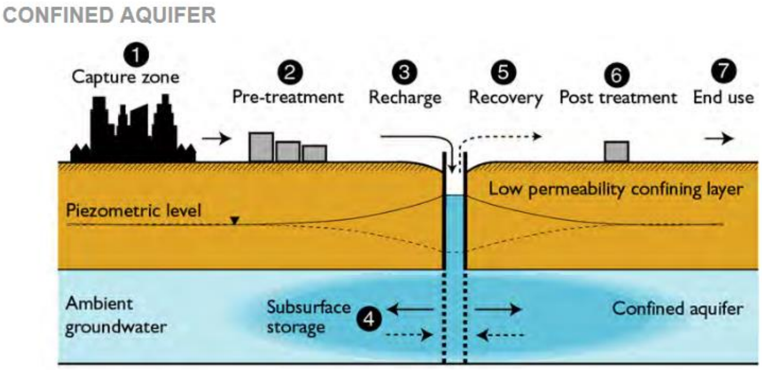


Figure 10: showing a confined aquifer with the aquifer storage and recovery method (ASR) (Dillon et al., 2009)

Many methods require low levels of technology and can be (and have been for centuries) implemented with little engineering knowledge. There are however differences between the methods considering implementation difficulty, for instance the use of (sand) storage dams or injection using the aquifer storage and recovery method is more difficult. Moreover, knowledge is required of the physical, hydraulic, geochemical and microbiological processes and how to manage them (Gale, 2005).

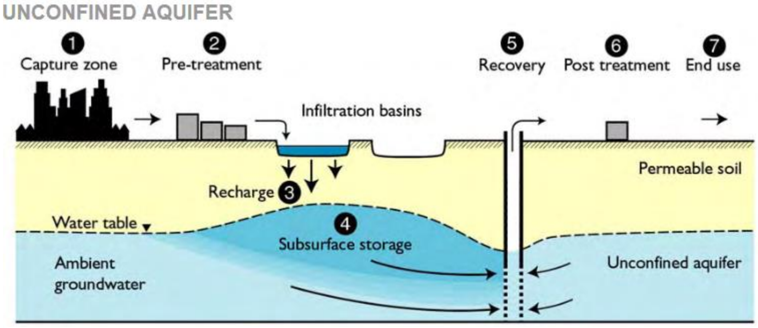


Figure 11: *showing an unconfined aquifer with the soil aquifer treatment (SAT). (Dillon et al., 2009)*

8.1.1 Methods for managed aquifer recharge

There are a large number of methods used for MAR internationally, of which the following are used most frequently (Dillon et al., 2009).

The first method is *aquifer storage and recovery (ASR),* which is defined as "*the storage of water in a suitable aquifer through a well during times when water is available and recovery of the water from the same well during times when it is needed*" (Zuurbier et al., 2013, p 1). This technology injects rainwater, surface water and/or treated wastewater in aquifers (see Figure 10). ASR is often considered the technology of choice in the world because of various reasons such as that water can be stored for extended periods of time and recovered as needed, water is well preserved and is protected from external influences. ASR is used in areas where the original groundwater quality is poor due to high salinity levels, or where the quality is suitable but where the aquifer is overexploited which in result can cause damage. For instance, in the Netherlands this technology is primarily applied at drinking water companies and in the greenhouse sector, where large amounts of rainwater are captured on a greenhouse roof and used as a low-cost source of water for irrigation (Zuurbier et al., 2013).

The second method is *aquifer storage, transfer and recovery (ASTR),* which involves injecting water into a well for storage, and recovery from another well. ASTR is often used to achieve supplementary water treatment in the aquifer by extending the residence time in the aquifer (Dillon et al., 2009). This technique is often used when groundwater is deep, or in mountainous areas, or when existing land use makes other techniques impractical or too expensive (Demeau, n.d.).

Another method to recharge water is by using *infiltration ponds,* which are either excavated or the water is directly flooded on land surrounded by a confining ditch. The pond retains the water until it has infiltrated to the underlying unconfined aquifer. Infiltration ponds are often constructed in areas with sufficient permeability and storage capacity of the targeted aquifer. In Europe, infiltration ponds are often combined with bank filtration to increase the quantity of water that can be abstracted (Demeau, n.d.).

Similar to infiltration ponds is the *soil aquifer treatment (SAT*) method, however treated wastewater is used as the water source (including precipitation, blackwater, greywater and treated water). SAT is used to enter wastewater through an infiltration basin or an injection well (see Figure 11). As the effluent moves through the soil and aquifer, the quality can improve significantly through physical, chemical and biological processes. Subsequently, the water is stored in the underlying (unconfined) aquifer for reuse. The suitability of SAT is closely related to the local conditions, including the characteristics of the aquifer and the recharge source, soil type and purpose of water. In general, SAT systems require a large surface area for infiltration of the wastewater into the aquifer (Tratschin, 2018).

The following method is *bank filtration,* which abstracts water from aquifers that are connected to a surface water body, in most cases a river or riverine system. By pumping from wells to a surface water body, the groundwater table is lowered and water from the surface water body infiltrates into the aquifer. As the water flows through the soil, it is filtered and its quality hence is improved (Tratschin & Spuhler, n.d.). The factors that determine the success of infiltration schemes is the quality of the surface water, and the permeability of the river and of the formations next to the surface water body (Gale, 2005). Bank filtration provides approximately 50% of potable water supplies in the Slovak Republic and 45% in Hungary. For the operation of a bank filtration system, the availability of surface water is essential. Moreover, it is important that the groundwater level in the surroundings of the bank filtration well does not decline below the threshold because of the aquifer recharge system (Tratschin & Spuhler, n.d.).

The last methods include *sand storage dams and subsurface dams,* which store water under the ground. A sand dam is a small dam that is built into the riverbed of a seasonal sand river. Seasonal available water is stored beneath sand. A subsurface dam hinders the groundwater flow of an aquifer and water is stored below ground level. Both dams are suitable for rural areas with arid or semi-arid climates, as seasonal water is stored and can be used during dry periods (Gur & Spuhler, 2018).

