Groundwater: Invisible importance, Visible impacts

Evaluating the spatial implications of groundwater level elevation for peatland emission reduction and climate-resilient rural landscapes in Midden-Delfland using spatial Multi-Criteria Decision Analysis

Maaike Jansen Venneboer

July 2025

Master thesis

Metropolitan Analysis, Design and Engineering

Maaike Jansen Venneboer

1435795

Supervisors

Dr. Maryam Ghodsvali

Wageningen University & Research

Department of Environmental Sciences

Laboratory of Geo-Information Science and Remote Sensing

Dr. Rodrigo V Cardoso

Delft University of Technology

Faculty of Architecture and the Built Environment

Department of Urbanism

In collaboration with Hoogheemraadschap van Delfland

Metropolitan Analysis Design & Engineering

Delft University of Technology and Wageningen University and Research

July 15th 2025

Acknowledgements

My academic journey began in the heart of the (sub)urban world. From architecture to urbanism in Delft, the path unfolded with every step. Yet as it grew longer, I felt a stronger pull toward rural areas. To escape the chaos of everyday life and recharge by being outside. In that shift, both professionally and personally, from the city to the calm, I started to see with my own eyes what climate change does.

This thesis could not have been a more fitting end to my studies. It brought together everything I've loved and learned over the past years into one cohesive whole. It gave me the chance to merge all the things that energize me: water management, rural transformation, climate and spatial planning. I'm proud I took the time and effort to shape a research project that truly aligned with my interests. That self-direction kept my energy and enthusiasm high throughout. I felt engaged in the conversations I had and felt like I could really contribute to them.

Thank you to Maryam and Rodrigo for your helpful guidance throughout this project. Maryam, thank you for your joyful and supportive supervision sessions, and for always being willing to help whenever I had had questions. Rodrigo, thank you for helping me find clarity when I lost track of the bigger picture, and for sharing your insights into the interconnectedness of complex systems.

Thank you to Claudia, for helping me focus on personal growth and my own path while also taking me along at the Hoogheemraadschap van Delfland and warmly welcoming me into my first real working experience. Thanks to all other colleagues helping me out, for answering all my questions with enthusiasm and care.

The street I called home for many years was named after a meadow bird: the Kemphaan. Ironically, these meadow birds became a symbol of the study area I would dive into for this thesis. And on that Kemphaan, I could always knock on the door, whether it was to talk about all of my ideas or to clear my mind. Mama, papa, and Bernadette: thank you, for everything.

I spent many hours in the study area: from 18 stretches of rowing on the Schie, to 35 rounds of running, and 10 cycling through the polder, or working from my home on the 17th floor with a panoramic view of Midden-Delfland. Additional field visits to the area and an early Sunday morning searching for meadow bird nests deepened my understanding of the area. You can imagine that emerging myself in the study area was pretty successful.

To Kate, my rowing companion for (over) 100 kilometres, to Kapot for the sporty and non-studying moments, my board for the laughs, and to my MADE friends who kept me motivated and joyful throughout.

And last, but by no means least: Mees. I'm endlessly thankful for your support, your realism, and your joy. You've been by my side through all the ups and downs of recent years, helping me navigate my interests and direction. Whether over the phone, in Dresden, or Delft, thank you for being there, always.

Maaike Jansen Venneboer, Delft, June 2025

Abstract

The Netherlands has a strong tradition of draining peatlands, often for agricultural purposes, resulting in CO_2 emissions, soil subsidence, and biodiversity loss. A higher groundwater level is often presented to combat these issues as it offers benefits for ecosystem restoration, reducing land subsidence, and achieving climate adaptation. However, implementation remains limited due to conflicts with conventional agricultural practices, possible methane emissions, water quality concerns, and policy contradictions. This study examines how spatial planning in the peatland region of Midden-Delfland can support climate adaptation through strategic groundwater elevation, while balancing environmental sustainability, infrastructure resilience, and agricultural viability.

Using a spatial Multi-Criteria Decision Analysis (MCDA) combined with expert insights, the research identifies areas where groundwater level adjustments are most necessary, feasible, and desirable. It proposes a spatial transition strategy that strengthens the region's landscape identity while enhancing resilience to climate change. Wet crop cultivation (paludiculture), such as reed, cattail, cranberries, or peat moss, is explored as a viable alternative in areas with thick peat layers and high greenhouse gas emission potential. Strategies such as water retention and multifunctional land use should form the foundation of climate-adaptive planning.

For this transition to succeed, several conditions must be met. First, freshwater availability is essential, as scarcity poses a significant risk to the effectiveness of groundwater elevation. Second, contradictory policies, such as subsidies promoting opposing objectives, must be resolved and clear, consistent sustainability frameworks for the agricultural sector are needed to take the lead in driving this transition forward. Third, economic uncertainty due to changing political priorities underscores the need for fair compensation for when transitioning to paludiculture and for providing ecosystem services. Lastly, a cultural shift is needed in how landscapes are valued. Provincial policies focused on preserving open views may unintentionally block transitioning to paludicultures. Whether heritage protection should limit climate adaptation remains a key question for further research. This study presents a planning framework that incorporates ecological, spatial, and socio-economic perspectives for making peat landscapes climate-resilient, applicable not only in the Netherlands but also beyond.

Key Words

Groundwater level elevation, peat soil, rural landscape, GIS MCDA, sustainable land-use transition, agricultural viability

Table of Contents

1 Introduction 14

2 Research Context 20

3 Study Area: Special Provincial Landscape Midden-Delfland 24

4 Literature Review 30

4.1 Groundwater: what is it and how does it work 30

4.2 Peat soils and greenhouse gas emissions 33

5 Theoretical Framework 40

5.1 Understanding the relationship between subsoil and spatial planning 40

5.2 Transitioning towards sustainable land-use planning 42

6 Conceptual Framework 44

6.1 A hierarchical approach 44

6.2 Environmental sustainability 45

6.3 Infrastructure resilience 46

6.4 Agricultural viability 46

6.5 Resilient groundwater management 47

7 Methodology 50

7.1 Research design 50

7.2 Data collection methods 51

7.3 Ethical considerations 60

8 Results Phase 1:

Understanding the spatial, environmental and social context of groundwater elevation 62

8.1 Expert perspectives on effects of groundwater elevation 62

8.2 Other findings and perspectives from discussions 65

8.3 Criteria 67

8.4 Summary 68

9 Results Phase 2:

Area-specific impact analysis of groundwater elevation 70

9.1 Environmental necessity for groundwater level elevation 70

9.2 Physical feasibility of groundwater level elevation 71

9.3 Spatial desirability of groundwater elevation 71

9.4 Spatial analyses 76

9.5 Summary 83

10 Results Phase 3:

Translate findings to spatial transitions for an environmentally sustainable future of Midden-Delfland 86

10.1 The current agricultural landscape of Midden-Delfland 86

10.2 Towards a climate-resilient Midden-Delfland: the design objectives 91

10.3 The future agricultural landscape of Midden-Delfland 94

10.4 Shaping the transition with Theory of Change 98

10.5 The design proposal 102

10.6 Summary 118

11 Discussion 120

12 Conclusion 126

13 References 130

14 Appendices 144

14.1 Appendix 1: AHP weighing and results 144

14.2 Appendix 2: Data action model 154

14.3 Appendix 3: Raster calculator expressions 157

List of Figures

Figure 1 The study area embedded in its larger context. Created by the author. 24

Figure 2 Visual impression of the study area surroundings. Created by the author. 26

Figure 3 Interaction between surface water and groundwater. Created by the author. 31

Figure 4 Groundwater usage in the Netherlands. Adapted from CBS (2021). 32

Figure 5 The global warming potential of greenhouse gases relative to each other. Created by the author. 34

Figure 6 GHG balance at different groundwater levels (Evans et al., 2021) 35

Figure 7 Furrow infiltration in field. Own image. 37

Figure 8 The Dutch layer approach. Top to bottom: occupation layer, networks layer, subsoil layer. De Hoog et al. (1998). 40

Figure 9 Conceptual framework for the research. Created by the author. 45

Figure 10 Research design. Created by the author. 50

Figure 11 Sources of groundwater pollution (IAEA, 2025). 63

Figure 12 Necessity analysis: spatial overlap of peat thickness and clay cover 77

Figure 13 (left) Feasibility analysis: required groundwater level elevation to -20cm 79

Figure 14 (right) Feasibility analysis: required groundwater level elevation to -40cm 79

Figure 15 (left) Desirability analysis: MCDA Infrastructure resilience 81

Figure 16(right) Desirability analysis: MCDA Agricultural viability 81

Figure 17 Desirability analysis: MCDA Environmental sustainability 81

Figure 18 Desirability analysis: MCDA 82

Figure 19 Current agricultural crops in Midden-Delfland. Adapted from PDOK (2022). 87

Figure 20 Landscape context of the study area.. Created by the author. 89

Figure 21 Collage of the identity of Midden-Delfland according to the conceptual framework. Created by the author. 90

Figure 22 The design objectives for the area, aligned with conceptual framework. Created by the author. 92

Figure 23 Vision map for Midden-Delfland 93

Figure 24 Images of paludicultures. Created by the author. 95

Figure 25 Types of agriculture and paludiculture possible at different groundwater levels. Created by the author. 96

Figure 26 Decision tree to guide spatial choices for paludiculture. Created by the author. 103

Figure 27 Necessity map. Created by the author. 104

Figure 28 Visual representation of transition for Midden-Delfland. Created by the author. 105

Figure 29 Proposed spatial transition plan Midden-Delfland. Created by the author. 106

Figure 30 Connection to ecological network. Own work. 108

Figure 31 Connection to recreational network. Own work. 108

Figure 32 Crop possibilities for water retention areas.Connection to ecological network. Own work. 108

Figure 33 Zoom in one. Created by the author. 109

Figure 34 Zoom in two. Created by the author. 110

Figure 35 Impression of a peat moss landscape and its characteristics according to conceptual framework. Created by the author. 112

Figure 36 Impression of a cranberry landscape and its characteristics according to conceptual framework. Created by the author 113

Figure 37 Problem identification Midden-Delfland. Created by the author. 114

Figure 38 Spatial transition applied in Midden-Delfland. Created by the author 116

List of Tables

Table 1 List of experts consulted for interviews52

Table 2 Data used for spatial analysis 53

Table 3 Classes of suitability to a groundwater level of -20 cm to assess on 57

Table 4 Weighting values for AHP (Saaty, 1980). 58

Table 5 Scores and desirability classifications of factors and constraints 75

Table 6 Relative scores for criteria agricultural viability, infrastructure resilience, environmental sustainability 80

Table 7 Proposed crops and their characteristics. Created by the author. 97

Introduction

1. Introduction

Water management has been a long-time approach for actively shaping the Netherlands' landscape. With nearly two-thirds of its land lying below sea level, it has always been in a delicate balance between land and water (Born et al., 2016). However, climate change, characterized by more frequent droughts, extreme rainfall, and rising sea levels, combined with the country's location in a major river delta, makes the Netherlands particularly vulnerable to the effects (KNMI, 2025; van Tilburg & Hudson, 2022). Over the past centuries, large areas of peatland in the Netherlands have been drained to support agriculture and increase yields (Aben et al., 2024). As a result, the land surface subsides and greenhouse gases are released. The increasing intensity of hot, dry, and wet conditions calls for urgent adaptation to safeguard the spatial, ecological, and economic resilience of the country. Ongoing population growth and urbanization make climate change an increasingly urgent issue that needs to be addressed. At the same time, this leads to a rise in the scarcity of space in the Netherlands, with competing demands for limited land. Besides the need for more houses, land is also needed for sustainable food production, economic growth, energy production, and nature (Ministerie van Landbouw Natuur en Voedselkwaliteit, 2020). Within the context of these challenges, this research concentrates on the Midden-Delfland region, a (partly) peat meadow landscape situated between two of the Netherlands' largest cities: Rotterdam and The Hague.

In the Netherlands, approximately 7 % of the land surface consists of peatlands. Drained peat soils occupy more than 90 % of the total peatland area and emit approximately 3 % to the country's total CO_2 emissions (Arets et al., 2023). In addition to emissions, the oxidation of peat leads to soil subsidence, which depends on local groundwater depths (Erkens & Kooi, 2018; TNO & Deltares, 2021), as well as biodiversity loss (van der Laan et al., 2024). The drainage of these peatlands occurred mainly for agricultural purposes, resulting in almost all drained peatlands having an agricultural function. This underscores a need for transition towards a sustainable agricultural sector, reducing the negative effects on greenhouse gas emissions from drained peatlands.

As part of its climate policy, the Dutch Climate Agreement (2019) outlines guidelines aimed at reducing greenhouse gas emissions from peat soils by 1 Mton in total by 2030 (Ministerie van Economische Zaken en Klimaat, 2019b). The primary strategy to reach this goal is to elevate the groundwater level. Raising the groundwater level in peat areas has been shown to reduce CO_2, N_2O and CH_4 emissions, slow down or prevent soil subsidence, and improve biodiversity (Aben et al., 2024; Becker et al., 2022). In line with this, the Dutch policy framework *Water and Soil Steering* proposes increasing groundwater levels in peat meadows to approximately 20 to 40 cm below surface level, thereby contributing to both climate mitigation and climate adaptation (Ministerie van Algemene Zaken, 2022).

From a spatial planning perspective, the implications of groundwater elevation are substantial. Homeowners, for instance, stand to benefit, as soil subsidence caused by peat oxidation damages building foundations and underground infrastructure. It results in significant economic consequences

(Born et al., 2016). Together with its ecological benefits, groundwater elevation provides a strong argument for its inclusion in long-term climate and land-use strategies.
However, raising groundwater levels is not without controversy. The Dutch farmers' union LTO Nederland has voiced strong opposition, stating that higher water tables negatively affect crop yields and dairy farming (LTO, 2023; Ministerie van Infrastructuur en Waterstaat, 2022). Additionally, higher groundwater levels have been shown to impact water quality and availability negatively (Wei et al., 2024). Other unfavourable consequences of high groundwater levels include damage to buildings, due to wet cellars, and increased maintenance for infrastructure.
Managing water in peat landscapes is all about balancing the conflicting interests of nature, agriculture, and urban development. Measures that favour one group often have undesired side effects for another. In some cases, trade-offs are inevitable, and shifts in land use may be necessary when the long-term benefits outweigh the short-term drawbacks.
These diverging stakeholder interests show the trade-offs involved in groundwater management and spatial planning. This highlights the need for local strategies that fit local context and balance ecological benefits with socio-economic concerns. This approach maximizes the most beneficial use of groundwater for both the environment and society, simultaneously maintaining a sustainable and healthy groundwater system.

1.1 Research gap

Despite increasing attention to groundwater management and climate adaptation, research has yet to fully explore how spatial planning can proactively address rising groundwater levels while balancing competing land-use demands. Studies (e.g., Ahmad et al., 2020; Loisel & Gallego-Sala, 2022; Page & Baird, 2016; Santoni et al., 2021) have analysed the hydrological effects of groundwater fluctuations, particularly on peatland degradation and climate resilience, but lack integration of GIS-based spatial analysis with decision-making, including stakeholder perspectives and feasibility, to develop working solutions.
Additionally, existing policy frameworks provide generic adaptation strategies but lack location-specific spatial designs tailored to regional hydrological, socio-economic, and infrastructural conditions. Next to that, climate-adaptive groundwater planning often focuses on sectoral solutions, like agriculture or water management, without considering broader spatial interdependencies. This fragmentation hinders the integrated translation of hydrological insights into planning policies.
This research bridges this gap by integrating a Geographic Information System (GIS) based Multi-Criteria Decision Analysis (MCDA) with stakeholder insights, creating spatially explicit planning strategies. Through this integration, the research aims to create effective spatially explicit transition strategies in a complex area.
Although this research focuses on rural areas, it indirectly contributes to the urban challenge of climate-resilient cities. Rural regions such as Midden-Delfland play a crucial role in supporting urban climate resilience, particularly through water regulation and landscape buffering. Additionally, by exploring sustainable agricultural practices, this study also contributes to the broader metropolitan food system and the long-term sustainability of peri-urban land use.

1.2 Research aim and objectives

This research aims to develop a spatially explicit evaluation of the necessity, feasibility, and desirability of groundwater level elevation in the agricultural landscape of Midden-Delfland. It seeks to identify where such measures can generate the greatest environmental and societal benefits. By taking a long-term perspective towards 2050, the study contributes to future-proofing the region through climate-resilient spatial planning.

The research specifically focuses on rural spatial planning, as rural peatland areas are essential for addressing climate adaptation challenges. These areas often have lower groundwater levels due to agricultural practices, making them a key target for intervention. The objective is to map suitable locations for groundwater elevation and additionally assess the broader spatial and ecological implications. Particular attention is given to minimizing negative side effects through transitional land-use strategies and to managing the diverse interests involved in strategic spatial decision-making.

The findings aim to inform future climate-proof spatial planning by contributing to two key goals: (1) the reduction of CO_2 emissions from drained peat soils and (2) the mitigation of land subsidence. These outcomes provide a foundation for spatial decision-making strategies that respond to the climate and land-use challenges of the region.

Midden-Delfland offers an ideal case study to explore this potential. As a region associated with peat soils, agriculture, and cultural landscape values, it exemplifies both the challenges and opportunities of planning with groundwater (BPL Midden-Delfland, n.d.). With a strong identity and diverse stakeholder landscape, the region could serve as a pioneer for sustainable land-use transitions.

1.3 Research questions

The research aims to answer the following main question:

How can spatial planning in Midden-Delfland adapt to rising groundwater levels while balancing the trade-offs between agricultural viability, environmental sustainability, and infrastructure resilience in the face of

climate change?

This main question will be addressed through the following sub-questions, structured across different research phases:

Phase 1: Understanding of the spatial and environmental context of Midden-Delfland

1. What are the main barriers and enabling conditions contributing to the successful implementation of groundwater elevation measures?
2. Which spatial and environmental factors determine the suitability of groundwater level elevation in peatland areas, given spatial tensions and opportunities?