8.1.2 Potential water sources for recharge

Groundwater, where unaffected by anthropogenic impacts, usually has good quality from the microbiological, chemical and turbidity perspectives. However, when aquifers have been overexploited the water quality eventually deteriorates. When considering the impact of recharge it is thus important to understand the natural quality of groundwater, the impact of human activities and the processes that impact the subsequent quality. Monitoring systems can be used to control the quality of groundwater in order to avoid undesirable impacts. It is however important to note that water quality requirements are less strict for irrigation then for domestic purposes (Gale et al., 2002). Therefore, also the purpose of aquifer recharge should be kept in mind.

A prerequisite for MAR is the availability of water of suitable quality, in sufficient quantity. Several sources of water can be considered for use as recharge water, including surface water, runoff water, treated wastewater or potable supply water (Gale et al., 2002).

Surface water

Depending on the local climate, surface water can be used as source of recharge water. River water can be diverted to adjacent recharge facilities or canalized to distant facilities (Gale, 2005). It is however important to consider the quality of surface water before using it as recharge water. For instance, river water can carry considerable amounts of silt or industrial waste discharges. Water from polluted rivers (or lakes) should therefore first be treated prior to recharge as it otherwise can result in clogging. It is also possible to use infiltration basins, which are used to improve the quality of water through biochemical and physical processes as the groundwater is recharged (Gale et al., 2002; Gale, 2005).

Surface water is predominantly used as a source because there are different MAR techniques available that enable the use of surface water, and in many countries laws exist about the use of surface water. Besides river water, sea water is also a recharge source. It should be desalinated before using it, but desalinated seawater is increasingly used in the world because of improved techniques that have decreased production costs. It is almost never used for MAR, because relatively small quantities are required and desalinated water is very costly (Jakeman et al., 2016).

Storm water runoff
Another source of recharge water is storm water runoff. Especially in urban areas, large quantities of storm water runoff are generated. However, the runoff is variable in quantity with for instance peak discharges after heavy rainfalls. To acquire a consistent supply, infiltration ponds can be used. Besides quantity variability, storm water runoff also highly differs in quality. The quality is affected by for instance atmospheric deposition on catchments, road surface accumulation, industrial runoff and waste from animals. The best quality runoff water is from rooftops, which can be used immediately to recharge groundwater. In contrast, runoff from agricultural areas can contain pesticides and fertilisers and is therefore not suitable to use immediately for recharge purposes. This runoff should first be treated before using it as a recharge source (Gale et al., 2002).

Treated wastewater
It is also possible to use treated wastewater as a recharge source. The production of treated wastewater is relatively stable over time. However, wastewater is of low quality and requires substantial treatment before it is of acceptable quality for aquifer recharge. It depends on the wastewater source how contaminated the water is. Contaminants are mainly found in wastewater produced by industrial and agricultural activities, including for instance pesticide residues and suspended solid (Gale, 2005).

Potable water
A major source of recharge water is potable water, which is mainly used in the ASR method. The high-quality treated water is injected through wells, *"into confined aquifers to create a bubble of potable water in the aquifer. These bubbles can be created in non-potable aquifers by displacing the native water"* (Gale et al. 2002, p. 25). This method is usually implemented near treatment systems as proximity to the recharge water minimizes costs (Gale, 2005).

8.2 Governance incentives for managed aquifer recharge

According to the research of Rupérez-Moreno et al. (2017), MAR systems can provide various benefits, including the relatively low costs for storage, an increased volume of stored water and the improvement of water quality. Furthermore, MAR schemes are usually feasible from an economic perspective when no other alternatives are available that are more cost-effective, and when the water is used for high-value activities. In dry areas where groundwater is overexploited while irrigation demands are increasing, the profitability of the MAR system increases because the environmental benefits of artificial recharge are taken into account (Rupérez-Moreno et al., 2017). In order to successfully develop MAR systems, the recharge water should be available near the aquifer site in order to ensure a steady supply and limit potential transport costs. Furthermore, succesful development depends on the local hydrogeological conditions. Water should be able to infiltrate into the aquifer, and the aquifer should have the capacity to store the infiltrated water. Therefore, MAR projects should be situated in areas which have low permeability and high storage capacity. Moreover, the quality of the recharge water should be compatible with the aquifer potential. In some countries and areas (e.g in Europe), there are laws which state that groundwater should be prevented of pollution. Knowledge should thus be present about the regulatory framework before a MAR project is developed (Jakeman et al., 2016).

Moreover, according to Dillon (2011) there are seven factors that support a successful development of a MAR project:

1. Maps showing the availability of aquifers that are suitable for recharge;
2. Local demonstrations and sharing of information;
3. Guidelines on MAR to protect health and the environment;
4. Water allocation policies that incorporate MAR;
5. Integrated water resources planning and management;
6. Stakeholder engagement;
7. Capability training on how MAR works (Dillon, 2011).

To ensure that the aquifers are replenished in an effective manner, the government can introduce groundwater protection zones. A groundwater protection area is defined as *"an area around a drinking water supply (the size and extent of which is given by the catchment area of a well or spring), which has restrictions on land use and human activities"* (El-Naqa & Al-Shayeb, 2009, p. 2388). It has been adopted in a number of countries, and is especially used to protect groundwater quality. The hydrogeologic characteristics of an aquifer determine the size and shape of the groundwater protection area. The following six steps should be considered when developing a groundwater protection zone (Nel et al., 2009):

1. *Involve stakeholders*: all stakeholders (e.g. local authorities and groundwater users) should be involved in the process to make sure that the groundwater protection zone plan will be successful. It is also important to educate users in order for them to recognize risks, and also that they have knowledge that it is to their own benefit that aquifers are protected against overdraft and pollution. Furthermore, information should be gathered on cultural and social characteristics, for instance to identify users that are dependent on groundwater;

2. *Define aquifer characteristics*: the characteristics of the water supply should be defined, as well as ecosystem dependence of aquifers. This will help to locate the aquifers that are vulnerable to overdraft and contamination;

3. *Identify potential threats:* the potential threats that could harm the sustainability of aquifers should be identified, so that these can be monitored. For instance, it should include the point and non-point sources of contamination as well as activities that impact quantity such as urban development;

4. *Protection zone delineation*: when the protection zones are defined, a balance between economic and ecologic benefits should be achieved. For instance, if the protection zone covers a large area, the local community could be affected in terms of economic development. Therefore, it is very important that these impacts are identified before delineating protection zones;

5. *Database of protection zones:* in order to build an effective system of aquifer protection zones it is of crucial importance to document all delineated protection zones, as this will increase the knowledge present on the areas;

6. *Monitoring of protection zone status:* another essential component of groundwater protection zones is that the water level and quality are monitored. First, the initial conditions should be assessed and

when the protection zones are implemented, monitoring systems can be used to assess the effectiveness of the protection measure (Nel et al., 2009).

8.3 Presence of conditions

This section presents the results of the assessment on the feasibility of managed aquifer recharge in the VMD, including the physical and technical, governance and economic conditions. Subsequently, the assessment result is explained for each condition.

8.3.1 Physical and technical conditions

The assessment results of the presence of the physical and technical conditions are presented in Table 19.

Table 19: Presence of the required physical and technical conditions for a successful development of managed aquifer recharge

Variables	Physical and technical conditions	Assessment result
Availability of recharge water	The recharge water source is sufficient and reliable in terms of quantity and quality	[+/-]
Availability of land	The land surface is appropriate for managed aquifer recharge	[+/-]
Degree of knowledge and skills	Expert knowledge is available on the characteristics of the aquifers in the delta	[+/-]
	Expert knowledge is available for monitoring the groundwater wells and injecting water into the aquifers	[-]
	Skilled people for the management and maintenance of MAR systems are available	[-]
Required equipment	Equipment is available for the infiltration or injection of water into the aquifer	[+]

Availability of recharge water

In the VMD different water resources are available that could be used for recharge, such as rainwater, surface water, seawater and treated wastewater. It is an option to use surface water for recharge, however the quality of river water is degraded in the delta [E6]. Thus, surface water should be treated before it is used for recharge in order to protect the quality of groundwater. As mentioned in Chapter 6, wastewater is not treated throughout the whole delta, so it is not yet possible to use this water source for recharge. Another option is seawater, but this source needs to be purified first. As this is an expensive technology, it is not appropriate for MAR. Another option is the use of rainwater, which is often of good quality so it will not affect the quality of groundwater in the aquifer, which is also mentioned by experts as a potential source for MAR systems [E1][E11]. It is also a possibility to link rainwater harvesting systems to managed aquifer recharge systems [E1]. However, the issue with rainwater is that it is not available during the whole year and that it is susceptible to climate change. Therefore, this condition is not fully present yet in the delta [+/-].

Availability of land

According to [E1] and [E11], natural recharge in deep aquifers is not possible, because of clay surfaces which leads to a too slow infiltration. Therefore, water resources should be injected. This is possible, but more difficult and expensive than infiltration. According to [E1] it is easier to infiltrate water into sand dunes. However, [E9] argues that *"if you have a lot of sand, you do not have as much land subsidence".* To conclude, it is possible to inject or infiltrate water in the delta however local conditions determine the level of complexity [+/-].

Degree of knowledge and skills

It is important that there is knowledge about groundwater resources and the characteristics of aquifers, before infiltrating or injecting recharge water into an aquifer. According to [E1], local governments have monitoring systems which they use to monitor wells, so data is gathered about groundwater. However, still not enough knowledge is available on groundwater use and who uses groundwater [E1]. Therefore, knowledge is present up to a certain level, but it can be improved for instance by obtaining information about who uses the groundwater and for what purpose [+/-].

Although there are small-scale experiments in the delta with MAR projects, there are still problems associated with the technology which are not solved. For instance there is not enough knowledge about the problems that occur when water is injected into aquifers [E1]. So even though there are initiatives to increase knowledge, at this moment there not enough expert knowledge and skills are available to develop MAR projects [-]. This is also highlighted by [E8]: *"groundwater recharge is something we can think about, but the problem for me at the moment is that if we do not use the right techniques the groundwater is polluted. This is difficult because you do not see changes in groundwater obviously, you will see it after recharge how big the impact is".*

Required equipment

For a MAR project equipment is required, such as basins and injection technologies. Infrastructure is also needed to transfer the recharge water to the aquifer. [E1] explains this by stating: "*Managed aquifer recharge is a possibility, but it does require a lot of infrastructure. What you are trying to do in mainly to capture the excess water that would normally flow away. However all the channels that are used for rice cultivation, can then also be used to ease supply to a point where water is injected".* As the expert explains, the channels that are already available can be used which also minimizes the amount of infrastructure needed. Furthermore, a pump is needed for injection into the well, but this equipment is also available in the delta [E11], as well as energy. There are already small-scale initiatives [E1] for MAR, which also implies that equipment is available [+].

8.3.2 Governance conditions

The assessment results of the presence of the governance conditions are presented in Table 20.

Table 20: Presence of the required governance conditions for a successful development of managed aquifer recharge

Variables	Governance conditions	Assessment result
Stakeholder engagement	Stakeholders are involved in the development of strategies and policy interventions that motivate the use of alternative water resources	[-]

	Information about groundwater issues is actively communicated to non-state actors	[-]
Institutional capacity	There are no regulatory constraints in the delta	[+/-]
	Capacity is available for the development, implementation and enforcement of regulations	[-]

Stakeholder engagement

For managed aquifer recharge systems it is of crucial important that the water that is infiltrated or injected into the aquifer is of good quality. This thus requires that stakeholders are aware of issues that could potentially affect the water quality in the aquifer. The previous chapters however showed that information about groundwater issues is not actively communicated to non-state actors and that stakeholders are not involved in the development of policies and strategies. Therefore, these conditions are not present in the delta [-].

Institutional capacity

Recently, regulatory constraints have been introduced for groundwater use in the delta [E11], as a new law is enacted that prohibits the use of groundwater. This means that managed aquifer recharge activities are limited because it is not allowed to use the groundwater, it can only be used for storage. However at the same time [E1] and [E8] stated that there are various projects for MAR. [E8] stated: *"they are thinking of recharging the groundwater body. At this moment this kind of activity is quite well-supported by some companies, and these activities are also advised by some local governments"*. This could imply that this condition is present, but because of recent developments in the regulatory framework it is not clear yet if this will have constraints on MAR projects [+/-].

Secondly, to ensure that good quality water is injected or infiltrated in the aquifer, there should be a system available that enforces regulations. According to experts [E4] and [E6] the level of enforcement of water regulations is very low in the VMD. However it differs per region and if someone is appointed for enforcing regulations, and whether "*he actually enforces the rules or fills his wallet*" [E4]. Therefore, this condition is not present yet in the VMD [-].