Phase 2: Spatial MCDA

3. Which areas of Midden-Delfland are higher groundwater levels contributing positively to environmental sustainability, infrastructure resilience, and agricultural viability, and where does it lead to negative impacts?

Phase 3: Translate findings to recommendations

4. Which agricultural alternatives are suitable for areas where groundwater levels are elevated as a climate adaptation measure?
5. What is the envisioned spatial transition needed to achieve a climate-resilient Midden-Delfland through groundwater level elevation?

1.4 Reading guide

This thesis is structured in three main phases, each building upon the previous to explore how spatial planning in Midden-Delfland can adapt to rising groundwater levels in a way that balances environmental sustainability, infrastructure resilience, and agricultural viability. Following the introduction, the context of the problem will be explained, including how it is embedded in society, and the study area will be further explored. Chapter 4 presents a literature review on the characteristics of groundwater management and groundwater level elevation measures.

Chapters 5 and 6 outline the theoretical and conceptual frameworks guiding this research. The methodology chapter, described in Chapter 7, then details the mixed-methods approach. Chapter 8, the first results chapter, explores the various criteria that influence or are influenced by groundwater levels. Chapter 9 applies these criteria spatially to identify areas within Midden-Delfland where groundwater level elevation is necessary, feasible, and desirable.

Finally, Chapter 10 integrates all findings into a spatial strategy for climate-resilient land use planning in Midden-Delfland by 2050. In doing so, the thesis not only provides insight into the suitability of groundwater elevation for this region but also presents a coherent vision for spatial planning in the face of climate change. The thesis concludes with a discussion of the results and final conclusions.

Research Context

2. Research Context

To better understand the circumstances of the transition toward elevated groundwater levels in Midden-Delfland, the broader context is explored on how the issue is embedded in the regional and national context, and background knowledge is given on spatial planning. Additionally, the broader societal and environmental challenges and the political context of the research are explored. Lastly, the study area will be introduced.

2.1 The challenge of climate adaptation in the Netherlands

Hotter, wetter, and drier: climate change is accelerating worldwide, including the Netherlands, with no signs yet of this slowing down (KNMI, 2025). Across the globe, its effects are becoming increasingly evident: temperatures are rising, weather patterns are intensifying with both heavier rainfall and prolonged droughts, and sea levels continue to rise. The Netherlands is particularly vulnerable due to its geographic location in a low-lying delta. With 60% of the country situated below sea level and 70% of its gross national product generated in flood-prone areas, the risks are exceptionally high (Ministry of the Interior and Kingdom Relations, 2024). These conditions demand urgent and strategic planning interventions to protect both people and critical infrastructure.
In 2024, the Netherlands recorded its hottest year yet, surpassing the previous record set in 2023. The country experienced more frequent heavy rainfall events and a complete absence of freezing days (KNMI, 2025). Alongside these climatic shifts, the seasonal volatility of precipitation intensified. These shifts have direct consequences for groundwater levels, resulting in longer droughts, delayed hydrological recharge cycles, and an increased frequency of water shortages and flooding.
Given this evolving climate reality, conventional water management strategies are no longer sufficient. The traditional Dutch focus on draining water as quickly as possible is now being questioned. Instead, there is growing consensus around the need to retain water in the landscape, as the Union of Water Boards (2023) call for buffering groundwater reserves for supporting ecosystems and agriculture during drier periods.

2.2 Groundwater and climate change

Groundwater plays a crucial, though often invisible, role in shaping the spatial and ecological landscape of the Netherlands. It sustains wetlands, provides more than half of the country's drinking water, and supports both agriculture and industry. However, this vital resource is under increasing

stress from overextraction, pollution, and the consequences of climate change (Becker et al., 2022; Unie van Waterschappen, 2023).
The groundwater system has a delayed responsiveness as groundwater levels respond to rainfall weeks or even months after precipitation events. Moreover, these systems are linked with land-use choices: agriculture, urban development, and infrastructure expansion can all influence recharge rates, water quality, and soil stability (Becker et al., 2022). With the extreme climate variations in the foreseeable future the main user of groundwater worldwide, agriculture, is set to increase groundwater usage by 14% by the end of this century (Srivastav et al., 2021).
One of the biggest spatial consequences of unsustainable groundwater management in peatland areas is soil subsidence (Ma et al., 2022). Additionally, the oxidation of peat, caused by low groundwater levels, releases significant volumes of CO_2. This puts increasing pressure on water systems, infrastructure, and climate goals.

2.3 The policy landscape

In recent years, numerous strategies and programmes have aimed to bring water, soil, nature, and climate concerns together in an integrated agenda to make the Netherlands more futureproof. To show the relevance of the issue at hand, the international, European Union, national, and regional policy documents applicable for the study area and within the research scope, are shortly elaborated on.
A lot of the nature and climate-related regulation is determined at the European level, and subsequently translated into national targets for the Netherlands. Additionally, due to the country's specific spatial challenges and its relatively large agricultural sector, the Netherlands has introduced several dedicated programmes focusing on spatial planning and agriculture. These aim to facilitate a necessary transition in light of various sustainability objectives.
At the global level, the Paris Agreement defines key targets for climate mitigation through CO_2 emission reductions (Paris Agreement, 2015). At the European level, the Birds and Habitats Directives aim to protect biodiversity, while the Water Framework Directive aims to protect and improve the quality of all water bodies across all member states (European Commission, n.d.; European Union, 1992, 2009).
These directives are translated into Dutch policy through the Dutch Climate Agreement, which aims to reduce CO_2 emissions by 49% by 2030 (Ministerie van Economische Zaken en Klimaat, 2019a). The Water Framework Directive has been directly transferred to Dutch law as the Kaderrichtlijn Water, holding onto its original objective of achieving clean surface and groundwater (CLO, 2020).
One of the most significant policies relevant to this research is the National Programme for Rural Area (NPLG) (Ministerie van Landbouw Natuur en Voedselkwaliteit, 2024). This programme recognized the urgent need for a transition in rural areas, addressing the combined challenges of climate change, biodiversity loss, and water quality degradation, while also thinking about the specific spatial and agricultural dynamics of the Netherlands. Although launched in 2022, the NPLG was discontinued in 2024 following a change in government, which introduced a different political agenda. This also meant that funding for initiatives supporting its goals was withdrawn.
In 2022, the Dutch government responded to growing concerns about the future of rural areas by publishing a policy letter called Water and Soil Leading. This document included clear choices about how to make water and soil more central in planning and development. One of the key

proposals was to raise groundwater levels in peatland areas to 20–40 cm below the surface, in order to reduce soil subsidence and cut CO_2 emissions (Ministerie van Algemene Zaken, 2022). However, under the current cabinet, this policy has been softened to a recommendation to “take water and soil into account.”
At the provincial level, the Province of Zuid-Holland has continued working on these goals. Even though the national programme was stopped, the province has launched its own programme, South-Holland Programme for Rural Area (ZHPLG), showing that the problems are still recognized and that action is still being taken.

2.4 The opportunity of spatial planning

The Netherlands has a tradition of spatial planning and managing land and water (Stead, 2014). The earliest known collaborations between local communities for water management led to the formation of the predecessors of the Dutch water boards (*waterschappen*) in the 13th century, while the national water agency, Rijkswaterstaat, was established in the 17th century (Ministerie van Infrastructuur en Waterstaat, 2019). The fact that Dutch water boards existed before the country had its own army underscores the critical role of water management in the Netherlands.
The Netherlands is a man-made country, its existence has been shaped by human intervention. For as long as the country existed, it fought against natural elements to ensure its safety. Through the construction of dikes and land reclamation, the Dutch have created land that would otherwise be under water, particularly in the western part of the country. From all sides, there are growing signals that the manufacturability of the Netherlands’ physical environment is reaching its limits. Increasingly, there is a call to align more closely with natural cycles, which is underscored by the policy brief of water and soil guiding (Ministerie van Infrastructuur en Waterstaat, 2024).

In the Netherlands, larger infrastructural or spatial planning projects are often only initiated after a severe event has occurred (Oukes et al., 2022). An example of this is the 1953 floods, which led to the rapid development of the Delta Works. Following this, discussions about climate change and future resilience gained momentum, raising the question of whether continuously reinforcing dikes would remain a sustainable solution. The country is now engaging in this debate, but obstacles occur in the implementation (Raad voor de leefomgeving en de infrastructuur, 2024). One of the obstacles to climate-resilient spatial planning is that political and administrative decision-making tends to prioritize addressing the most immediate societal challenges, such as the housing crisis, often at the expense of long-term water management considerations (Carter, 2007; Oukes et al., 2022). However, the increasing urgency of climate adaptation did lead to the implementation of national programs aimed at enhancing the country’s resilience. A key example which illustrates this is the *Deltaprogramma*, designed to enhance the country’s resilience to climate change. It is unique, because it functions as an independent institution, making it less susceptible to fluctuations in political leadership, which helps long-term continuity in water governance and spatial adaptation strategies (Ministerie van Infrastructuur en Waterstaat, 2025b).

This shows how groundwater is embedded in spatial, ecological, and societal concerns, which stresses the need for an integrated approach in spatial planning with groundwater.

Study Area

3. Study Area

Midden-Delfland is a rural landscape situated in the province of South Holland, in the western Netherlands. Positioned between the urban centres of Rotterdam, The Hague, and Delft, visible in Figure 1, the region functions as a crucial green buffer zone in an otherwise heavily urbanized environment. Officially designated as a *Bijzonder Provinciaal Landschap* (BPL) (Special Provincial Landscape), from now on referred to as Midden-Delfland, this area holds significant ecological, agricultural, and cultural value. The main ambition for the area is "to strengthen its role as a green-blue oasis where nature, agriculture, and recreation coexist in balance." (BPL Midden-Delfland, n.d.; Provincie Zuid-Holland, n.d.). This combination makes it a strategic case study for examining how spatial planning can respond to rising groundwater levels.

3.1 A cultural and ecological landscape

Midden-Delfland covers an area of 50 km^2 and has with approximately 20,000 inhabitants, a relatively low population density: about ten times lower than the large cities surrounding (Centraal Bureau voor de Statistiek, 2024). The settlement pattern is mainly rural, consisting of three larger villages: Maasland, Schipluiden, and Den Hoorn, and several smaller ones. In total, the region encompasses (parts of) nine different municipalities. These scattered, ribbon-like settlement structure reflects the area's historical development, shaped by its hydrological conditions.

The region's primary soil type is peat, with some areas consisting of clay or sand (Basisregistratie Ondergrond, 2024). These peat soils are agriculturally productive, and support dairy farming and limited arable land, but are also environmentally vulnerable (Aben et al., 2024). Intensive drainage over time has caused significant soil subsidence, making the region highly sensitive to shifts in water management and climate change. Additionally, the area includes recreational and greenhouse horticulture zones, as well as nature areas that have been largely adapted for human use.

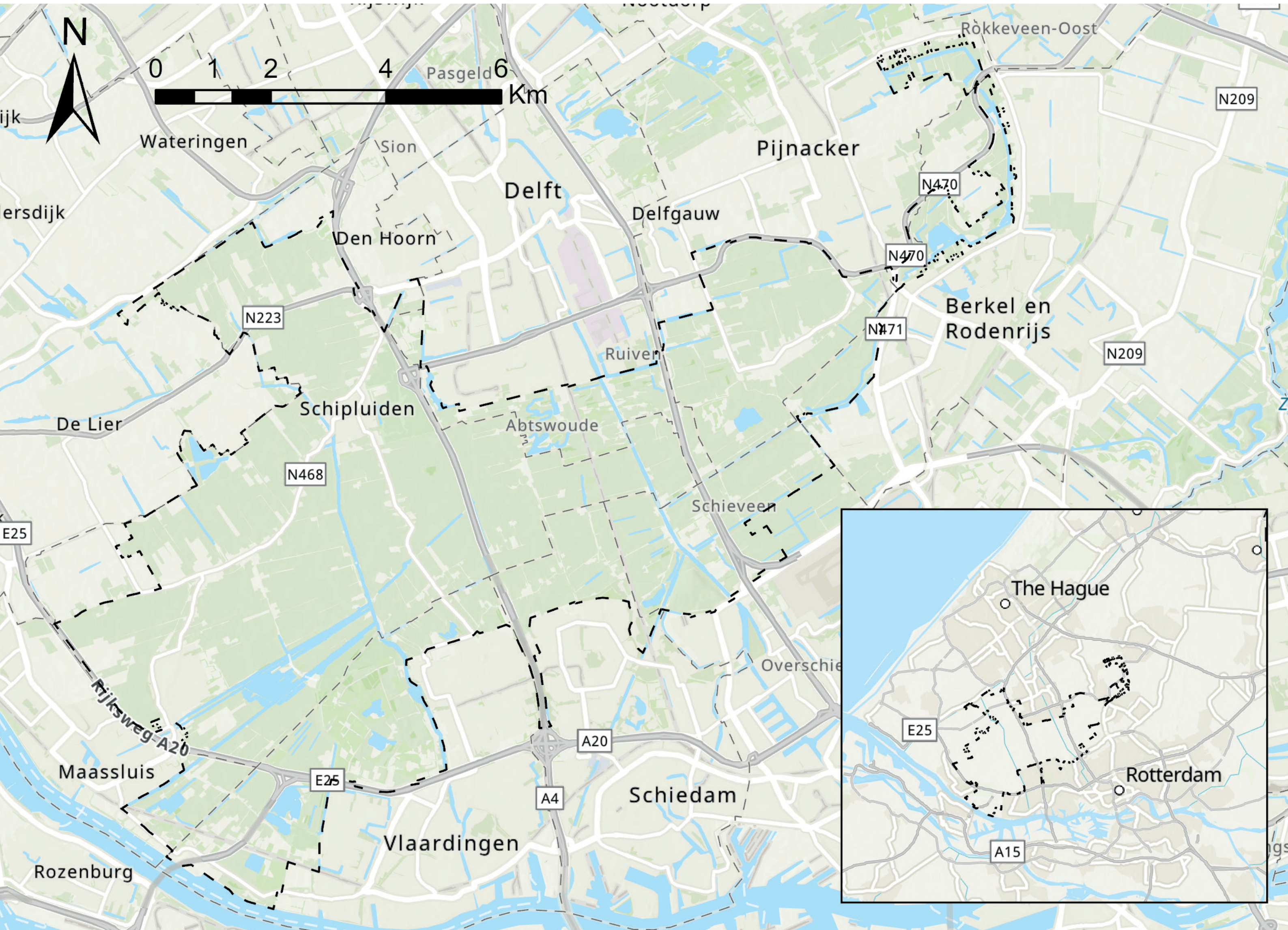
Historically, Midden-Delfland evolved from a marshy peat lagoon some 5,000 years ago. Human cultivation of peatlands began around the 10th century, marking the start of their current agricultural function. The area's landscape was further shaped by centuries of drainage, peat extraction, and canal construction. These landscape dynamics remain visible today and play a large role in current spatial and environmental challenges (Born et al., 2016).

Additionally, the area is designated as a core meadow bird habitat. Within the urbanised Randstad, Midden-Delfland stands out as a stronghold for these traditional Dutch bird species. Its open landscape offers ideal breeding conditions. The Netherlands has international obligations to protect meadow birds under the Birds and Habitats Directive and related treaties (European Union, 2009; Provincie Zuid-Holland, 2019).

3.2 The rural landscape under pressure

Midden-Delfland faces pressing land subsidence issues due to ongoing peat oxidation. According to TNO & Deltares (2021), subsidence rates range from 10 mm to 60 mm per decade, depending on location and land use. This process is environmentally undesirable and, additionally, a severe threat to the economy, leading to costly damage to infrastructure such as roads, pipelines, and housing foundations.
The necessity of groundwater in this region is twofold: it is essential to prevent further peat oxidation by maintaining higher water tables, while simultaneously managing competing land-use demands. During periods of drought, groundwater levels drop significantly, requiring water to be imported from surrounding areas. On the other hand, during heavy rainfall, the long and narrow polder canals must evacuate excess water quickly to prevent inundation. The area's geomorphologic characteristics, which are lower than those of its surrounding cities, make this particularly difficult. Next to this, the space for canal widening or dike reinforcement is limited since roads and houses are built close to the water.

Figure 1 The study area embedded in its larger context. Created by the author.



3.3 Midden-Delfland's identity

Midden-Delfland's landscape is both socially and culturally significant and has its specific 'Dutch' peatland characteristics. The area's identity is connected to its openness, historic continuity, and role as a quiet recreational escape for the 1,3 million urban residents from the large surrounding cities (Provincie Zuid-Holland, n.d.). These qualities are protected through regional planning instruments that have their roots in the former *Rijksbufferzones,* national policies that limited urban expansion. While national directives have shifted, the provincial and municipal governments continue to proceed these principles in their spatial visions (BPL Midden-Delfland, n.d.; Provincie Zuid-Holland, n.d).

The region's multifunctional character, balancing agriculture, nature, and recreation, creates both tensions and options for collaboration. On one hand, it presents the challenge of diverging interests competing over the same space. On the other hand, it opens up opportunities for integrated land-use strategies that embrace all landscape functions and tackle climate change.