8.3.3 Economic conditions

The assessment results of the presence of the economic conditions are presented in Table 21.

Table 21: Presence of the required economic conditions for a successful development of managed aquifer recharge

Variable	Economic conditions	Assessment result
Financial capacity	Capital is available for the initial investments of managed aquifer recharge	[-]
	Capital is available for the continuous monitoring and	[-]

	maintenance of managed aquifer recharge projects	

Financial capacity

Little information exists on the actual cost of aquifer recharge and storage facilities, as it depends on local conditions. According to [E1] there have been multiple pilot projects in the delta for MAR, but eventually it is not implemented further because of the investment costs. Because there is a lot of clay on the surface in the delta, water cannot be infiltrated because it needs to pass the clay first. This means that injection wells need to be developed, which makes it more expensive. So to inject in deep aquifers (50-100) is expensive in the delta. An alternative could be to infiltrate water into sand dunes as this is easier and less expensive [E1]. However [E9] mentions that sand dunes are indeed easier to infiltrate, however in those areas there is not as much land subsidence so it may not be necessary to implement MAR systems there. Furthermore, [E9] emphasizes that *"it is really only a small-scale solution for very high urban density, for example the centre of Ho Chi Minh city and perhaps the centre of Can Tho. That kind of scale levels but not for the rest of the Mekong Delta. My suspicion would be that 95% of the Mekong Delta is too thinly populated to do Managed Aquifer Recharge".*

At the moment there is not enough financial capacity to invest and maintain MAR systems [-], however it could be more financially attractive in cases where there is an economic system with more money: *"for example for drink water supply is being paid for, but also for the intensive production of shrimp where there is a lot of consumption and a lot of added water per cubic meter as a result of that shrimp culture. If the shrimp farmer will implement an aquifer infiltration system it should need to recover the costs with shrimp cultivation".* In terms of funding there are opportunities in the World Bank program to start experimenting with these kind of techniques [E6].

8.4 Conclusion

The assessment results show that most of the physical and technical, governance and economic conditions are not present in the delta. The main barriers for developing managed aquifer recharge systems in the VMD are the costs, unavailability of knowledge and skills, and that stakeholders are not involved in the development of strategies and policies. Furthermore, local characteristics influence the level of success of MAR, for instance soil characteristics and the availability of good quality recharge water play a very important role in whether the strategy can successfully be developed in the delta. In the next chapter, a conclusion is provided on the feasibility of all prior strategies. Moreover, methodological limitations are elaborated, and recommendations on feasible strategies to reduce groundwater over-extraction are presented.

Chapter 9

Conclusion and Recommendations

This chapter covers the conclusions of this research and addresses the main research question. Furthermore, limitations of this study are discussed. This chapter ends with recommendations for future interventions in the delta as well as for further research.

9.1 Presence of conditions in the Vietnamese Mekong Delta

This research set out to assess the feasibility of potential strategies that can reduce groundwater overexploitation in the VMD, by addressing the following question: "*To what degree are required conditions for implementing strategies that reduce groundwater over-extraction present in the Vietnamese Mekong Delta?*". To answer this question, literature was reviewed and expert interviews were conducted to gather knowledge on the presence of the conditions in the delta. Based on the analysis of the assessment results, the answer to the main research question is listed in Table 22.

Table 22: Overview of the assessment results on the presence of the physical and technical, governance and economic conditions in the VMD

Variables	Physical and Technical Conditions	Rainwater harvesting	Surface water use	Wastewater treatment	Seawater desalination	Managed aquifer recharge
Availability of water	Alternative water resources are sufficient and reliable in terms of quantity and quality	[+/-]	[+/-]	-	[+]	[+/-]
Availability of land	Land is available for the development of the technology	[+/-]	[+]	[+]	[+]	[+/-]
Degree of knowledge and skills	Expert knowledge is available for the development of the technology	[+]	[+]	[-]	[+/-]	[+/-]
	Skilled people are available for the development of the technology	[+]	[+]	[-]	[+/-]	[-]
Required equipment	Equipment is available for the development of the technology	[+/-]	[+]	[-]	[+]	[+]
	Governance Conditions					
Stakeholder engagement	Stakeholders are involved in the development of strategies and policy interventions that will potentially affect them	[-]	[-]	[-]	[-]	[-]
	Information about groundwater issues is actively communicated to non-state actors	[-]	[-]	[-]	[-]	[-]
Institutional capacity	There are no regulatory constraints for the development of the technology	[+]	[+]	[+]	[+]	[+/-]

	Capacity is available for the development, implementation and enforcement of regulations	[+/-]	[+/-]	[+/-]	[+/-]	[-]
	Economic Conditions					
Financial capacity	Capital is available for the initial investments of the technology	[+/-]	[-]	[-]	[-]	[-]
	Capital is available for the continuous maintenance of the technology	[-]	[-]	[-]	[-]	[-]

9.1.1 Presence of physical and technical conditions

Table 22 shows the results of the assessment on the presence of physical and technical conditions in the delta for each strategy. In Chapter 1 of this research, it was stated that a strategy is feasible when all required conditions are present. For none of the strategies, all of the physical and technical conditions are present. However, at the same time there is not a strategy where all conditions are absent in the delta.

Regarding the feasibility of surface water treatment, all physical and technical conditions are fully present except the availability of surface water. It is important to note that surface water is abundant in the VMD, in terms of quantity. However, surface water is not accessible throughout the whole delta which means that it is a location-specific strategy. Furthermore, surface water increasingly has to deal with saltwater intrusion. It is possible to combine desalination with a treatment system, however these technologies have different purposes which could make development difficult.

Regarding the feasibility of rainwater harvesting in the delta, expert knowledge and skills are available because it is a strategy that is already being applied throughout the delta. The main barrier to RWH is rainfall variability, which is expected to further exacerbate because of climate change impacts. This means that large reservoirs are needed to ensure that the water demand can also be met during the dry season, which also requires more land.

In comparison to the aforementioned strategies, almost no physical and technical conditions are present in the delta for wastewater reuse. Thus, from a technical perspective it is the least feasible strategy. This is because treatment of wastewater is not common in the delta, and most wastewater is still discharged into natural waterways. Although reuse may not seem feasible yet, it is still very important that wastewater is treated in the delta to protect the environment and public health.

From a technical perspective, both seawater desalination and managed aquifer recharge are problematic to develop within the delta because not enough expert knowledge and skills are available. This could however be solved by providing education on how these technologies work. Furthermore, seawater desalination and MAR are location-specific strategies, as local characteristics influence the success of the systems.

Besides the presence of the physical and technical conditions, it is also clear that there is a variation per condition. Regarding the variable '*availability of water',* as mentioned previously rainwater and surface water are also available however in the future these supplies are likely to decrease. Thus, for future development of strategies it is important to incorporate this because it influences the results.

Furthermore, also for the variable '*degree of knowledge and skills'* it can be concluded that there are large differences between the strategies. This mainly has to do with the fact that RWH and surface water use are strategies that are already developed to a certain extent in the delta. In comparison, the other strategies are relatively uncommon which results in less knowledge and skills.

9.1.2 Presence of governance conditions

The assessment results show that there are no large differences between the strategies concerning the presence of governance conditions. This also has to do with the fact that the conditions under the variable '*stakeholder engagement'* are the same for each strategy. For all strategies, stakeholders are not involved in or informed about the development of strategies and groundwater issues. Thus, solely based on this variable none of the strategies are feasible. The current governance system in Vietnam is top-down, so all regulations and policies are developed by the central government. Subsequently, the local governments have to implement these regulations but no guidance is given how these regulations should be implemented or enforced. It should be noted here that the governance system is not static, as experts also argue that the government attempts to work more from a bottom-up approach but currently these conditions are not present yet. From a legal perspective, the strategies can be developed without much difficulty since there are no regulatory constraints.

9.1.3 Presence of economic conditions

The results illustrate that the financial capacity is the largest barrier for all strategies, since there is no capital available for both investment costs and maintenance costs. Only for RWH there seems to be potential, this is because there is capital available for small subsidies in the delta for poorer households to (partly) compensate initial investment costs. However, in general there seems to be a lock-in situation, where the lack of capital leads to not developing strategies to reduce groundwater over-extraction.

9.1.4 Overall conclusion

Currently, for none of the strategies all physical and technical, governance and economic conditions are present in the delta. The VMD is however continuously changing, as institutional arrangements and the economic situation are not static. If the government decides that it is a priority to reduce groundwater over-extraction, then all of the strategies will be more feasible for a successful development in the delta.

Overall, most conditions are present for the surface water use strategy. The main barrier to developing this strategy is the unavailability of capital for initial investments and continuous maintenance. This is also the case for all other strategies. Vietnam is still a developing country and this limits the availability of money to invest in water management technologies. Experts however emphasize that although initial costs are high, if people continue using groundwater resources then the costs in the future will be even higher. If the government is not capable or willing to invest in one of the strategies, another option is to find investors such as the World Bank.

Another barrier to sustainably manage groundwater resources in the VMD is related to the institutional capacity to develop, implement and enforce regulations. In Vietnam regulations are developed by the central government in Hanoi, located in the Northern part of the country, far from the VMD. There are quite a few regulations present in the delta, however the central government does not give guidance on how to implement and enforce these regulations locally. The enforcement is not only poor because of limited guidance by the central government but also because water is an essential part of the economy. Both aquaculture and agriculture thrive on water, so for poor farmers who are trying to make a living water is crucial. This could also be one of the reasons why enforcement is not very strict currently.

Furthermore, to successfully develop the strategies it is important that people in the delta are aware about issues related to groundwater over-extraction. Currently, there are no public education programs about the effects of groundwater pumping, and especially locals lack knowledge on groundwater issues. The experts propose that this could be solved by providing better education or by awareness campaigns, which can be combined with all of the researched strategies.

To conclude, this research set out to assess the feasibility of strategies that could reduce groundwater over-extraction in the delta. To further develop strategies, results however show that it is important to take local characteristics into account because in some areas in the delta surface water treatment could be a feasible strategy, whereas in another part of the delta managed aquifer recharge is a feasible strategy.

9.2 Limitations

It is important to acknowledge several limitations of this study. First, a strategy was defined as an approach to reduce groundwater over-extraction, consisting of three components: an alternative water source, governance measures and technical measures. Reflecting on this definition, it is important to mention that there are more strategies available to reduce groundwater use. During the interviews, experts addressed alternative strategies that are not discussed in this thesis, including, improving of water use efficiency by minimizing high-quality water leakages, optimizing pumping practices and changing agricultural practices. However, these strategies do not consist of alternative water resources and thus are only one part of the solution. The clear definition of a strategy ensured a well-defined scope.

Furthermore, whether the conditions are present in the delta was estimated based on expert opinions. In total eleven experts were interviews, mainly within the Netherlands. A limitation to this research is the fact that there were almost no stakeholders interviewed within the delta. For instance, government officials and water supply companies were not interviewed. If stakeholder opinions were also included in the assessment, this would have led to a more reliable study. However, this research gives a first indication of the feasibility of potential strategies, and further research should focus on the opinions of stakeholders.

Another limitation regarding the expert interviews is that all experts have their own specialization. It was therefore sometimes difficult to obtain knowledge on the presence of conditions. For instance, one expert focused solely on MAR but was not able to answer questions about other strategies. However, since the saturation point was reached after interviewing the available experts this limitation is not deemed very important.

Furthermore, a limitation to this research is that the conditions could have been assessed more in-depth. For instance, to assess the economic feasibility, a cost-benefit analysis might be conducted. It should however be noted that this is rather difficult, because data on costs of different strategies is difficult to retrieve. Since this is a time demanding method, it was decided to not include it in the scope.

Finally, a limitation to the research could be that mainly English literature is used for this thesis, which could give a bias. To minimize this, the Vietnamese partner university in the Rise and Fall project has provided additional literature from Vietnamese sources.

9.3 Recommendations

Based on the results of this study, several recommendations are provided for specific interventions in the delta as well as for further research.

First, it is recommended that the national government, in collaboration with the regional government, increases available information on groundwater use in the delta. The sustainable use and management of groundwater in the VMD remains a crucial research and societal challenge, because groundwater is being depleted in many areas in the delta. Still, not enough information is available on the hydrologic characteristics of the VMD. Further research should focus on groundwater users. More knowledge is required on who uses groundwater in the delta, how much groundwater is extracted and for what purpose. This information is essential to develop strategies that make the delta more sustainable in the future.