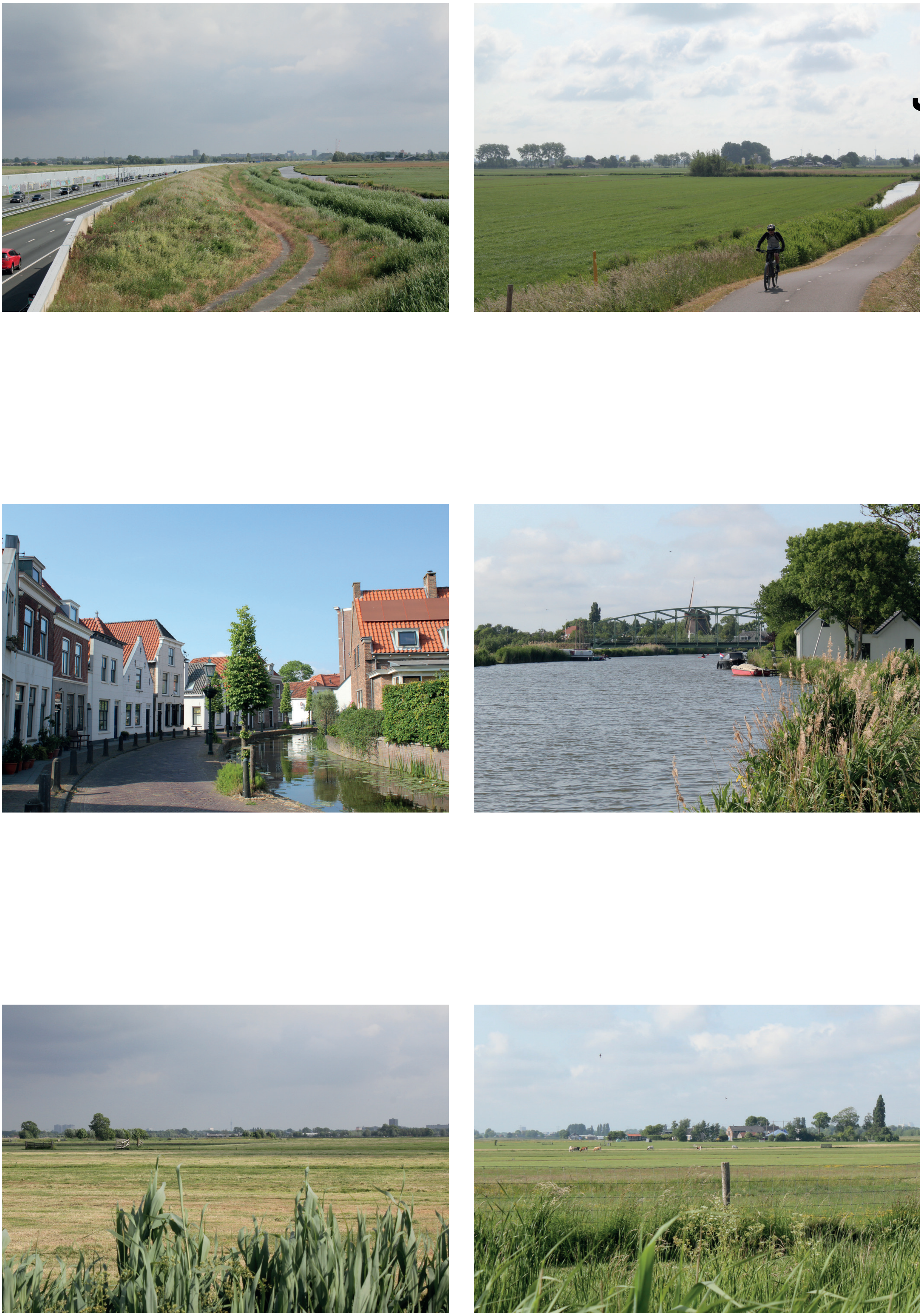


Figure 2 Visual impression of the study area surroundings. Pictures made by the author.

Literature Review

4. Literature Review

This chapter provides the scientific foundation for understanding the role of groundwater in climate-resilient spatial planning. This chapter outlines the natural dynamics and importance of groundwater, with a focus on its management in the Dutch context. It highlights the link between groundwater and peat soils, and explores the different strategies and measurements for groundwater elevation to support climate adaptation. These sections form the technical basis for evaluating the feasibility and implications of groundwater elevation in Midden-Delfland.

4.1 Groundwater: what is it and how does it work

Groundwater refers to water stored beneath the earth's surface, occupying the pore spaces of soil and rock from a certain depth downward. It infiltrates from precipitation, rivers, lakes, and other surface waters and accumulates in permeable underground layers until reaching an impermeable boundary. These groundwater reserves are essential to global water cycles and form the foundation of ecosystems, water supplies, and land use systems (Becker et al., 2022; Wei et al., 2024).

A distinction is made between unconfined and confined aquifers. The upper, unconfined aquifer is in direct contact with the atmosphere and is most responsive to seasonal cycles, typically replenishing during wetter winter months and declining in summer. Discussions on groundwater elevation refer to adjustments in the upper aquifer. These shallow zones are actively managed through surface water level regulation. In contrast, deeper confined aquifers, which are isolated by impermeable clay layers, contain ancient groundwater that recharges very slowly and is generally only used for specific industrial purposes or thermal energy systems due to its lower water quality (Wei et al., 2024).

While surface water bodies like rivers and lakes renew on timescales ranging from days to decades, groundwater regeneration is far slower. On average, groundwater takes about 1,400 years to renew, with fossil reserves taking up to millions of years (Mays, 2013). This slow renewal rate underlines its vulnerability and the urgency of sustainable management.

Natural Dynamics and Seasonal Fluctuations

Groundwater levels naturally fluctuate as part of the hydrological cycle, although it does have significant delays. While rainfall impacts surface water almost immediately, it may take weeks or even months before changes are observed in groundwater measurements due to the slow percolation of water through soil layers (Becker et al., 2022). This lag contributes to the invisibility of groundwater dynamics in public awareness and policymaking, as it often only surfacing in debates when scarcity or damage becomes apparent.
Rivers can either drain or refill groundwater reserves, as illustrated in Figure 3 (Safeeq & Fares, 2016). Periods of high surface water levels, such as floods, recharge groundwater. The depth of the water table depends heavily on soil composition, topography, and land use. In lowland areas with clay or peat soils, the water table is generally shallow and more sensitive to manipulation than high lying areas with sandy soils.

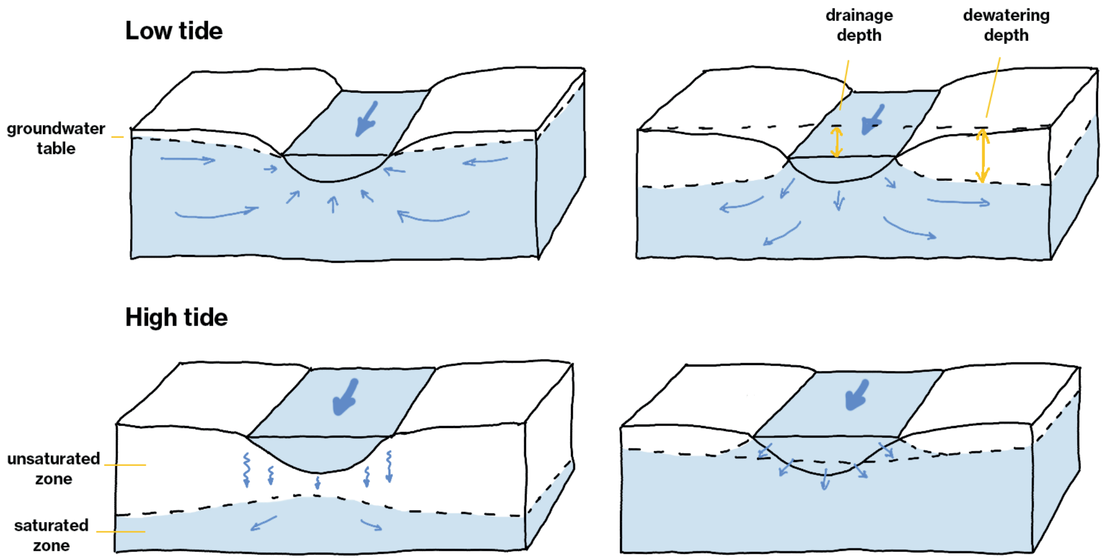


Figure 3 Interaction between surface water and groundwater. Created by the author.

Pressures on the Groundwater System

In the Netherlands, multiple challenges threaten the sustainability of groundwater systems. These include over-extraction for agriculture and drinking water, pollution from surface activities, and climate-induced shifts in precipitation and evaporation patterns (Becker et al., 2022). As groundwater levels drop, soil subsidence increases, and natural areas can dry out.
Looking ahead, groundwater usage is projected to increase globally, with agricultural demands alone expected to rise by 14% by the end of this century (Srivastav et al., 2021). While groundwater is a renewable resource, it can only support this growing pressure if managed carefully. When mismanaged, it risks becoming a temporarily non-renewable source, with long periods of drought exacerbating scarcity (Eulenstein et al., 2016).
Pollution adds another layer of complexity. Surface contaminants such as pesticides, fertilizers, road runoff, industrial waste, leaking infrastructure, and acid rain infiltrate soils and gradually degrade groundwater quality. Due to its slow movement, it often goes unnoticed, and once contaminated, it is extremely difficult to purify (Tiemeyer et al., 2007).

Groundwater in the Netherlands

Origins of Dutch Groundwater

In the Netherlands, groundwater stems from three main sources (Centraal Bureau voor de Statistiek, 2021):

1. Precipitation
2. Infiltration from surface water bodies
3. Ancient groundwater reserves

Each of these sources plays a different role across regions. In provinces like South Holland, where surface water is abundant, groundwater is primarily used to support ecosystems, agriculture, and thermal storage, while in eastern regions it remains a major source of drinking water.

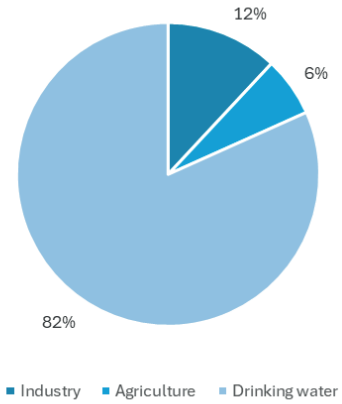


Figure 4 Groundwater usage in the Netherlands. Adapted from CBS (2021).

Usage of groundwater

Groundwater supports different sectors, which are in the Netherlands the following: 82% drinking water supply, which contributes to 50% of the national total, 6% agriculture, used for irrigation of crops, and 12% industry, for cooling and processing needs (Centraal Bureau voor de Statistiek, 2021). The distribution of the water to these sectors is visible in Figure 4.

Apart from the sectors which take the groundwater out of the groundwater system, there are also sectors which use the water by not taking it out of the system. This is the case for ecosystem functions (wetlands, forest root zones) and thermal energy systems (Aquifer Thermal Energy Storage). The multifunctionality of groundwater creates significant tensions in land use and spatial planning, especially in times of drought or when land use changes, like urbanization, increase extraction pressure. Growing population and a growing economy contribute to this pressure on the groundwater reserves (Centraal Bureau voor de Statistiek, 2021). The sustainability of the system is based on the ability to balance these competing needs.

Concludingly, groundwater is a slow-moving yet indispensable component of environmental and spatial systems. Yet it is increasingly under threat from overuse, pollution, and climate change. In the Netherlands, groundwater is tightly integrated into spatial planning and is one of the key foundations of a climate-resilient, liveable future. Managing this resource requires balancing ecological needs, societal demands, and land-use functions.

Groundwater management

Groundwater levels regulation

In the western Netherlands, including Midden-Delfland, natural groundwater levels no longer exist. Water boards actively control all water levels through surface water management. This is done on the scale of a water management unit, varying from size between several plots to a polder. Canals, ditches, and lakes are regulated by pumps and sluices that infiltrate adjacent soils, and with that raising or lowering the groundwater level (Becker et al., 2022).

This management system is controlled by a formal water level management decision. Each water level management decision is tailored to local land use and typically balances conflicting interests: farmers require lower groundwater levels to access fields with machinery, while nature managers prefer wetter conditions to preserve biodiversity and reduce CO_2 emissions from peat oxidation. Water level management decision are adapted when land uses change or problems arise. This is done in dialogue with the stakeholders being affected in that specific area.

Seasonal variation

To help regulate groundwater levels, different surface water levels for summer and winter are often maintained (Rozemeijer et al., 2019). These levels are managed in ditches, canals, and lakes and reflect seasonal differences in temperature, precipitation, and water demand. During summer, higher temperatures and increased evaporation coincide with the growing season, when vegetation extracts more water from the soil. Without regulation, groundwater levels tend to curve inward (drop) in summer and outward (rise) in winter. The natural outward curve in wetter months can hinder agricultural activities, such as fertilizing and mowing, while the inward curve in drier periods accelerates peat oxidation and soil subsidence. To counter this, higher surface water levels are maintained during summer to reduce groundwater depletion and enable continued agricultural use, especially in rural areas where vegetation-driven water demand is high (Rozemeijer et al., 2019).

Technical and physical determinants

The effectiveness of groundwater regulation is influenced by multiple physical factors (Zhang et al., 2017):

- Distance between ditches and canals
- Soil porosity and permeability
- Rainfall and evaporation
- Drainage infrastructure (pipes and infiltration systems)
- Regional groundwater dynamics (infiltration, upward seepage)

In anticipation of heavy rainfall, water levels are sometimes lowered as a precaution to create storage space. These dynamics are carefully monitored by regional water boards, who respond proactively when significant rainfall or drought is forecasted.

4.2 Peat soils and greenhouse gas emissions

Groundwater levels play a decisive role in the functioning of peat soils. In the Netherlands, peatlands cover around 7% of the surface area and are known for their organic, carbon-rich composition. These soils are formed by the accumulation of dead organic matter in saturated, anaerobic conditions, without the input of oxygen, over centuries (Aben et al., 2024; Page & Baird, 2016). When the water table drops and oxygen penetrates the peat, microbial decomposition is triggered. This oxidation process results in the release of carbon dioxide (CO_2) and nitrous oxide (N_2O) and contributes significantly to greenhouse gas (GHG) emissions, while simultaneously causing soil subsidence.

Peatlands can act both as a source and a sink of greenhouse gases. When peat is drained and oxidized, CO_2 and N_2O are released into the atmosphere (Paul et al., 2024). Fertilizer application further increases the availability of degradable nitrogen, leading to additional N_2O emissions. Methane (CH_4), in contrast, is produced when organic material decomposes under waterlogged conditions. It is important to note that N_2O and CH_4 have a much greater global warming potential than CO_2: one kilogram of N_2O has the same warming effect as 296 kilograms of CO_2, while one kilogram of CH_4 equals 23 kilograms of CO_2.

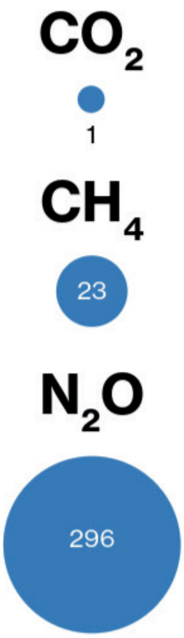


Figure 5 The global warming potential of greenhouse gases relative to each other. Created by the author.

Looking specifically at the different GHGs emitted, a strong correlation can be found between CH_4 emissions and groundwater depth. Furthermore, CO_2 emissions are strongest linked to soil temperature and N_2O emissions are primarily linked with nitrogen content in soil (Purvina et al., 2023). Research on GHG emissions from peat soils also indicates that the thickness of the peat layer significantly affects emission rates. Thicker peat layers are associated with increased CO_2 and CH_4 emissions, with CH_4 emissions becoming significant when peat depth exceeds 40 cm (Purvina et al., 2023).

In addition, the presence of an inorganic topsoil layer influences the vulnerability of the underlying peat to oxidation (Paul et al., 2024) In the study area, some parts of the peat meadow landscape have been covered for centuries by a layer of marine or river clay (Basisregistratie Ondergrond, 2024). Such a clay layer has low permeability and poor air and water infiltration capacity, which limits oxygen penetration into the peat. As a result, peat oxidation, and thus CO_2 emission, is reduced (Y. Wang et al., 2021). According to Paul et al., (2021), increasing the groundwater table in combination with mineral soil coverage can reduce GHG emissions, specifically the N_2O emissions. While adding a mineral soil cover to drained peatlands as a GHG mitigation strategy did not significantly reduce soil organic carbon losses, it did lower N_2O emissions and improved the overall GHG balance.

Other factors influencing peat oxidation include higher temperatures, which increase bacterial activity and lead to greater GHG emissions. Microbial decomposition of peat approximately doubles with every 10°C rise in temperature (Hilasvuori et al., 2013). Additionally, a high pH level promotes peat oxidation, whereas a low pH can slow the process. Finally, seasonal variations in the water cycle contribute to higher peat oxidation rates during the summer, when groundwater levels are naturally lower, compared to winter conditions (Aben et al., 2024).

The current water table in agricultural peat areas in the western part of the Netherlands is maintained at approximately 60 cm below surface level, primarily to facilitate machinery use for agricultural practices and provide optimal conditions for grass growth (de Jong et al., 2021). However, this depth also accelerates peat degradation. Climate change further exacerbates the issue, as warmer and drier summers intensify oxidation. Over 80% of annual peat oxidation occurs in these warmer months, underscoring the relevance of seasonal water management.

The optimal groundwater level for climate mitigation

Scientific research identifies a groundwater depth of -20 cm below surface level as most favourable to minimise GHG emissions from peat soils (Aben et al., 2024; Evans et al., 2021; Tiemeyer et al., 2007). This is also referred to as a dewatering depth of 20 cm. Water levels below this point increase CO_2 emissions due to oxidation, while levels above it increase the net GHG balance due to occurring methane (CH_4) emissions, a gas which is 28 times more potent than CO_2. Drainage significantly increases N_2O emissions, especially in nutrient-rich peat soils, although this remains a relatively under-researched aspect of GHG dynamics in peatlands (Minkkinen et al., 2020). However, studies suggest that groundwater elevation, also called rewetting, can reduce N_2O emissions to levels comparable to or even lower than those of undrained peat (Minkkinen et al., 2020; Wei et al., 2024). These findings underscore the importance of precise groundwater management. Even small changes in water level, such as a 10 cm increase, can substantially reduce net emissions while allowing continued agricultural use, as illustrated by the correlation displayed in Figure 6.
The Water and Soil Guiding Policy of the Dutch government also aligns with this as they state in the policy the following: *groundwater levels in peatland areas should rise to 20–40 cm below the surface to reduce subsidence and emissions* (Ministerie van Algemene Zaken, 2022).