Furthermore, this study recommends that the national government increases the knowledge of groundwater users and local governments on issues related to over-extraction. This is crucial information that needs to be actively communicated to all stakeholders. It is also recommended to involve local actors, both state and non-state actors, in sustainable groundwater management efforts as this can help improve awareness and may motivate to better enforce or use groundwater resources.

This study also recommends to develop strategies on a small-scale. Whether a strategy is appropriate to be implemented is namely dependent on the local characteristics such as availability of alternative water resources and land use practices. Based on the presence of the physical and technical, governance and economic conditions, surface water treatment is the most feasible strategy. However, surface water is not available throughout the whole delta. It is thus recommended that the regional government determines which locations are appropriate for treatment plants or other strategies. Furthermore, this research recommends that the Vietnamese government or other researchers should conduct a cost-benefit analysis on the different strategies, which can be confronted with the costs of continued groundwater pumping. This can give more insight into the actual costs of the strategies, and potentially could lead to the prioritization of sustainable groundwater management and an increased budget for groundwater management. Moreover, this study recommends that technological implementation needs to be complemented with governance measures that raise awareness and change incentive constructions to encourage groundwater-saving behaviour. Only technological implementations will not lead to a reduction in groundwater over-extraction in the future, since behaviour needs to change in the delta in order for the resource to be used sustainably.

Finally, this study recommends to continue research on the VMD regarding further approaches to sustainable groundwater management and strategies. It is important to also take climate change into consideration when developing feasible strategies. Climate change is one of the most important threats to sustainable development around the world as well as in Vietnam. Since the VMD is a low-lying delta it is particularly vulnerable to climate change impacts. For instance, climate change will further increase saltwater intrusion into the delta, which could result in damage of infrastructure. Although surface water treatment plants may seem as a good investment at this moment, it is crucial to look at the longer term. When saltwater further intrudes in the delta, it could be that locations for these treatment plants are no longer suitable.

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Appendices

Appendix I: Summary of the workshop

Date:	February 22, 2018
Time:	12.00 – 14.00
Place of interview:	Deltares, Utrecht
Participants of Deltares and Utrecht University:	C. Dieperink, G. Erkens, P. Minderhoud, H. Otter, G. Oude Essink, E. Stouthamer

The workshop included researchers within the Rise and Fall project, both from Deltares and Utrecht University. The aim of the workshop was to get a first impression of potential strategies to reduce groundwater over-extraction and the feasibility of these strategies. First, a short presentation was given on the strategies that were identified during the literature review. After this presentation, five discussion points were provided.

1. What do you think of the suggested strategies to reduce pressure on groundwater?
2. How feasible are the proposed strategies for implementation in the VMD (from a technical, governance, economical and geographical perspective?)
3. Which strategies are most promising in terms of reducing groundwater extraction?
4. Can the strategies be translated to each of the provinces of the VMD, or will the strategies be different in one region to another?
5. What combination of strategies is possible?

Summary

In the workshop it is mentioned that besides governance and technical measures, it is also possible to include institutional measures (law and regulations). Furthermore, it is mentioned that there should be more of a focus in the research. Shrimp farmers are more the focus then rice farmers. Although rice farmers use groundwater sometimes, shrimp farmers use groundwater consistently. For rice mainly surface water is used (although in large quantities), rice farmers are located more upstream/inland (not in coastal regions) where river water can be tapped. In contrast, in coastal regions, farmers are forced to use groundwater. Findings in the research of Minderhoud also shows that shrimp farms are the largest non-urban source of groundwater. When the context is land subsidence, you do not have to focus on rice culture. Moreover, when looking at land subsidence in relation to land use, it is important to keep in mind that for instance in areas where there are three harvests a year, part of the year the crops need to be irrigated, which stops land subsidence. Therefore, strategies such as 'land use change' should be nuanced. If you extract on a deeper level, the effect will be larger on a larger area, whereas less deep extraction mainly affects the local situation. Shrimp farms and urban areas are the largest components in land subsidence.

So, the line of reasoning could be as follows. It is about groundwater, therefore you could look at an urban area and shrimp farms. Develop a strategy for shrimp farmers and a strategy for an urban area (who are the people that use groundwater and for what purpose). From the paper of Minderhoud it is showed that shrimp farmers and urban areas cause most land subsidence. So the research should focus on these two and then the different strategies that can be included. For instance in Can Tho you do not have to implement a desalination plant. So if you focus on these two, then you already choose a specific area. Do not stay too general, focus on a couple cases, what does it mean when you implement the strategies and what is feasible. Industry is not such an important user of groundwater (in quantity) although it can have an impact. Start at delta scale: then you can present the measures. After that use cases, such as Can Tho as an urban area and as a sector for instance shrimp farms. You can then look if the same rules are in place in a province such as Soc Trang and if these rules are as well enforced as for instance in Tra Vinh.

In the model of Minderhoud, different scenarios are used. All of these scenarios are on delta scale. The first scenario in this model is that not more is extracted than the recharge. The second scenario is business-as-usual. The third scenario is an increase in groundwater extraction, based on the socio-economic developments. And the fourth scenario is stabilizing, the curve will run horizontally.

As mentioned previously, the participants of the workshop emphasize that the narrative should be that there is land subsidence. Groundwater extraction is an important component in land subsidence, so that will be the focus and within those groundwater extractions it can be seen that shrimp farms are a large user so therefore focus on shrimp farms and an urban area (not specifically because of the large groundwater use but also because of the effects and the exposure is bigger in the cities). Potential alternatives for shrimp farmers that use groundwater are rainwater or surface water. A disadvantage of rainwater harvesting is that it influences the recharge, if you look at a system scale.

A potential technical measure could be that the users make an agreement that they cannot extract groundwater at the same time, but they take turns. Because if everyone extracts at the same time, it has a larger effect (radiation on each other). Maybe a groundwater alliance/cooperation could be developed. Another measure is to look for a trigger so that people experience an economic benefit. For instance, if a farmer produces in a sustainable manner, give a sustainability certificate (quality label). To make farmers willing to produce more sustainably, for instance through the introduction of a certification label.

Some strategies could be fitting to the city whereas others fit better to shrimp farmers. Write it in a narrative: which way is groundwater used in the city, who extracts it, are there also domestic users that pump groundwater or is it all done through water companies. And with shrimp farmers, what is the cycle of the water use, when are they really dependent on the use of groundwater and when is it possible that they use other sources of water.

In principal nobody can use groundwater in the delta, unless you have a permit but under a certain point you do not need a permit but you can still not extract groundwater but this is not enforced. For rice cultivation it is prohibited to use groundwater, and they do not use it (at least they say so), but if the quality of surface water is poor they use groundwater. With shrimp farming it is allowed to use groundwater as a water source. Laws, regulations and how to enforce could be limiting factors regarding the strategies. In Can Tho (within the city) it is not allowed to extract the water. Another possibility is that groundwater is used for 20 more years in Soc Trang for shrimp farms, and then people will move from the area (when groundwater is depleted).

Surface water is too far way (for shrimp farming in the coastal areas) and rainwater is too little (everything needs to be stored underground). Large underground storage is not easy. The only alternative is rainwater, but it is not feasible because you need to store it. There is no room for it. Potentially you could desalinate or install treatment plants, but there is no room to store it. The delta is flat, so you cannot store more than the 1 meter. This can mean that a part of the shrimp farms is located unfavourable and that there are no technical solutions possible. Another potential solution is to install pipelines but this is financially probably not feasible. Or designate areas that can be used or not.

Groundwater is cheap, so this means that there should be rules. Desalination of seawater produces salt brine: could it be an idea to eat this, in order for this strategy to become economically profitable.

The participants mention that there should be an overview of how much groundwater shrimp farmers extract and how this relate to other users. The story now is that shrimp farmers are the largest users, but there is no information on the relations between the users. So more information is needed on (1) total quantity water demand, (2) realistic extractions, and (3) contribution of different users in land subsidence. It is mentioned that there should be an overview within the Rise and Fall project of numbers to prevent the use of different numbers in papers.

It seems that 80 per cent of the total extractions are small household wells (local farmers) thus the big industries (of drinking water) can have an impact locally, but over the whole delta this is not the problem. Shrimp farmers are included in the 80%. On delta level it seems that small extractions are dominant. In urban areas there are big players such as industries, hotels and drinking water companies. In Bac Lieu drinking water companies are pumping the whole city empty.

Appendix II: Expert interviews

Appendix IIA: Date and time of expert interviews

Table II: Detailed information on the expert interviews, including date and time of interviews

Number	Date of interview	Time of interview	Institution	Function
[E1]	March 28th, 2018	14.00-14.50	IHE Delft Institute for Water Education	Senior Lecturer in Hydrogeology and Groundwater Resources (project: SALINPROVE)
[E2]	March 29th, 2018	12.30-13.00	Deltares	Specialist Coastal Management and Flood Risk Management
[E3]	March 29th, 2018	14.00-14.45	Delft University of Technology	Postdoctoral Researcher (project: Strengthening Strategic Delta Planning in Bangladesh, Netherlands, Vietnam and beyond)
[E4]	March 30th, 2018	11.00-11.50	Wageningen University & Research	Project Manager, Aquaculture and Fisheries group
[E5]	April 5th, 2018	09.05-09.55	Vitens Evides International	Resident Project Manager, Water Supply Expert
[E6]	April 6th, 2018	15.00-16.00	Waterland Experts	Expert on Land and Water Management in Vietnam and Indonesia
[E7]	April 16th, 2018	10.10-11.15	IUCN, Vietnam	Mekong Delta Programme Manager
[E8]	April 19th, 2018	11.45-12.15	Can Tho University, Vietnam	Associate Professor in Water Resources Management and Modelling
[E9]	April 25th, 2018	16.00-16.30	Deltares, Utrecht University	Senior Geologist, Researcher
[E10]	April 26th, 2018	16.00-16.30	HZ University of Applied Sciences (Dutch Delta Academy)	Senior Lecturer and Researcher
[E11]	May 3rd, 2018	13.30-14.30	Deltares, Utrecht University	PhD Researcher (project: Rise and Fall)

Appendix IIB: Interview guide

Date:	
Place of interview:	
Interviewee:	
Organisation:	
Function of interviewee:	

The aim of the interview is to get insights into the presence of the required physical and technical, governance and economic conditions for a successful development of potential strategies in the Vietnamese Mekong Delta. The type of questions that were asked depended on the expertise of the interviewee. The list of questions can be found below. The experts were asked if they agreed with the interview being recorded. These recordings are used solely to transcribe the outcomes of the interviews and for the analysis.

Introduction questions

1. Could you shortly introduce yourself and your past research/work experience in Vietnam?

2. To what extent would you say groundwater use should be reduced in the delta? And when is the use of groundwater crucial in the delta?

3. In your opinion, how can groundwater extraction be minimized? Which sector or user should be mainly addressed according to your opinion?

Potential strategies to reduce groundwater over-extraction:

- Rainwater harvesting: *the utilization of rainwater as a source of freshwater*
- Surface water use: *improving surface water quality through the implementation of surface water treatment plants*
- Desalination of seawater: *purifying seawater through the use of desalination systems*
- Wastewater reuse: *treatment of wastewater for reuse, e.g. for domestic purposes*
- Managed aquifer recharge: *purposeful recharge of water to suitable aquifers*

4. What do you think of the suggested strategies (above) to reduce groundwater extraction in the delta?

5. What alternative strategies would you consider?

Presence of conditions

6. What do you think of the alternative water sources to groundwater: rainwater, surface water, seawater or treated wastewater. Is one of these alternatives sufficient in terms quantity and quality, in comparison to groundwater?

7. Is enough land available for the different technical measures? (*Is there for instance sufficient land available to build a surface water treatment plant or a rainwater storage system?)*

8. Is equipment sufficiently available to implement the different technical measures? (*For instance, are chemicals available for the treatment process?)*

9. Are there any regulatory constraints for the use of alternative water sources in the delta, such as the reuse of wastewater?

10. To what extent do you think that there is sufficient expert knowledge and skills available in the delta for the implementation and maintenance of these strategies?