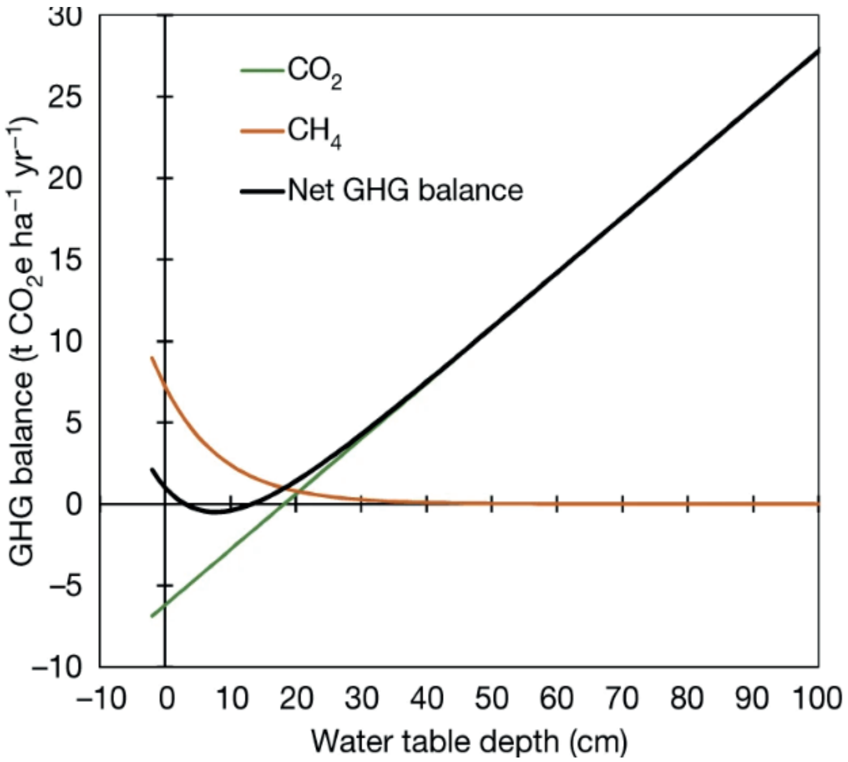


Figure 6 GHG balance at different groundwater levels (Evans et al., 2021)

Local emissions and broader impacts

In Midden-Delfland, annual CO_2 emissions from peat oxidation were estimated between 29,000 and 35,000 tons in 2022 (Arcadis et al., 2024). Groundwater elevation in such areas can offer an effective strategy to reduce emissions. This mitigation also has co-benefits: reduced soil subsidence, improved biodiversity, increased water retention, decreased salinisation risks, and lower irrigation needs during summer months. These outcomes align with national strategies such as the Climate Agreement and the Water and Soil guiding policy, which both promote peatland rewetting (Ministerie van Algemene Zaken, 2022; Ministerie van Economische Zaken en Klimaat, 2019b).

Groundwater elevation measures

Groundwater elevation can be achieved through a variety of strategies. Below are several different measurements for rewetting illustrated, applicable to the low-lying Dutch peatlands. Some measurements directly rewet peat soils to reduce GHG emissions, while others support this aim indirectly by modifying the landscape or agricultural practice. These different measurements are gathered from expert interviews and literature review.

- **Surface water level management:** This is the most traditional way of reaching groundwater elevation, and has been used for centuries (Becker et al., 2022). This involves raising ditch and canal water levels to promote infiltration. This measurement is highly dependent on soil infiltration capacity, to create an effect on the groundwater table. Therefore, its effectiveness in peat areas is limited ,unless combined with more targeted subsurface interventions, as peat has a low infiltration capacity. This measurement would have an effect up until two metres from the designated surface water on peat soils (expert 2).

- **Underwater drainage (WIS):** A subsurface rewetting technique that distributes surface water through perforated pipes buried 30–60 cm deep (Aben et al., 2024). This method is already being used in some dairy farms in low-lying areas. This method is only effective in peat layers thicker than 60 cm and requires a surface water level, where it attracts the water from, at the same height. It is primarily suitable where the land remains in agricultural use, particularly for grassland. Long-term flexibility is limited since installation depth fixes the maximum achievable groundwater level.

Figure 7 Furrow infiltration in field. Own image.

- **Furrow infiltration:** Shallow ditches allow surface water to infiltrate during dry periods. With a typical depth of 60 cm, this strategy is comparable to WIS in effectiveness and is often used seasonally (Daun et al., 2023). In summer, added water helps elevate the groundwater level, while in winter, these shallow ditches will drain the water from the field. These ditches are depicted in Figure 7. However, there are risks such as trampling by livestock and operational hindrance for machinery. It is a relatively low-cost rewetting strategy, best suited to areas where minor infrastructural change is feasible.

- **Fixed water level management:** Instead of adjusting water levels to be lower when the soil subsides, to keep the same dewatering depth, this strategy keeps the surface water level constant, allowing natural groundwater rebound. It is a long-term rewetting strategy that is especially effective in conservation and biodiversity zones. This is a strategy which goes together with surface water level management.

Other complementary or alternative strategies which focus on GHG emission reduction are:

- **“Do nothing” in shallow peat:** In areas with limited peat depth, rewetting may be ineffective. Here, CO_2 emissions and subsidence could be accepted as unavoidable. However, climate targets for 2050 increasingly challenge this passive approach. This is named as a measurement for areas with less than 40 cm peat thickness.
- **Clay addition to peat:** This measure aims to chemically bind carbon in peat, which would reduce the carbon emissions while keeping the same groundwater level. While this measure is promising in theory, its practical and ecological benefits remain uncertain (Z. Wang et al., 2022).
- **Farm management changes:** Adapting agricultural practices to higher water levels is an option to continue agricultural practices. This could be done with different, lighter machinery, and different cattle. These changes reduce soil compaction and enable higher water tables while maintaining some productive use, although agricultural viability most likely will be decreased. This is still in an experimental phase.
- **Wet agriculture (paludiculture):** This rewetting-based land use involves crops like reed or peat moss, cultivated in saturated soils, with groundwater levels between -40 cm until +20 cm. While these paludicultures are promising, the practice is still developing and requires market growth and technical support (de Jong et al., 2021).
- **Land use change:** Another measurement is shifting land away from agriculture toward functions that accommodate higher water levels. This could be a structural solution where land is repurposed for nature, water storage, or recreation. This would be a robust strategy for long-term emission reduction, especially in the lowest and wettest peat zones, where yields from agriculture would be too low.

As can be seen multiple strategies can be proposed, but all have different preconditions, such as scale or costs, which can make some more favourable than others in a specific context. Additionally, peat depth, infrastructure availability, desired land use, and water system capacity play a big role in the consideration. The choice of measure depends on whether GHG reduction is pursued through direct rewetting or through adaptation and landscape redesign. In most cases, a combination of approaches will be required to meet environmental goals while maintaining social and economic viability, as was mentioned by multiple experts. The cost of implementing groundwater elevation measures varies widely. While systems like WIS are technically effective, adoption depends on subsidies and long-term land use intentions. In general, the deeper the initial drainage, the longer rewetting takes, and the more intensive the investment. For some farmers, switching to extensive agriculture or ecosystem service compensation schemes might offer a sustainable transition path (Born et al., 2016).

In conclusion, groundwater elevation is a key strategy to reduce GHG emissions from Dutch peatlands, but it requires careful balancing of ecological benefits, economic viability, and practical feasibility. Precision in water management is essential to achieve the desired climate mitigation outcomes. The challenge ahead lies in combining climate goals with the realities of agriculture, infrastructure, and water management in vulnerable landscapes like Midden-Delfland.Groundwater in the Netherlands

Theoretical Framework

5. Theoretical Framework

This chapter outlines the theoretical foundation of this research, drawing from existing literature to establish the connection between natural systems, social uses, and spatial planning. The framework is structured in three key components: it consists of an analytical framework, a relational framework between different components and a strategical framework. These components are theoretically supported, respectively, by the Dutch layers approach, theories on the connection between land use and ecosystem services, and Theory of Change. By integrating these perspectives, this chapter provides the theories necessary to interpret, shape, and support the transition towards a sustainable land-use planning in Midden-Delfland.

5.1 Understanding the relationship between subsoil and spatial planning

Spatial planning plays a crucial role in adapting to climate change, as it influences how external factors, such as rainfall infiltration and heat stress, interact with the subsurface (Hurlimann & March, 2012). Stead (2014) highlights that urban resilience is widely acknowledged as a necessary objective within spatial planning, given its role in both climate change adaptation and mitigation.

5.1.1 The Dutch layers approach

The Dutch layers approach offers a framework to objectively analyse how one layer of spatial planning influences another, while accounting for the spatial planning system as a whole. Developed in the late 1990s by De Hoog, Sijmons, and Verschuuren, the model recognizes that spatial planning should be rooted in the physical characteristics of the underlying soil and water systems (van Schaick & Klaasen, 2011). The model divides the landscape into three interdependent layers, visible in Figure 8, each with its own dynamics.

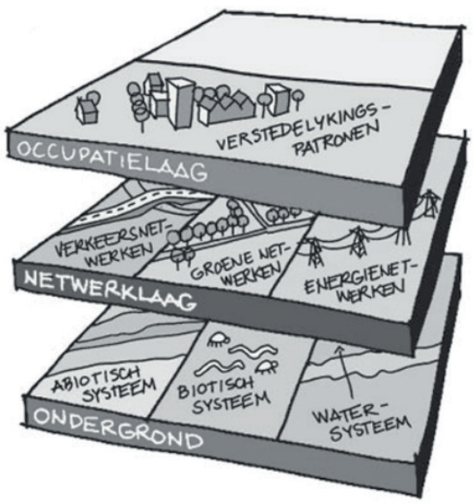


Figure 8 The Dutch layer approach. Top to bottom: occupation layer, networks layer, subsoil layer. De Hoog et al. (1998).

Subsoil

The subsoil layer encompasses the coherent physical, chemical and biological processes of the substratum (van Schaick & Klaasen, 2011). The soil holds a historical archive and carries the landscape identity. It examines the geological processes of a place, the soil composition and topography. The layer has the longest 'lifecycle', with the slowest dynamics. Long-term processes such as climate change and land subsidence have profound effects on the subsurface, particularly on water management. The subsoil specifically endures the physical effects of climate change.

Networks

Networks include the physical flows and infrastructure of goods and resources (van Schaick & Klaasen, 2011). It is about how the food, energy, water and data systems are laid out spatially. The networks are critical in spatial plannings. These infrastructures are an important prerequisite for urban and economic dynamics. The economic development and urbanization pattern are strongly linked to transportation opportunities and other critical infrastructures. Moreover, once a network like a road- or watersystem is created, other occupations will emerge as self-evident and a function of an area will change inevitably. The networks layer has a renewal cycle of approximately 50-100 years.

Occupation

The occupation layer is most dynamic with a life cycle of 25-50 years (van Schaick & Klaasen, 2011). This is the layer which indicates the spatial use patterns that result from human utilization of the subsurface and networks. It examines the way the land is used by humans, with for instance housing, sports fields, factories and greenhouses, wind turbines, nature areas and recreational zones. Although this layer has the quickest renewal cycle, the *political* debate often focuses on this layer as it is the most visible and affects inhabitants directly.

All in all, the layer approach makes the different components from each layer visible and ensures that development is shaped based on a thorough understanding of the landscape.

5.1.2 Connecting land use to ecosystem services

Landscapes provide ecosystem services that sustain both human and environmental well-being. Among these are water purification, climate regulation, carbon storage, and food production. Assis et al. (2023) emphasize that the spatial configuration of landscapes directly influences how these services are supplied, distributed, and accessed. At the same time, ecological constraints, such as limited water availability or declining soil quality, sets boundaries on how land can be used and developed. Understanding this two-way interaction between land use and ecosystem services is of importance for sustainable spatial planning.

Ecosystem services can be seen as the benefits humans derive from a healthy environment. The research categorizes ecosystem services into three parts: supply: the capacity of an ecosystem to provide a service, flow: the process of how the service reaches the end user, and demand: the societal need or desire for a particular service (Assis et al., 2023). In these systems, spatial arrangement matters, as it determines how supply can effectively meet the demand. Small changes in landscape structure, such as fragmentation or connectivity, can significantly alter the flow of an ecosystem service.

For this research, one of the important ecosystem service is water regulation. Understanding how land-use patterns affect groundwater recharge and hydrological cycles is critical for designing climate-adaptive planning strategies. By incorporating ecosystem service principles, this research develops a framework that maximizes the benefits of groundwater sustainability for both nature and society.

Building upon the work of M. Liu et al. (2022), this study acknowledges the interconnectedness between land-use change, ecosystem service flows, and human well-being. These interdependencies highlight the need for spatially explicit and multiscale planning tools, to help align the spatial scale of ecological processes with socio-economic decisions, enabling more informed and context-specific planning.

Vagge et al. (2024) highlight how landscape ecology helps to understand what makes a landscape vulnerable or resilient. By looking at the landscape as a dynamic system, it becomes easier to see how changes, like climate impacts, human activity, or land-use shifts, might affect it. This perspective can support the development of strategies that improve ecosystem services, help rebalance the relationship between urban and rural areas, and strengthen the landscape's ability to cope with the effects of climate change.

The interconnection between landscape structures and water dynamics reinforces the need for integrated hydrological and spatial planning. Combining this perspective with the Dutch Layers Approach strengthens the foundation for designing climate resilient land-use strategies.

5.2 Transitioning towards sustainable land-use

Addressing groundwater challenges in spatial planning requires a strategic transition framework that maps out how these changes can occur. Theory of Change (ToC) serves as a guiding framework for designing, implementing, and evaluating this transition (Piras et al., 2022). ToC is process-oriented, making it suitable for structuring long-term climate adaptation strategies.

ToC serves in this research as a guiding lens for analysing how and why changes in spatial planning for sustainable groundwater management can lead to sustainable outcomes. The framework of ToC helps structure a transition by going through several steps. Firstly, the current problem is identified, then mapping short-term interventions, defining the long term vision, making assumptions explicit, and mitigating risks (Connell & Kubisch, 1998)

According to (Piras et al., 2022), ToC is an approach that visualizes the logical flow of change, specifying how short-term actions lead to long-term social, environmental, or economic transformations. It is particularly useful for addressing complex sustainability challenges.
Ultimately, by structuring the process of adaptation in a logical sequence, identifying risks, challenges, and key stakeholders and ensuring that scientific findings translate into real-world action, Theory of Change can help make actionable and socially viable recommendations.

In conclusion, by integrating the Dutch layers approach, the ecosystem service framework, and Theory of Change, this research establishes a thorough theoretical foundation for land-use planning with groundwater.

Conceptual Framework

6. Conceptual Framework

This chapter presents the core concepts which are relevant for the research to create a common understanding. This will then be used to operationalise the concepts in order to work with them in the research. The approach involves looking at the topic through three hierarchic layers: ecology, society, and economy.

6.1 A hierarchical approach

The hierarchy applied in this research is inspired by the nested model developed by Pryn et al. (2015), which conceptualises sustainability as a layered system. In this model, ecological systems form the foundational layer upon which societal systems depend, and in turn, economic systems are nested within society. The nested model recognises the conditional dependencies between these layers and emphasises that long-term sustainability can only be achieved if ecological limits are respected first.

The applied hierarchical framework, looks, in the context of the research as follows, and is presented in Figure 9:

- Ecology: environmental sustainability - the foundation that supports all other systems
- Society: infrastructure resilience - the essential systems enabling social function
- Economy: agricultural viability - the economic land-use dimension necessary for sustainable livelihoods

Each layer is essential, but dependent on the layer(s) beneath it. The conditionality anchored in this framework is essential, as, for instance, without a functional ecological base, both infrastructure resilience and agricultural viability cannot be sustained. These layers provide the guiding lenses for the approach to sustainable land-use planning in this research. This research specifically approaches this from a robust water system from which the sustainable land-use will be built around and upon.

The division in the three categories also coincides with the goals of the area, set by the involved interest groups of BPL Midden-Delfland (n.d.): to protect and enhance the 1) natural landscape (ecology) 2) agricultural landscape (economy) and the 3) recreational landscape (society).

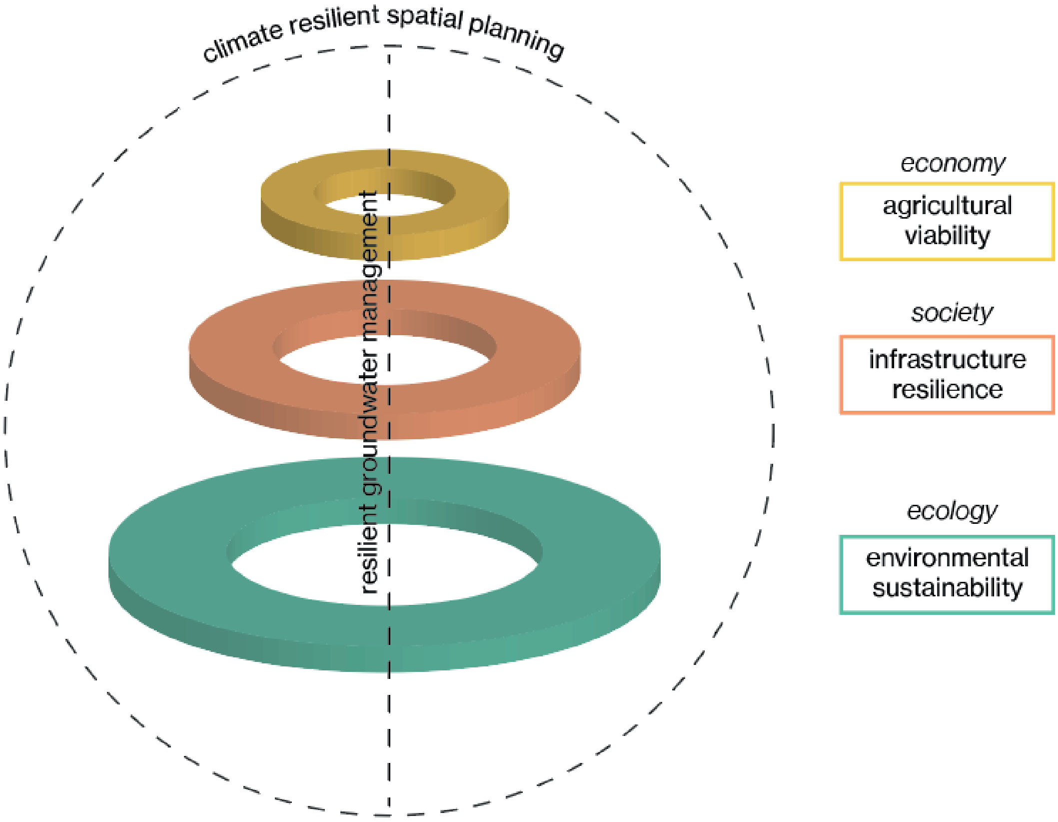


Figure 9 Conceptual framework for the research. Created by the author.

6.2 Environmental sustainability

First of all, the concept of environmental sustainability is explored. This perspective is related to the ecology layer and is most dominant perspective in this research, as without a functional ecosystem, the other perspectives cannot work effectively. The definition of this concept is drawn and adapted from Brundtland (1987) and encompasses managing natural resources and ecosystems in ways that meet current needs without compromising the ability of future generations to meet theirs. In the environmental scope, it focusses on reducing effects of pollution, conserving biodiversity, and promoting sustainable land use, water management, and energy consumption (Goodland, 1995). Goodland stresses the monumental challenge of "ensuring this within less than two human generations, that as many as ten billion people are decently fed and housed without damaging the environment on which we all depend, means that the goal of environmental sustainability must be reached as soon as humanly possible" (1995, p.21).

In this research specifically, the water management part of environmental sustainability is looked into, which is, as elaborated on in the previous chapter, of great importance for battling climate change.
Water management entails: 'the planning, development, distribution, and optimal use of water resources, encompassing both surface water and sewage systems'. The management of water resources must consider both quantity and quality aspects, particularly in the case of freshwater (Lavoie et al., 2014).

As climate change intensifies, effective groundwater management must integrate both quality and quantity dimensions to adapt to water inflows from rainfall, surface water, and rising sea levels (Srivastav et al., 2021). Resilient groundwater management is therefore critical to supporting environmental sustainability.

6.3 Infrastructure resilience

Looking at the society layer, infrastructure resilience is an important concept for this research. To achieve a well-functioning society in the context of the problem at hand, infrastructural systems must be robust and adaptable. It can be seen as all critical societal functions.

Infrastructure resilience refers to the ability of critical systems to society, such as roads, bridges, water supply, energy grids, and communication networks, to withstand, adapt to, and recover from disruptions, including natural disasters, climate change, cyberattacks, and other shocks (Vamvakeridou-Lyroudia et al., 2020). Additionally, recreational infrastructure can be seen as an infrastructure which keeps society functioning and enhance societies well-being.

In this research, infrastructure resilience is the capacity of the built environment to function safely and effectively under changing environmental conditions (climate change), while minimizing long-term damage, risk, and costs, especially in a peat-based landscape affected by subsidence and climate change.

While this layer is less foundational than environmental sustainability, it still remains essential. Without stable infrastructure, societal functioning worsens. However, this infrastructure must be supported by an ecologically stable base. By embedding infrastructure resilience within a sustainable land-use framework, this research aims to design a spatial strategy that can respond to various disturbances.

6.4 Agricultural viability

At the top layer of the conceptual framework is agricultural viability, which is essential for economic sustainability within the research context. The agricultural sector is necessary for maintaining rural economies, food security, and landscape management. Viability is crucial in this case, since without a viable business plan, system change is hard to reach as it is one of the key factors herein (van der Hilst et al., 2010). Agricultural viability refers to the ability of farmers to maintain a productive and economically sustainable agricultural business.

For this research, agricultural viability is analysed in relation to groundwater management, exploring how water availability impacts farming productivity, how sustainable land-use strategies can reduce vulnerability to climate change and how multifunctional land use can support multiple pillars as nature and agriculture.

By focusing on long-term agricultural sustainability, this research goes beyond short-term profitability concerns. It emphasizes how climate-adaptive farming practices can ensure continued agricultural viability in the coming decades.

6.5 Resilient groundwater management

Tying the three layers together is the concept of resilient groundwater management. In this research, groundwater management is about a careful balance between the previously mentioned environmental needs, societal functioning, and economic viability.

Resilient groundwater management means using water resources wisely and adaptively (Carter, 2007). High water tables can reduce subsidence and support biodiversity, but may also lead to increased flooding or damage to infrastructure. A resilient system anticipates and navigates these trade-offs. It requires raising water levels where possible, lowering them where necessary, and being aware of the system-wide consequences of those decisions.

Sustainability in water management, including groundwater management, is crucial in the context of climate change. Mays (2013, p. 4412) defines sustainable water management as "the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life".
In conclusion, this conceptual framework highlights the importance of building a resilient groundwater system in Midden-Delfland by working through three interconnected layers: ecology, society, and economy. Starting with a sustainable ecological foundation, then adding robust (social) infrastructure, and finally ensuring agricultural viability, the framework provides a structured approach for developing climate-resilient spatial strategies.

Methodology

7. Methodology

This chapter describes the different research methods used for evaluating water level elevation in Midden-Delfland. To address the main research question, sub-questions have been developed divided into three different parts. To explore these sub-questions, the three-phase approach integrates both quantitative and qualitative methods to evaluate the feasibility and implications of higher groundwater levels in Midden-Delfland.

7.1 Research design

According to Bryman (2016), the combination of qualitative and quantitative approaches strengthens the validity of research findings through methodological triangulation. In this study, GIS and MCDA provide an objective spatial analysis of groundwater elevation suitability. In contrast, expert interviews and policy analysis contextualize these findings with insights from stakeholders and existing regulations. This mixed-methods approach provides a more thorough understanding and suits the

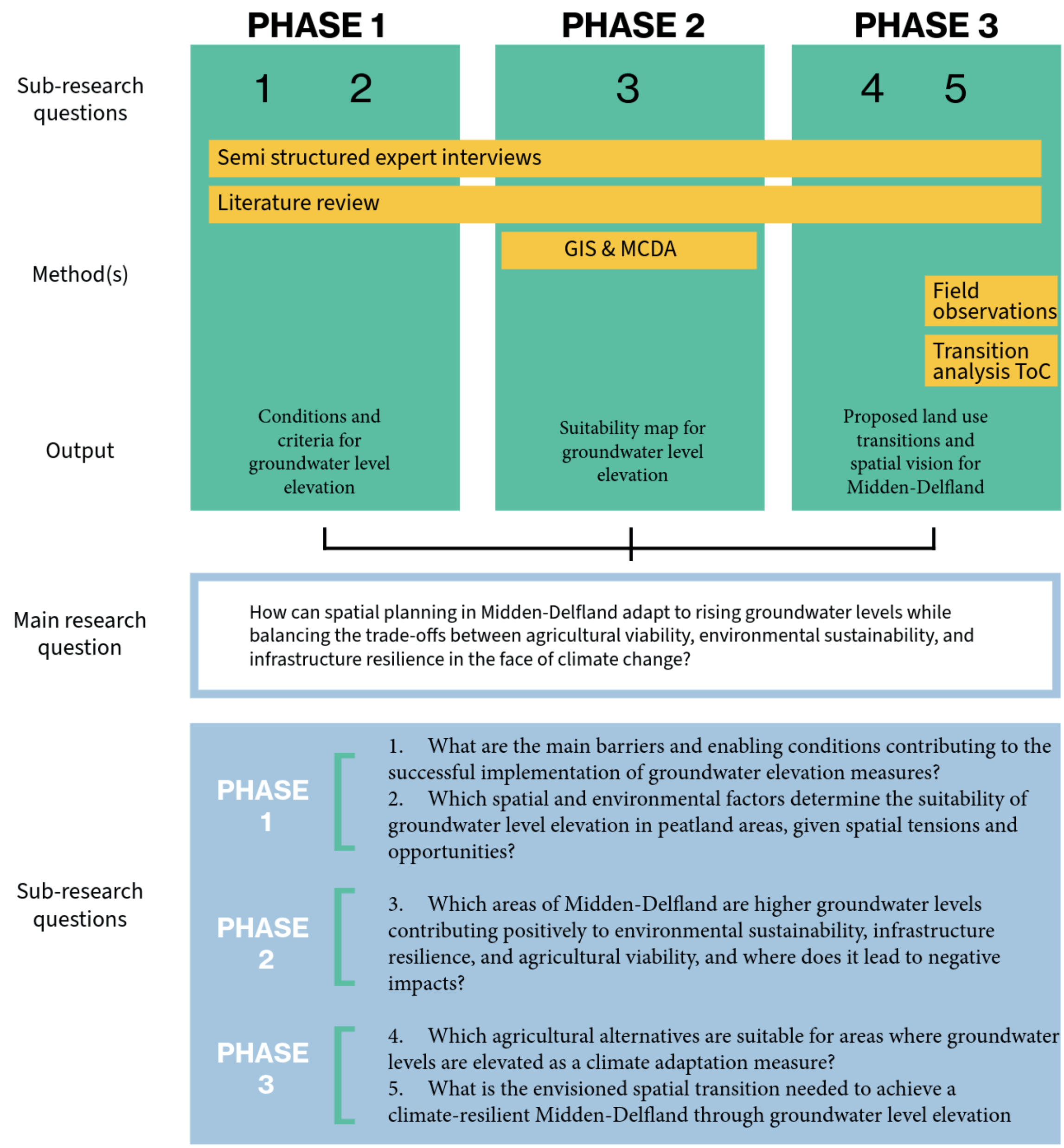


Figure 10 Research design. Created by the author.

interdisciplinary nature of this research on groundwater level adaptation, creating a relevant spatial vision proposal for Midden-Delfland.

In Figure 10 the research design is visualized, showing the different methods used for each of the research questions, and the objectives and expected outcomes.

7.1.1 Phase one

The first phase focused on identifying and analysing the key environmental and spatial criteria that influence or are influenced by groundwater levels, specifically in the Midden-Delfland region. Through literature review and expert consultations, this phase explored how these factors interact within the landscape and what implications they have for transitioning toward higher groundwater levels. The aim was to establish the main variables that should be considered for spatial planning decisions regarding groundwater levels.

7.1.2 Phase two

The second phase focused on analysing the current spatial conditions in Midden-Delfland using Geographic Information Systems (GIS) and a Multi-Criteria Decision Analysis (MCDA). The objective was to develop a verified suitability map identifying areas where higher groundwater levels would have the most positive impact on the three layers of the conceptual framework: environmental sustainability, infrastructure resilience, and agricultural viability.

7.1.3 Phase three

The third phase translated the spatial analysis findings into a vision for future planning of the area. This was achieved through qualitative research methods, including literature review, expert interviews, policy analysis, and transition analysis using the Theory of Change (ToC).

7.2 Data collection methods

7.2.1 Literature review

The literature review focused on gaining more knowledge on the research questions. Literature reviews are critical in identifying key factors and constraints relevant to a study (Bryman, 2016). In this research, the literature review informed the selection of environmental, hydrological, and land-use criteria for MCDA. Additionally, Literature was used to gain insight into how future spatial planning can be addressed in the present, and how the proposed spatial transition plan can best support long-term sustainability. Additionally, existing literature on (agricultural) land uses with different groundwater levels were consulted to identify viable land uses to include in the proposed spatial plan.

Scopus has been used as main search engine. Searching terms included: groundwater and spatial planning, groundwater elevation peatlands, spatial planning for future scenarios, drained peatlands GHG emissions, agriculture and high groundwater levels, land-use transition peat areas, agricultural viability paludiculture, and multi-criteria decision analysis spatial planning. Articles were initially screened based on title and abstract. Inclusion criteria were: (1) peer-reviewed or government-commissioned studies published after 2010 (unless foundational work); (2) relevance to peatland regions with comparable characterises; (3) a focus on spatial, hydrological, or policy aspects of groundwater level management. Grey literature, such as Dutch policy documents, reports from water boards, and white papers, was included where relevant to supplement academic findings.

A total of 52 papers or academic studies, relevant for the research, have been read. An additional 27 policy documents from the Dutch government, provinces and water boards have been consulted.

7.2.2 Expert interviews

Expert knowledge was gathered by interviews in various fields, related to the research, to gain further knowledge on the context and help determining weights of different criteria for the MCDA.

The experts which were consulted can be found in Table 1. All experts were from water board *Hoogheemraadschap van Delfland*. Acquiring interviewees went according to the snowball method. Experts mentioned other people which should be contacted for further information on relevant topics for the research.

Table 1 List of experts consulted for interviews

Role and expertise	**Expert no.**
Groundwater (hydrology) specialist	1
Peat soil specialist	2
Water level monitor for Midden-Delfland	3
Regional water management specialist	4
Biodiversity specialist	5
Water quantity Midden-Delfland	6
Agricultural advisor	7
Policy expert rural spatial strategy	8
Policy expert water and soil governance	9
Water level monitor for Oostland	10
Peat land-use and ecosystem specialist	11

All interviews were semi-structured, which provided a clear direction in the interview to collect in-depth insights from experts, but also give the opportunity to get off track to other important topics, that were not initially thought of. In social research, semi-structured interviews provide a balance between structure and flexibility, which allows researchers to explore key themes while adapting to new insights (Bryman, 2016). In this study, interviews with stakeholders from water management organizations served to validate indicators found in literature and provide insight into practical implementation challenges. This approach ensured that the study's recommendations were both scientifically valid and contextually relevant.

For the next phases, the expert interviews were conducted to assess the feasibility of the land use transitions. Stakeholders with different expertise provided insights into practical and theoretical challenges. These interviews helped refine the spatial plan by incorporating practical implementation considerations.

The following questions guided the semi-structured interviews:

- What physical characteristics determine the groundwater level in Midden-Delfland?
- What are the positive or negative impacts of a high groundwater level?
- Are there areas in Midden-Delfland where the groundwater level has already been raised, or where attempts have been made to do so?
- Which agricultural, infrastructure, and environmental characteristics make an area suitable or unsuitable for groundwater level elevation?
- What are the technical and social preconditions for raising groundwater levels in Midden-Delfland? What challenges have you encountered in the past in your work?
- In what situations has groundwater elevation been successful in the past? What were the key success factors?
- Where do you see tensions arising between different interests, when it comes to raising water levels?
- Are there areas where raising groundwater levels could bring multiple benefits, such as both CO_2 reduction and biodiversity enhancement?

7.2.3 Spatial multi-criteria analysis

Geographic Information Systems (GIS) are widely recognized as a powerful tool for spatial analysis, offering the ability to manage, analyse, and visualize large and complex datasets (Bryman, 2016). In the context of this research, GIS was used to evaluate key spatial variables in identifying areas where raising the groundwater table would be most impactful. When combined with the spatially weighted output of an MCDA, GIS enables a transparent and structured weighting of multi-dimensional criteria, resulting in a suitability map that reflects both scientific insight and policy relevance. This method supported spatial prioritisation and additionally helped to visualise trade-offs and matches. For this process, ArcGIS Pro was used, and all data processing steps can be found in Appendix 2. The data used in this research and its source can be found in Table 2.

Table 2 Data used for spatial analysis

No.	GIS Dataset	Type	Temporal aspect	Description	Source
1	Dikte oxideerbaar veen	Raster 250x250m	Determined in 2016	Thickness of oxidizable peat layer	Wageningen Environmental Research
2	Dikte kleidek op veen	Polygon	Determined in 2016	Clay soil presence over peat areas	Wageningen Environmental Research
3	Projected soil subsidence 2050 and 2100	Raster 250x250m	Modeled in 2021	Forecast of soil subsidence	Deltares & TNO
4	Gemiddeld laagste grondwaterstand	Raster 250x250m	Modeled in 2019	Average lowest groundwater level	Deltares & Wageningen Environmental Research
5	BRP Gewaspercelen	Polygon	Determined in 2022	Agricultural parcels and crop types	PDOK
6	Omgevingsbeleid - Werkingsgebied - belangrijk weidevogelgebied	Polygon	Determined in 2018	Designated meadow bird protection areas	Provincie Zuid-Holland
7	Ligging grensvlak zoet & zout grondwater	Raster 250x250m	Modeled in 2020	Depth of saline groundwater intrusion	Deltares
8	Klimaateffectatlas, overstromingsdiepte, middelgrote kans + waterdiepte bij hevige bui 140 mm	Raster 2x2m	Modeled in 2018	Flood depth under heavy rainfall scenario (140 mm/2hr)	Deltares
9	BAG	Polygon	Determined in 2023	Building footprints and construction years	Kadaster
10	Draagkracht	Polygon	Determined in 2024	Soil bearing capacity	Provincie Zuid-Holland
11	NWB	Polyline	Determined in 2023	National road network	Rijkswaterstaat
12	NatuurNetwerk Nederland	Polygon	Determined in 2018	Protected ecological areas	Provincie Zuid-Holland
13	Natte ecologische zones Delfland	Polygon	Determined in 2024	Important ecological network	Hoogheemraadschap van Delfland
14	Groenblauwe structuur Delfland	Polygon	Determined in 2024	Important ecological network	Hoogheemraadschap van Delfland

Necessity analysis

To determine where intervention is most needed, a necessity analysis was conducted focusing on vulnerability to peat oxidation and soil subsidence. This was done using three geospatial datasets: peat thickness (1), clay cover depth (2), and projected soil subsidence rates (3).