11a. How aware would you say the public is about issues associated with groundwater overexploitation?
11b. Are stakeholders involved and informed about decision-making that influences them?
11c. Do you think awareness campaigns or educational programs could lead to more sustainable use of groundwater? For instance, are farmers willing to get education?
11d. What is the view of the public towards measures that decrease groundwater use? (*For instance, the reuse of wastewater or a shift towards treated surface water)*

12. Who should be responsible for the initial investment, installation and maintenance of the different strategies?

13. Do you think that there is enough capital available to implement these strategies or is one strategy more economically feasible than others in your opinion?

Closure

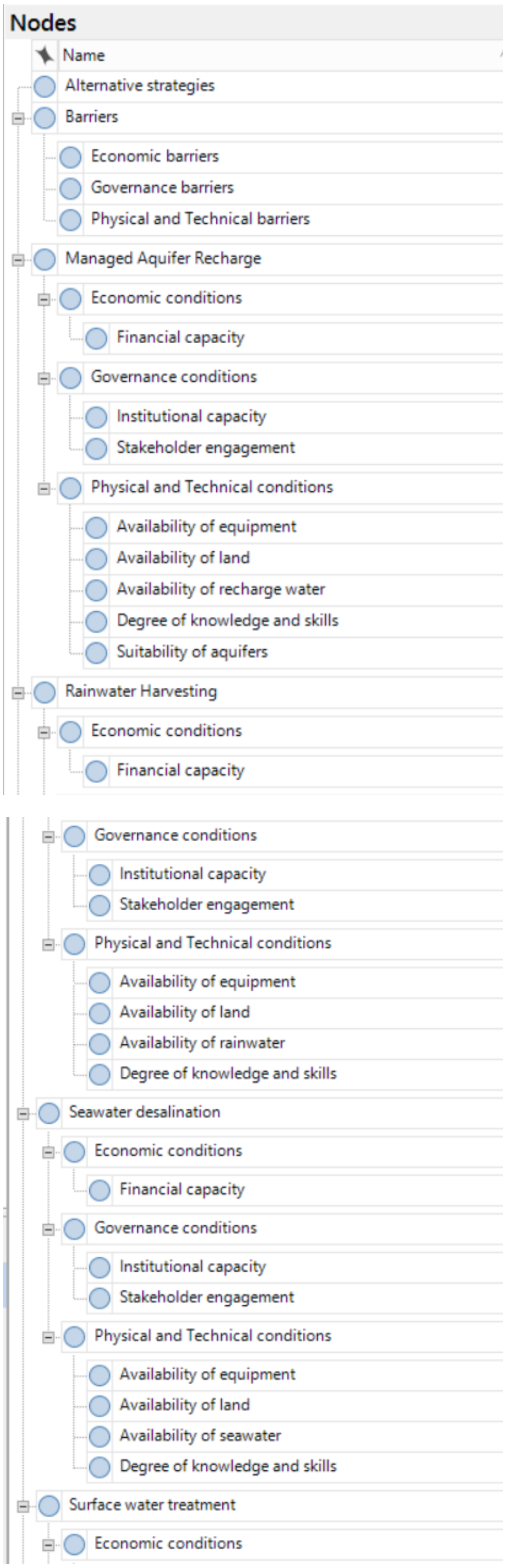
14. What are the barriers towards sustainably managing groundwater in the delta?

15. Can the strategies be translated to all provinces in the Vietnamese Mekong Delta in your opinion, or are the strategies location-specific?

16. Are there any additional aspects that I should have asked you, or that you would like to add?

Appendix III: Coding structure in NVIVO

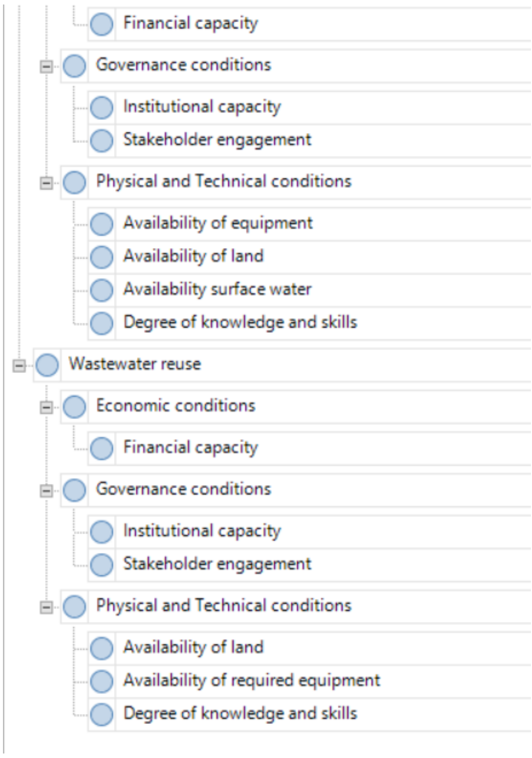
Figure III: *Nodes, including sub-nodes*



Nodes

Name

- Alternative strategies
- Barriers
  - Economic barriers
  - Governance barriers
  - Physical and Technical barriers
- Managed Aquifer Recharge
  - Economic conditions
    - Financial capacity
  - Governance conditions
    - Institutional capacity
    - Stakeholder engagement
  - Physical and Technical conditions
    - Availability of equipment
    - Availability of land
    - Availability of recharge water
    - Degree of knowledge and skills
    - Suitability of aquifers
- Rainwater Harvesting
  - Economic conditions
    - Financial capacity
  - Governance conditions
    - Institutional capacity
    - Stakeholder engagement
  - Physical and Technical conditions
    - Availability of equipment
    - Availability of land
    - Availability of rainwater
    - Degree of knowledge and skills
- Seawater desalination
  - Economic conditions
    - Financial capacity
  - Governance conditions
    - Institutional capacity
    - Stakeholder engagement
  - Physical and Technical conditions
    - Availability of equipment
    - Availability of land
    - Availability of seawater
    - Degree of knowledge and skills
- Surface water treatment
  - Economic conditions



- Financial capacity
- Governance conditions
  - Institutional capacity
  - Stakeholder engagement
- Physical and Technical conditions
  - Availability of equipment
  - Availability of land
  - Availability surface water
  - Degree of knowledge and skills
- Wastewater reuse
  - Economic conditions
    - Financial capacity
  - Governance conditions
    - Institutional capacity
    - Stakeholder engagement
  - Physical and Technical conditions
    - Availability of land
    - Availability of required equipment
    - Degree of knowledge and skills