- The peat thickness raster layer (1), developed by Wageningen University & Research (2016) for the Province of Zuid-Holland, provides detailed information on the depth and spatial distribution of peat soils in Midden-Delfland. With a resolution of 250 x 250 metres, it forms a reliable base for identifying areas where deeper peat deposits are more prone to carbon loss.

- The clay cover depth layer (2), available as a polygon dataset from Wageningen University & Research (2016), indicates the presence of a clay top layer overlying the peat. This dataset was used to refine the vulnerability assessment by incorporating the mitigating effect of clay on oxidation potential. Additionally, the polygon dataset also provided the more reliable form of location of different soil types, compared to raster layer 1.

- The soil subsidence rate projection for 2050 and 2100 (3) was obtained from the Klimaateffectatlas, developed by Deltares, WenO, and TNO (2021). This raster dataset, with a resolution of 100 x 100 metres, provides projections of land subsidence under the moste negative climate change scenario. This gives insights into areas at risk of severe degradation if groundwater levels remain as they currently are.

To operationalize the necessity analysis, peat thickness was reclassified assigning higher necessity values to deeper peat areas. The clay cover dataset was used to adjust this analysis by accounting for the potential protective effect of overlying clay layers.

The first two datasets were visually combined using bivariate overlay analysis to evaluate the interaction between peat depth and clay cover. The output served as an input layer for the Multi-Criteria Decision Analysis (MCDA) conducted later in the study.

Finally, the three datasets were visually overlayed in phase three to identify zones where deep peat, minimal protective cover, and high projected subsidence coincide. This composite layer was used as one of the inputs for determining the spatial transitions in phase three.

Feasibility analysis

For the feasibility part, the average lowest groundwater level dataset (4) was used. This raster dataset, based on a model by Deltares (2019), represents the average of the three lowest groundwater level measurements per year over an eight-year period (up to 2019), capturing extreme low groundwater conditions for each location. The dataset has a spatial resolution of 250 x 250 metres.

The feasibility analysis involved calculating the difference between the current average lowest groundwater level and the preferred groundwater levels of -20 cm and -40 cm below the ground surface. This was done using the Raster Calculator tool in ArcGIS Pro.

These target levels were derived from the Water and Soil Guiding policy brief, which identifies -20 cm as the optimal groundwater level for peat areas. When -20 cm is too far out of reach, -40 cm is considered an acceptable alternative (Ministerie van Algemene Zaken, 2022).

Desirability analysis
The last part of the GIS analysis consists of the desirability analysis. For this part, this research used MCDA as a spatial decision-making framework to use as guiding principle in the final phase for translating theoretical insights from experts into practical planning strategies. MCDA helps facilitate the translation of subjective data into an objective analysis, which supports the objective policy recommendations (Cherney et al., 2012; Greene et al., 2011). These subjective preferences, such as differing perspectives on controversial issues across the various layers of the conceptual framework, can be expressed in terms of their relative importance, allowing them to be quantified. A GIS analysis then makes it possible to spatially visualize these quantified relationships, which in turn enables more concrete conclusions to be drawn than would be possible based on qualitative opinions alone (Ruppert et al., 2015).

Within the GIS analysis, MCDA was therefore used as a sub-component to help generate the suitability map output in ArcGIS Pro. The MCDA output, the relative weights of different criteria, served as an input for the spatial analysis by combining the weights with spatially distributed criterion maps including its determined relative weights.

A weighting method is essential in MCDA to assign relative importance to different criteria to make sure that the evaluation reflects their relevance. Without weighting, all criteria would be treated equally, which may not align with actual priorities or stakeholder values.

The specific method chosen for the MCDA was the Analytic Hierarchy Process (AHP) method, a structured decision-making method developed by Saaty (Saaty, 1980). AHP enables the systematic comparison of multiple criteria by performing pairwise comparisons, allowing each factor to be evaluated relative to others in terms of importance. This results in a consistent set of weighted values that reflect expert judgement on the context-specific priorities. AHP was used to give different weights to different variables depending on their importance to influence the final suitability map. This way, the final analysis reflects the relative importance of each factor rather than relying solely on unweighted spatial data.

Objective and structure

The first step of the MCDA was determining the goal and objectives. The objective of the analysis was to identify areas where raising the groundwater level to -0.2 meters would have the most positive impact on three conceptual framework layers: environmental sustainability, infrastructure resilience, and agricultural viability.

Criteria selection and classification

Criteria were selected through a triangulated approach including a literature review, semi-structured expert interviews (n = 11), and data availability analysis. Each criterion was classified according to Table 3 either positively

influencing suitability or negatively influencing suitability.
To assess the suitability of different locations for a groundwater level of -0.2 meters, each criterion was standardized using a classification scale ranging from 1 to 10. This scale reflects the degree to which each area is negatively or positively affected by this groundwater level. Class 1 represents areas that are strongly negatively affected and therefore least suitable. Classes 2 to 4 indicate varying degrees of negative impact. Class 5 represents a neutral impact, areas that are neither positively nor negatively affected. Classes 6 to 9 reflect increasing levels of positive impact, while class 10 represents the most suitable areas, those very strongly positively affected. These classes were chosen to produce an MCDA output that highlights both the most negatively affected areas and the most positively affected areas, thereby identifying where groundwater level elevation can be applied most effectively.

These classes were assigned by combining insights from expert interviews, and literature on the hydrological and ecological effects of groundwater levels. For each criterion, thresholds were defined to distinguish between zones with clearly negative, neutral, or positive responses to groundwater elevation. These thresholds were then mapped onto the 1–10 scale for consistency across all criteria, enabling effective weighting and comparison within the AHP-MCDA framework.

Table 3 Classes of suitability to a groundwater level of -20 cm to assess on

Class	Description
1	Strongly negatively affected (least suitable areas for groundwater level of -0,2m)
2	Moderately to strongly negatively affected
3	Moderately negatively affected
4	Slightly negatively affected
5	Neutral: neither positively nor negatively affected by a groundwater level of -0,2m
6	Slightly positively affected
7	Moderately positively affected
8	Moderately to strongly positively affected
9	Strongly positively affected (highly suitable; supports key goals)
10	Very strongly positively affected (most suitable areas for groundwater level of -0,2m)

Data preprocessing in ArcGIS Pro

To prepare all datasets for the spatially weighted map of the MCDA, all input datasets were transformed into raster format with the same resolution and extent. The steps taken in this process are elaborated on in Appendix 2.

Weighting with Analytic Hierarchy Process (AHP)

To derive relative weights for the selected criteria, the Analytic Hierarchy Process (AHP), was applied. The resulting weights were then used to determine the relative influence of each criterion in the GIS-based suitability analysis. The following steps were taken to generate the weights:

1. Consulting experts

Experts (Table 1) knowledgeable on groundwater, spatial planning, and environmental systems were consulted to fill in a pairwise comparison matrix. Each expert assessed the relative importance of one criterion over another using Saaty's scale, Table 4.

Table 4 Weighting values for AHP (Saaty, 1980).

Value	Meaning
1	Both criteria are equally important
3	One criterion is somewhat more important than the other
5	One criterion is clearly more important
7	One criterion is much more important
9	One criterion is extremely important
2,4,6,8	An intermediate value between two choices mentioned above

For group aggregation, Saaty (1980) recommends using the geometric mean to combine individual assessments into a single group matrix. This aggregated matrix forms the input for the next steps.

2. Pairwise comparison matrix

The expert judgments were put into a pairwise comparison matrix A, where each element a_{ij} indicated how much more important criterion i is compared to criterion j. The matrix is reciprocal, meaning that:

$$a_{ij} = \frac{1}{a_{ji}} \; and \; a_{ii} = 1$$

3. Normalization and weight calculation

To derive the relative weights (W) from the matrix, the following steps were taken:

First, the matrix was normalized by dividing each element by the sum of its column:

$$\hat{a}_{ij} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}}$$

Second, the average of each row was calculated in the normalized matrix to find the relative scores, the weights:

$$w_i = \frac{1}{n} \sum_{j=1}^{n} \hat{a}_{ij}$$

This resulted in a weight vector W, where $\sum w_i = 1$, with each w_i representing the relative importance of each criterion.

4. Consistency check

To verify that the pairwise comparisons given by the experts were logically consistent, the Consistency Index (CI) and Consistency Ratio (CR) were calculated. This was done with the following steps:

Multiply the original matrix A by the weight vector W:

$$AW = A \cdot W$$

For each row i, compute:

$$\lambda_i = \frac{(AW)_i}{W_i}$$

Calculate the maximum eigenvalue:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} \lambda_i$$

Determine the Consistency Index:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Calculate the Consistency Ratio:

$$CR = \frac{CI}{RI}$$

Where RI was the Random Index, a benchmark value based on the matrix size, which varies depending on the number of criteria *n*. A CR value below 0.10 indicated an acceptable level of consistency.

Suitability mapping in ArcGIS Pro

With the weights, the final spatially weighted suitability map was produced using the Raster Calculator tool where each raster layer was assigned its corresponding weight. The expressions used for raster calculations are included in Appendix 3.

7.2.4 Field observations

For the third phase, in addition to the literature review and expert interviews, field observations were done. Multiple site visits to the study area were taken to get familiar with the area and deepen the contextual understanding to make sure the spatial plan would fit the local conditions of the area.

7.2.5 Transition analysis with Theory of Change

Lastly, the Theory of Change (ToC) was applied to map out the process of implementing spatial planning adaptation strategies. ToC can be used to analyse a process when the transition has already happened, or during, to guide successful change (Mayne, 2017).

According to Mayne (2017), ToC provides a structured framework that identifies the following:

- Stakeholders involved in (groundwater/spatial planning) policy
- Barriers and enablers influencing spatial adaptation
- Phased transition pathways for policy implementation

This approach provided the proposed spatial planning strategies to be both technically feasible and socially and politically viable. As Bryman (2016) states, ToC strengthens the impact of (policy) recommendations by linking scientific analysis with governance mechanisms (Bryman, 2016).

7.3 Ethical considerations

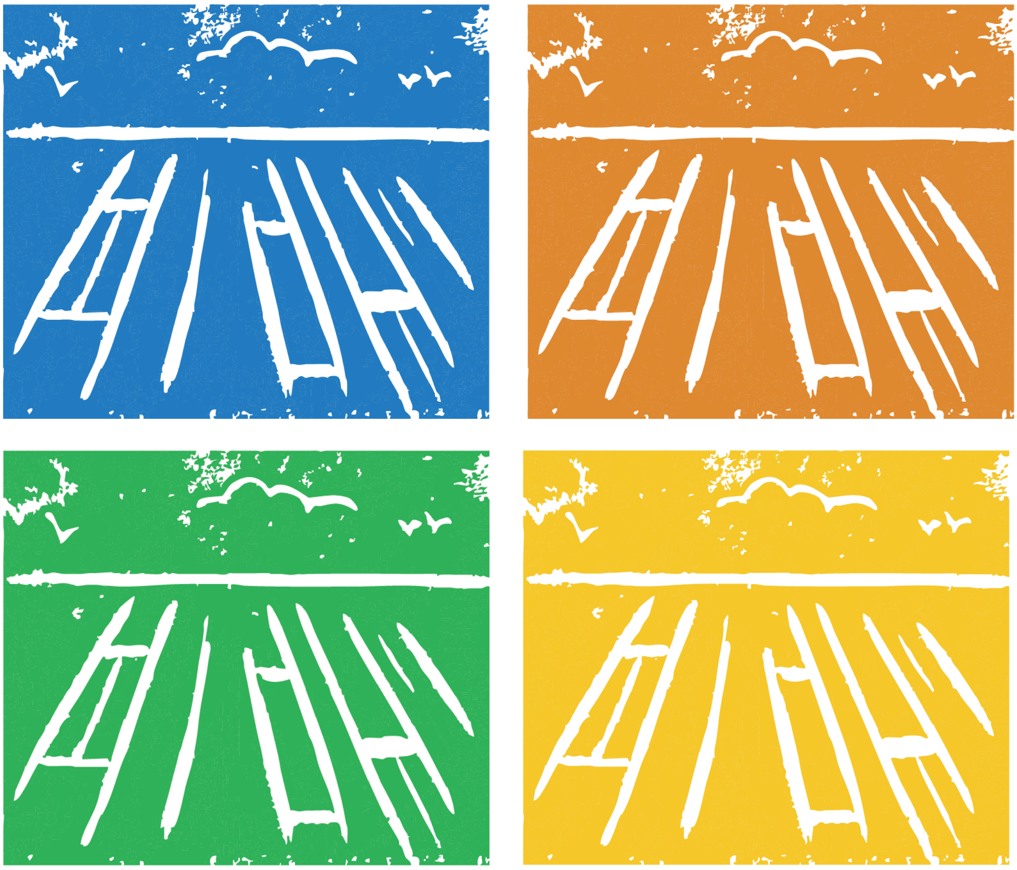
All expert interviews were conducted on a voluntary basis and with informed consent. Participants were briefed on the aim of the research and informed on how their input would be used. All interviewees are identified only by a number and professional role to guarantee anonymity. Given the potentially sensitive nature of land use transitions and the impact on stakeholders, care was taken to present findings neutrally and respectfully, to not misrepresent any individual or organization. No personal or private data was collected. Spatial datasets used in this study were publicly available or shared with permission from relevant institutions. All data sources have been cited, and the analysis complies with institutional and academic standards.

With the use of a mixed-methods approach this research explores how spatial planning in Midden-Delfland can adapt to groundwater management. Phase one and two provide conditions for groundwater elevation and a spatially explicit suitability assessment using GIS and MCDA, validated by expert interviews. Phase three contextualizes these findings by using the previous insights as well as the Theory of Change to implement the findings into the study area.

With the combination of quantitative and qualitative methods, the study provides both scientific and policy-relevant recommendations for spatial planning transition strategies in Midden-Delfland.

Results Phase One

Understanding the spatial and environmental context of groundwater elevation



8. Results phase one

This chapter explores why groundwater level elevation, despite its potential benefits, is not yet widely implemented, and what conditions are needed to make it feasible in practice. It examines the barriers and enabling factors that influence implementation, drawing on expert interviews and additional literature review. The chapter begins with a synthesis of expert perspectives on the effects of groundwater elevation in the study area of Midden-Delfland. Following this, additional reflections from the expert discussions are presented. Finally, a consolidated set of spatial and environmental criteria is derived, informed by both literature and practice, which will be used to guide the next phase of the research: identifying where groundwater elevation in Midden-Delfland is most necessary, feasible and desirable.

8.1 Expert perspectives on effects of groundwater elevation

While the literature review in Chapter 4 outlined the technical potential and environmental benefits of groundwater elevation in peat areas, the expert interviews and field observations in Midden-Delfland reveal a more nuanced reality. Four key dimensions emerged consistently across the expert discussions: water quality, water nuisance, water quantity, and ecological considerations. These dimensions illustrate the multifaceted nature of groundwater elevation and underscore the trade-offs involved in implementing rewetting strategies. In the sections that follow, additional recurring insights that reflect the broader system dynamics are further explored.

8.1.1 Water quality

Groundwater elevation has complex and often contradictory effects on water quality. On the one hand, higher water levels can support ecological restoration by stabilising peat soils, reducing peat oxidation, and enhancing the natural purification capacity of wetlands. On the other hand, raising the groundwater table, particularly in agricultural areas, can significantly increase nutrient leaching. Elevated water tables reduce the unsaturated buffer zone in soils, which means that nitrogen (N) and phosphorus (P) from fertilisers and pesticides will leach and reach surface waters through runoff or seepage (Eulenstein et al., 2016). This poses serious challenges for achieving the objectives set by the European Water Framework Directive, which requires significant reductions in nutrient concentrations in surface water bodies by 2027, as was mentioned by expert 4.

The Dutch subsurface has accumulated a large amount of phosphorus due to historical over-fertilisation for an increasing agricultural productivity. Peat soils, in particular, contain phosphorus tightly bound to organic matter (van der Laan et al., 2024). When these soils become saturated as a result of rewetting, the phosphorus can be released into the surface water.
Adding to the complexity, other pollutants, such as microplastics, heavy metals, and residual chemicals from industry and transport, also infiltrate groundwater, which are depicted in Figure 11. Because of its slow velocity and long residence time, groundwater acts as a delayed conveyor of these contaminants (Becker et al., 2022). The effects of today's pollution may only surface years or decades later, which makes it very difficult to clean once contaminated.

Another dimension of water quality is salinization. As sea levels rise and river discharges become more unpredictable due to climate change, saltwater intrusion into coastal aquifers becomes a growing threat (Hendriks et al., 2023). Although currently not a severe issue in Midden-Delfland, as mentioned by an expert on water quantity, higher groundwater levels may play a positive role of prevention by maintaining hydraulic pressure against intruding saltwater.

Finally, the interaction between water quality and rewetting strategies is strongly dependent on the type and source of water introduced into the existing water system. Infiltrating external "foreign" water, or not clean water can worsen water quality if its characteristics differ from the local ecosystem needs. Rewetting soils is therefore not always possible with water from the regional water system from the bigger canals, as it is has a different chemical composition (Duin, personal communication, 2025). Multiple experts stress the opportunities within this scope, to avoid such inflows and instead retain winter water surpluses on-site. This minimises nutrient displacement and reduces the need for importing water during periods of drought, with potentially incompatible chemical profiles.
As several experts noted, rewetting and farming systems must be adapted together to avoid unintended consequences for the quality of the current water system.

Figure 11 Sources of groundwater pollution (IAEA, 2025).

8.1.2 Water nuisance

Another frequently mentioned concern in expert interviews is water safety and risks of water nuisance. This is correlated with the mission of a water board, which is to keep all inhabitants safe from the water. When groundwater levels are elevated, the unsaturated buffer layer decreases, leaving less space to temporarily store incoming water. As a result, waterlogging and surface flooding can occur more rapidly, especially during peak rainfall events (Wei et al., 2024).

This buffering loss is worsened by changes in the surface water system for groundwater elevation. Rewetting interventions, such as raising ditch water levels or implementing infiltration systems, reduce both the storage capacity in the canals and other surface waters as well as in the soil itself. During wet periods, the combination of higher water levels and increased surface runoff from saturated fields can overwhelm the system, leading to inundation risks, mentioned by experts on water quantity.

The consequences of water nuisance are broad and affect both urban and rural environments. In residential areas, elevated groundwater levels can cause moisture infiltration in basements, mould formation in crawlspaces and walls, and high humidity in homes, all bad for h, as mentioned by experts in the field. Public green spaces suffer as waterlogged soil leads to root suffocation, tree instability, and damage to lawns or plantings. Foundations, crawl spaces and cellars may experience upward pressure from saturated soil, resulting in structural instability. Infrastructure such as roads and pavements may subside unevenly or develop ruts due to the reduced soil bearing capacity. This, however, differs per soil type (Born et al., 2016).

In agricultural areas, farmers may face fields too wet for machinery to enter during key maintenance periods, such as fertilising, mowing or harvesting. Crops can fail due to root saturation, leading to economic losses (Srivastav et al., 2021). These consequences show that water nuisance must be integrated when developing rewetting strategies.

8.1.3 Water availability and quantity

The effects of groundwater elevation on water quantity are equally complex. Groundwater elevation typically requires a steady supply of water, which places added stress on the water need of existing water infrastructure, in specific during dry periods under the increasing pressures of climate change.

Experts from the water board on water quantity and policy highlighted that the current system in Delfland is facing more and more issues in supplying sufficient water everywhere, especially during hot and dry summers. This increases dependency on external water sources, and when combined with rising evaporation rates, creates tensions in freshwater allocation. The type of groundwater elevation measure chosen directly affects water demand, and differs per measure. The *nationale verdringingsreeks*, a priority system for water allocation, becomes critical in times of drought, where nature and low-value uses are deprioritised (Ministerie van Infrastructuur en Waterstaat, 2025a). Water used for groundwater level elevation would fall under the highest priority category of ‘safety and the prevention of irreversible damage’.

A potential benefit of groundwater elevation is its sponge effect. Higher groundwater tables enhance the soil's capacity to retain water, which can reduce the overall demand on the main water supply system. Some studies estimate a reduction in system-wide water demand by approximately 7% (L. Liu & Jensen, 2018). Still, this benefit is context-dependent and must be weighed against supply limitations.

Current land use also presents challenges, from the perspective of the water board, priorities remain focused on preventing water nuisance, safeguarding water quality, and managing drought impacts, as mentioned by experts on water quantity, quality and in the field. The imbalance between water supply and demand during dry months raises serious concerns about the resilience of the water system and indicates a well-thought approach is needed.

8.1.4 Ecological and land use implications

Ecologically, groundwater elevation opens new opportunities, particularly for biodiversity restoration in low-lying peat areas, according to the expert on biodiversity. Restoring wetland habitats can support a wide range of flora and fauna that thrive in wetter environments. In particular, breeding zones for meadow birds benefit from higher water levels, aligning with key policy goals for Midden-Delfland set by the Province of Zuid-Holland (Provincie Zuid-Holland, 2019). The ecologist emphasized that well-managed water levels can improve habitat quality and ecological functioning. Yet, the ecological benefits are not universally positive. Long-time high saturation can cause phosphorus release from peat, as mentioned in the water quality paragraph, loss of plant diversity, and destruction of worm populations that serve as a food source for birds. Moreover, some wetland management practices, like year-round flooding, may increase unwanted methane emissions (Blondeau et al., 2024). Thus, even within ecological goals, careful calibration is needed.

A recurring issue raised in expert discussions is the misalignment between current land use and hydrological logic. The expert on the area of Midden-Delfland, argued that the region should be restructured based on subsurface characteristics, such as height differences in the area, rather than historical ownership patterns. Doing so could minimise ecological trade-offs and maximise long-term water system efficiency.

8.2 Other findings and perspectives from discussions

The dimensions mentioned beforehand show that groundwater elevation is not a simple win-win solution. It stresses that it is a multidimensional intervention with context-specific outcomes. Addressing one objective, may challenge another. Insights from expert interviews and field observations in Midden-Delfland reveal a complex picture and point to the interconnected, sometimes conflicting, relationships between groundwater levels and water sustainability, land use, and ecological objectives.

Groundwater elevation alone is not sufficient to achieve the goals of reduced carbon emissions while remaining a infrastructural resilient and agricultural viable Midden-Delfland. According to multiple experts, a shift in both hydrological and agricultural systems is necessary. Measures to raise the water table often impact the soil's load-bearing capacity, thereby limiting agricultural productivity. At the same time, stakeholders acknowledge that groundwater elevation can improve biodiversity and reduce subsidence. The challenge lies in negotiating these trade-offs.

Soil subsidence was repeatedly identified as a major concern, specifically regarding the costs of it to society. While rewetting effectively reduces peat oxidation, which is the primary driver of subsidence, experts stressed that benefits are gradual and depend on peat thickness, drainage depth, and existing land use. Moreover, the economic impact on farmers must be carefully weighed. Several interviewees, such as the agricultural advisor and area expert, emphasized the role of short-term economic priorities in land decisions. In practice, investments in measures like under-drainage systems or nature-based solutions often need external subsidies or favourable market conditions, most entrepreneurs would not invest out of themselves, 'just' for the environmental sustainability.

Another factor that was mentioned, was the importance of choosing appropriate scales. Working at the level of water level compartments or hydrological units offers more effective results for carbon emission reduction than implementing isolated parcel-based measures. Reconfiguring land ownership and reallocating land uses according to subsoil properties would significantly improve efficiency.

Landscape identity further complicates this dynamic. As expert 11 pointed out, provincial policies in Zuid-Holland strongly protect the visual character of the peat meadow landscape. Trees, for example, are often prohibited to preserve the open characteristics and protect meadow bird habitats, which are sensitive to predation risk. However, in some areas, strategic introduction of landscape elements like agroforestry could enhance biodiversity and contribute to climate goals. Additionally, groundwater level elevation might result in a different landscape then the current one. This raises a fundamental question: should our landscapes remain static in appearance, or should they adapt in response to new ecological and climatic realities?

A perspective shared by the biodiversity expert linked the current water quality problems to past agricultural intensification *"The contaminants we are now dealing with are the result of choices we made ourselves regarding farming efficiency, these pollutants in the soil would need to come out at some point."* This underscores the long-term consequences of historic land use and the need for coherent policy action across different time horizons.

A contradiction was pointed out by a water level manager in Midden-Delfland: due to subsidies promoting meadow bird habitats, an investor purchased a high-lying parcel of land and applied for 'meadow bird area management' subsidies. This led to artificial rewetting in one of the driest, highest parts of the area, in contrary to the hydrological logic. This example shows how poorly aligned subsidies can lead to unintended consequences, and why better coordination is needed between nature goals and water management.

Finally, future resilience requires a transition mindset. The region has already seen positive examples of circular agriculture and nature-inclusive farming, according to experts 3 and 7. But to scale these approaches and commit to groundwater level elevation, new economic models are needed, like cooperative land management, differentiated subsidy schemes for ecosystem services, and new roles for nature managers, came up in the conversations had. A recurring theme is the risk of placing disproportionate expectations on farmers without providing adequate support or ownership in the transition. As several experts stated, groundwater elevation is, alongside a technical or ecological issue, a socio-economic one.ne.

8.3 Criteria

Out of these conversations different environmental and spatial factors influencing groundwater levels were mentioned. While many of the expert insights confirm the findings from the literature review in Chapter 4, the conversations held throughout this research phase also new and nuanced perspectives can be derived.

Experts frequently referred to criteria that were already theoretically established, such as *soil type, peat thickness*, and *land subsidence*. Contextualising the meaning of a factor to Midden-Delfland often was mentioned together with *feasibility* of a measurement in the study area.

Simultaneously, several new criteria surfaced during discussions. For example, the *type of building foundation b*ecame relevant when assessing vulnerability to higher groundwater levels. Older houses, particularly those built before 1970 on wooden piles, since drying out wooden foundations leads to decay and subsidence.

Salinization was another factor brought forward. Although not currently a major issue in Midden-Delfland, some hydrologists pointed to the role of elevated groundwater in maintaining hydraulic pressure against saltwater intrusion. This shows how groundwater level elevation can help in prevention of issues. Rewetting here may not just be a response to present conditions, but can help combatting future risks. Still, the effectiveness of such a strategy would depend on *water availability*. As the experts stressed, a crucial question is where water can be delivered during droughts and considering logistical feasibility. Practicalities also surfaced in the form of *subsurface infiltration capacity* and the distribution of water across parcels. Experts highlighted that different soils (peat, clay or sand) react differently to infiltration, and that water may not be evenly distributed across a parcel with some elevation measurements. This influences both the feasibility and efficiency of rewetting.

Land use emerged as one of the most layered and multifaceted criteria. While surface-level classifications such as “agriculture” or “nature” are mainly mentioned in policy documents, conversations stressed that the characteristics of the land uses mattered most: What crops are grown? How intensively is the land used? How does management vary across seasons? It all refers to the *type of agriculture*. It plays a significant role in determining whether groundwater elevation is desirable. Similarly, the ecological ambitions of the area, such as creating *biodiversity corridors* or *meadow bird zones*, sometimes conflict with *water quality* goals.

The value placed on *open landscape preservation* added an additional constraint. Experts noted that Midden-Delfland’s identity as a ‘green buffer’ between urban areas, as well as the typical peat meadow landscape, hinges on its wide, open views and historical land patterns. These visual and cultural values are not necessarily incompatible with rewetting, but they can restrict certain spatial interventions.

Other spatial and physical characteristics also became clearer through expert discussions. *Height variation*, when combined with the polder structure and water infrastructure layout, differences in elevation determine where water will accumulate or drain. Some parts of Midden-Delfland have deep polders, while other areas are relatively high. These differences create a patchwork of opportunities and constraints for rewetting.

The role of *infrastructure* added another dimension. Roads, pavements, and buildings respond to changing subsurface conditions. Interviewees from the water board expressed concern about *resilience of infrastructure* when rewetting, pointing to costly consequences such as 'floating' roads on sandy soil, to the contrary of peat soils where groundwater elevation can stabilize infrastructure.

What becomes evident is that these criteria interact. These tensions form the foundation of the next research phase. In the next chapter, these criteria will be further categorised and operationalised according to the conceptual framework. This will allow for a structured evaluation of where groundwater elevation in Midden-Delfland is most promising, where trade-offs are unavoidable, and where targeted interventions may lead to synergies.

8.4 Summary

This chapter explored the complex reality of groundwater elevation in Midden-Delfland, showing it is both a promising strategy but also context-dependent. While the environmental benefits, such as reduced subsidence and enhanced biodiversity, are clear, practical implementation is shaped by spatial, ecological, and socio-economic conditions.

Freshwater scarcity stands out as a major limiting factor, especially in dry periods when external water supply is insufficient or incompatible with local ecosystems. At the same time, water retention opportunities and the potential buffering role of elevated groundwater offer a chance to reduce dependency on regional systems. Additionally, water quality and water nuisance added constraints. Experts highlighted that current land use often clashes with hydrological logic, pointing to the need for spatial restructuring based on subsoil characteristics.

Peat thickness, soil type, elevation differences, and existing water infrastructure were repeatedly mentioned as key environmental and spatial factors influencing where groundwater elevation is feasible. The suitability of rewetting strategies is further shaped by land use intensity, ecological goals, and the resilience of built infrastructure.

Institutional and social dynamics also play a decisive role. Misaligned subsidies, policy contradictions, and lack of long-term coordination hinder progress, while participatory planning and fair economic models for landowners were seen as essential conditions for success. Additionally, the policies regarding the preservation of the current open landscape might stand in the way of transforming the spatial planning of the area with regards to groundwater level elevation. Across the expert conversations, the recurring message was: groundwater elevation cannot be treated as a mere technical solution. Important factors for successful groundwater elevation are shared willingness by all stakeholders to navigate trade-offs, realign competing interests and work towards broader systemic change, in a transition needed for spatial planning and agricultural practices.

Area-specific impact analysis of groundwater elevation

Results Phase Two

9. Results phase two

This chapter focuses on integrating the criteria established in Chapter 8 and developing them into a spatial analysis using GIS. It examines how the current spatial structure of Midden-Delfland can contribute positively to environmental sustainability, infrastructure resilience, and agricultural viability in the context of groundwater level elevation. The analysis explores which elements of the existing land use can remain unchanged under elevated groundwater levels, and which aspects require adaptation.

Using GIS, the study aims to determine the spatial feasibility and impact of raising groundwater levels in Midden-Delfland given the current situation. Specifically, it investigates whether and where groundwater elevation is beneficial, technically feasible, and environmentally or socially constrained. The analysis is structured to assess:

1. **Environmental necessity**

   Where is groundwater elevation most urgently needed?

2. **Physical feasibility**

   Where is it physically most feasible to elevate the water table?

3. **Spatial desirability**

   Which locations are most suitable from a land-use perspective, considering the conceptual framework with its ecological, agricultural, and infrastructural implications?

9.1 Environmental necessity for groundwater level elevation

The reason to elevate the groundwater level is due to its environmental necessity. This is therefore the first step. Only these areas should be considered for groundwater elevation towards -20 cm since it is necessary for this cause, as is stressed by the literature in Chapter 4.

9.1.1 Carbon emission reduction potential

The primary environmental rationale for groundwater elevation is to reduce CO_2 emissions from oxidizing peat soils. Emissions are most significant in areas with:

- Peat presence: Identified through soil type data
- Peat thickness: Thicker peat layers have higher emission potential, as oxidation occurs over a longer period.
- Soil layering: Where peat is covered by other soils, specifically clay, a mineral soil, CO_2 emissions can be buffered.

The focus will be on areas with the thickest peat layers, as these offer the highest mitigation potential for both emissions and subsidence.

9.1.2 Soil subsidence mitigation

Soil subsidence is directly correlated with peat degradation. Areas experiencing the most rapid subsidence are often those with peat and clay soils (Born et al., 2016). To identify where groundwater level elevation would be most effective in reducing subsidence, a dataset of projected soil subsidence for 2050 and 2100 was combined with the previously mentioned map of the reduction potential for carbon emission.

By overlaying the most critical subsidence projections with the peat thickness map, areas with critical zones for intervention were identified and a cross-check for inconsistencies and blind spots was done.

9.2 Physical feasibility of groundwater level elevation

Physical feasibility was a recurring theme in nearly all expert interviews, mentioned explicitly by six experts. It refers to how practically possible it is to realise groundwater level elevation in a given location. This theme is crucial because it explains why groundwater elevation has not yet been widely implemented in Midden-Delfland. For the GIS analysis, dewatering depth covers the feasibility.

9.2.1 Dewatering depth

Drainage depth, which is the vertical distance between the ground surface and the current groundwater level, is a crucial factor in determining the feasibility of groundwater elevation. It directly influences the effort required to achieve the preferred target of -20 cm below ground level. The shallower the existing drainage depth (the closer the groundwater table is to the target level), the less intervention is needed, and the higher the implementation potential, specifically with regards to the pressure on water quantity.

Accurate groundwater data is essential for this analysis. However, the available datasets present limitations. The most commonly accurate and up to date data are water level management plans (*peilbesluiten*) but these do not directly reflect actual groundwater levels. The translation from surface water to groundwater depends heavily on the type of soil and the proximity to surface water bodies. While field measurements offer more precision, Midden-Delfland only has four measurement points, which is insufficient given the spatial variation and significance of this variable.

Therefore, this research uses the ‘average lowest groundwater level’ (*GLG*) as the most accurate and detailed available dataset (Deltares & WENR, 2019). It provides a reliable estimation of groundwater conditions and is based on well-informed and systematically calculated data, making it a suitable foundation for spatial analysis.

9.3 Spatial desirability of groundwater elevation: an assessment based on the conceptual framework

To evaluate where raising groundwater levels in Midden-Delfland would have the greatest benefits and the fewest risks, a GIS-based Multi-Criteria Decision Analysis (MCDA) was conducted. This method allows the integration of spatial data, expert knowledge, and the conceptual framework that anchors this research: environmental sustainability, infrastructure resilience, and agricultural viability.

The assessment criteria were derived through a combination of literature review and expert interviews in the previous chapter, and evaluation of regional datasets. To ensure an extensive and valid analysis, the criteria all together must clearly describe the underlying concepts and fully capture their scope. Several experts from the regional water authority contributed to the development and validation of these criteria. Their involvement strengthens the credibility and applicability of the results for decision-making in spatial planning.

All selected criteria relate directly to groundwater characteristics and their influence on environmental, agricultural, and infrastructural systems. The resulting spatial layers allow identification of zones where water level elevation is most promising or, most problematic. The thematic breakdown below explains each set of criteria, their spatial indicators, and the reasoning for inclusion.

9.3.1 Environmental Sustainability

This category considers both the mitigation of environmental degradation and the enhancement of ecological systems. Groundwater elevation can directly influence soil chemistry, biodiversity, and water retention functions. The aim is to find out the most beneficial places for groundwater elevation for nature to thrive.

Peatland extend and carbon emissions

Thick peat layers prioritized for groundwater elevation

As discussed prior, in the environmental necessity section, deep and active peat layers emit significant amounts of CO_2 when exposed to oxygen due to drainage, this was also pointed out by experts 2, 8 and 9. Groundwater elevation slows this process, preserving organic matter and mitigating soil subsidence. This criterion spatially targets the thickest and most active peat areas determined previously.

Ecological network

Wetland and ecological corridor areas prioritized for groundwater level elevation

Nature areas and ecological corridors are increasingly threatened by prolonged droughts, leading to vegetation stress and biodiversity loss. Experts 3, 5, and 9 emphasized that groundwater-dependent ecosystems like wet grasslands, which are indicated by Klimaateffectatlas, are among the first to deteriorate during drought. Zones designated for nature development or ecological connectivity are prioritized.

Areas at risk of salinization

Zones threatened by salinization prioritized for groundwater level elevation

Salinization not only threatens agriculture, but also detoriates freshwater ecosystems, which is highlighted by experts 1, 6, and 9. Freshwater influx through groundwater elevation can reduce the upward pressure of saline water and protect wet habitats, as most flora and fauna reacts negatively to saline water, resulting in unwanted changes in ecology (Hendriks et al., 2023). For this criterion the layer of important ecological networks can be combined with the areas threatened by salinization.

9.3.2 Infrastructure Resilience

The infrastructural component focuses on the vulnerability of buildings, underground networks, and engineered systems to higher groundwater levels. The aim is to identify areas where infrastructure could benefit from stabilization, such as reduced subsidence, or where risks such as flooding or structural damage might increase.

Sensitivity to water nuisance

Avoid locations with high flooding susceptibility

In areas with high risk of surface water flooding, sufficient infiltration capacity is crucial. During peak rainfall events, saturated soils in these zones have limited ability to absorb excess water. Raising the groundwater level in such locations can increase flood risk. Therefore, groundwater elevation is generally not desirable in areas prone to surface water nuisance. This importance was emphasized by experts 1, 9 and 6.

Foundation vulnerability

Groundwater elevation for pre-1970 buildings with wooden piles sensitive to low groundwater levels

Older buildings in Midden-Delfland, particularly when constructed before 1970, are likely to have a wooden pile foundations (Born et al., 2016). Experts 1, 2, and 10 noted that this foundation type is sensitive to low groundwater levels as wooden piles are susceptible to “pile rot” when water tables drop. This criterion flags areas with likely foundation vulnerability.

Soil bearing capacity

Peat and clay soils will be stabilized with high groundwater levels

This criterion examines how groundwater levels influence subsurface infrastructure such as roads, pipelines, tunnels, and cables. According to experts 1, 7, and 10, on peat or clay soils, elevated groundwater can reduce further subsidence, extending infrastructure lifespan. However, in sandy or loamy soils, higher water levels may increase upward forces, destabilizing infrastructure. Locations with weak soils and heavy infrastructure concentration are critical areas for this analysis.

9.3.3 Agricultural Viability

The dimension of agricultural viability assesses the potential impacts of elevated groundwater levels on farming practices. It aims to identify which agricultural areas can tolerate, benefit from, or be limited by higher water tables. Expert insights, particularly from field specialists (experts 2, 3, 7, and 8), emphasized the need to account for agricultural viability to be incorporated as a main concept.

Crop specific optimal groundwater level

Crops requiring high groundwater access during droughts preferred; dry-soil crops limited

Different crops have distinct optimal groundwater levels. For example, grasslands, which dominate the region, are generally more tolerant of high water tables compared to crops like potatoes, which are highly sensitive to saturation. This criterion was supported by experts 2 and 7. The different categories of crops which can be found in the Midden-Delfland area are: grassland, silage maize, sugar beet, alfalfa, and field beans. Each crop type was spatially analysed for its preferred groundwater level range. Crops that are highly vulnerable to high groundwater levels indicate spatial constraints for water level elevation.

Crop tolerance to inundation (damage from waterlogging)

Crops that fail under seasonal inundation are avoided

Some crops can withstand occasional flooding without significant yield loss. Others can suffer complete crop failure (van Oort et al., 2023). Expert 7 mentioned this criterion, since it assesses the damage potential in case of seasonal or prolonged inundation, which can occur more frequent when the water level is elevated. It is therefore a crucial element for the agricultural operations.
Crop-specific thresholds were identified using agronomic studies and validated by experts. Areas with inundation-sensitive crops are marked as zones with high vulnerability, potentially requiring mitigation measures or crop transition.

Crop water demand (drought-related damage)

Crops requiring high groundwater levels access during droughts preferred; dry-soil crops limited

This factor identifies crops that require higher levels of groundwater access to meet evapotranspiration demands during dry seasons. It also accounts for root depth and general drought tolerance (van Oort et al., 2023). Expert 7 explained that crops with high water requirements, such as maize and alfalfa, could benefit from higher groundwater levels, reducing irrigation dependency. Conversely, crops adapted to dry soils might be negatively impacted.

Meadow bird areas

Areas already managed with high groundwater levels during breeding period, are more likely to have elevated groundwater levels during the whole year

Meadow bird areas are protected zones in which groundwater levels are already managed close to the surface during the breeding season (March to July) to support meadow birds breeding. Because of their seasonal tolerance to high water tables, these areas offer promising conditions for year-round groundwater level elevation. Expert 10 added that such farmers are more accustomed to adaptive management, offering a potential road to nature-inclusive farming.

Though not directly tied to agriculture, expert 7 explained that farmers operating in these zones often cooperate with water boards to maintain higher water levels in spring. These insights were integrated to explain why these areas might tolerate year-round elevation more readily.

Salinized agricultural areas

Areas with high saline intrusion are targeted for groundwater level elevation for increased crop yield

In areas affected by saline intrusion, which happens particularly during periods of droughts, groundwater elevation may help push back saltwater by increasing freshwater pressure. As saline water compromises both crop and soil health and productivity, resulting in unsuitability for certain crops, raising the water table in these zones may serve as a dual-purpose mitigation measure, as was stressed by experts 1, 6, and 7. In cases where salinization is severe, salt-tolerant crops may also be introduced as part of adaptation strategies (Hendriks et al., 2023). Specific crop tolerances in this area are for sugar beet tolerates EC values up to 7–8 dS/m, while field beans show yield loss already at 1.5–2 dS/m (Stuyt et al., 2016).

9.3.4 The classification of the criteria

The classes as stated in Methodology Table 5 are applied to the criteria. These classes are the following of which the classes of the criteria of infrastructure resilience and environmental sustainability were validated by experts.

Table 5 Scores and desirability classifications of factors and constraints

No	Name of the criteria	Factors/ constraints	Class (1-10)
1	Crop specific optimal groundwater level	Grassland (0,4/0,6–0.8 m) Silage maize (0.6–1.0 m) Field beans (0.8–1.0 m) Sugar beet (1.0-1.2m) Alfalfa (1.0-1.5)	4 3 3 2 1
2	Crop tolerance to inundation	Sugar beet < Alfalfa < Field beans < Silage maize < Grassland	1 1 1 2 3
3	Crop water demand	Alfalfa Silage maize Grassland Sugar beet Field beans	10 7 7 7 6
4	Meadow bird areas	Meadow bird area	10
5	Salinized agricultural areas	Field beans Alfalfa Silage maize Grassland Sugar beet	10 9 8 7 6
6	Sensitivity to water nuisance	Water depth 20-30 cm Water depth >30 cm	3 2
7	Foundation vulnerability	Building year < 1910 Building year 1910-1945 Building year 1945-1970 Building year 1970-1995 Building year >1995	10 9 9 6 5
8	Soil bearing capacity	Infrastructure on sand Infrastructure on loam Infrastructure on peat layer <3m thickness Infrastructure on peat layer >3m thickness	3 7 8 9
9	Peatland extent and carbon emissions	Peat layer thickness >4m Peat layer thickness 3-4m Peat layer thickness 2-3m Peat layer thickness >3m with clay cover Peat layer thickness 1-2m	10 9 8 7 6
10	Ecological network	NNN Important ecological areas HHD Ecological corridors	10 9 7
11	Areas at risk of salinization	Depth salinized groundwater: 0 to -5 m Depth salinized groundwater: -5 to -10 m Depth salinized groundwater: -10 to -15 m	10 9 8

9.4 Spatial analyses

The GIS analysis for this study was conducted using ArcGIS Pro. All relevant layers were collected and processed to align with the three-step analytical structure aimed at evaluating: (1) necessity, (2) feasibility, and (3) desirability for groundwater level elevation in the Midden-Delfland region. The specific processing steps for each analysis are further illustrated in a flow chart in Appendix 2. The data used for determining MCDA weights for the 'desirability' component are included in Appendix 1.

9.4.1 Necessity analysis

A spatial analysis was conducted to assess where groundwater level elevation is most urgently needed from the perspective of GHG emission reduction. This analysis combined three datasets: peat thickness, clay cover presence, and projected soil subsidence rates (Deltares & TNO, 2021; WENR, 2016).
The necessity analysis begins with evaluating the carbon emission reduction potential by identifying areas where peat layers are thick and not protected by an overlying clay layer. In these locations, oxygen can more easily reach the peat, resulting in peat oxidation and therefore higher CO_2 emissions. In contrast, a clay cover acts as a protective barrier that reduces oxygen infiltration and slows down the oxidation process, as was elaborated on in Chapter 4.
Figure 12 illustrates the outcome of this necessity analysis, based on the spatial overlap of peat thickness and presence or absence of clay cover. In the resulting map, darker blue areas represent high urgency for intervention due to deeper peat without protective clay topsoil. Pink areas, on the other hand, indicate that the peat layer is covered by a clay layer and therefore at lower risk of peat oxidation and thus has less carbon reduction potential.

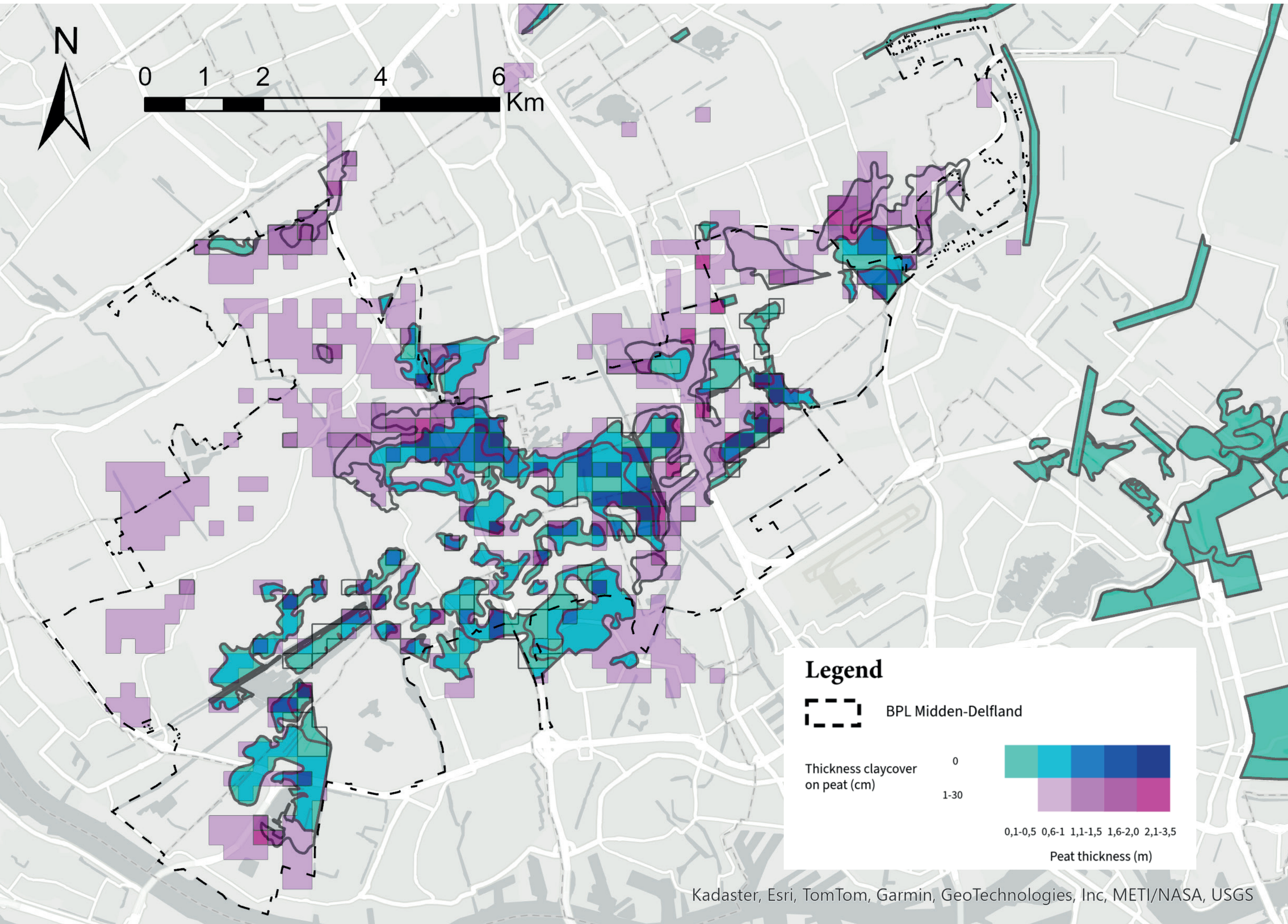


Figure 12 Necessity analysis: spatial overlap of peat thickness and clay cover

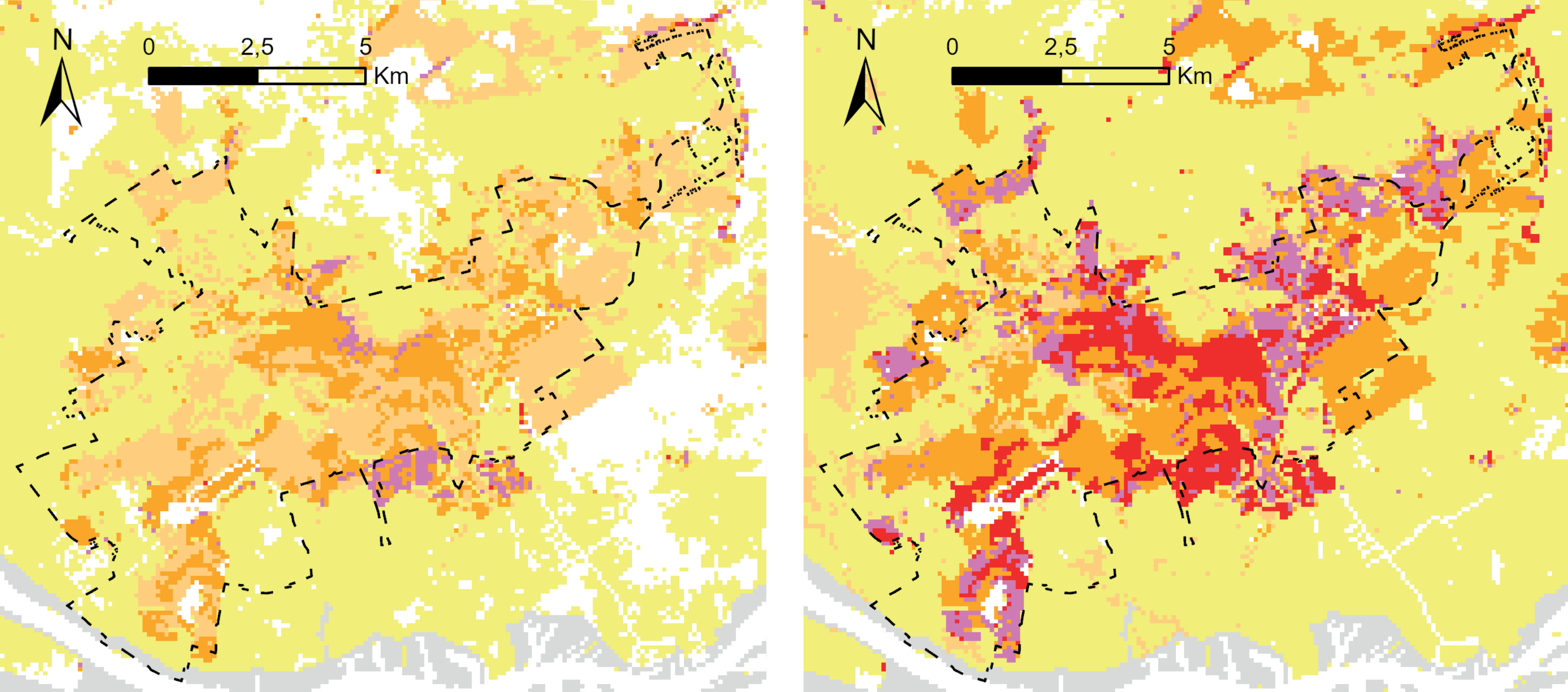


Figure 13 Soil subsidence projection rates

(left) projection for 2050
(right) projection for 2100

Legend
Expected soil subsidence (cm)

3-10
40-60
10-20
>60
20-40
BPL Midden-Delfland

Furthermore, the modelled soil subsidence projections for 2050 and 2100 was looked at, based on data from the Klimaateffectatlas. This is presented in Figure 13. By overlaying these projections with the generated map, zones were identified where peat vulnerable to oxidation and high expected subsidence coincide. Additionally, the soil type map was used to cross-check for inconsistencies and blind spots in the data on peat soils, as soil characteristics can be highly variable and unpredictable. This step provided a more reliable interpretation of where groundwater elevation would be most necessary.

This combined assessment shows the areas where groundwater level elevation is most necessary, considering the potential for reducing CO_2 emissions. These zones serve as the basis for areas where groundwater elevation is needed in the first place, building the foundation of the proposed spatial plan.

9.4.2 Feasibility analysis

The feasibility of raising groundwater levels was assessed using a raster dataset representing the average of the three lowest measured groundwater levels per year, based on an eight-year period up to 2019 (Deltares & WENR, 2019), This dataset reflects late-summer conditions, when groundwater levels are typically at their lowest due to seasonal evapotranspiration. It therefore provides a conservative baseline for evaluating the potential for rewetting.

Figure 14 presents the spatial distribution of current groundwater levels relative to the target zones of -40 cm and -20 cm below surface level, the groundwater levels considered desirable for reducing peat oxidation and subsidence (Ministerie van Algemene Zaken, 2022). The map shows that, under these dry conditions, only a limited number of locations in Midden-Delfland currently meet or approach these thresholds. Most agricultural plots remain significantly below the -40 cm mark, indicating limited feasibility during peak summer dry seasons.

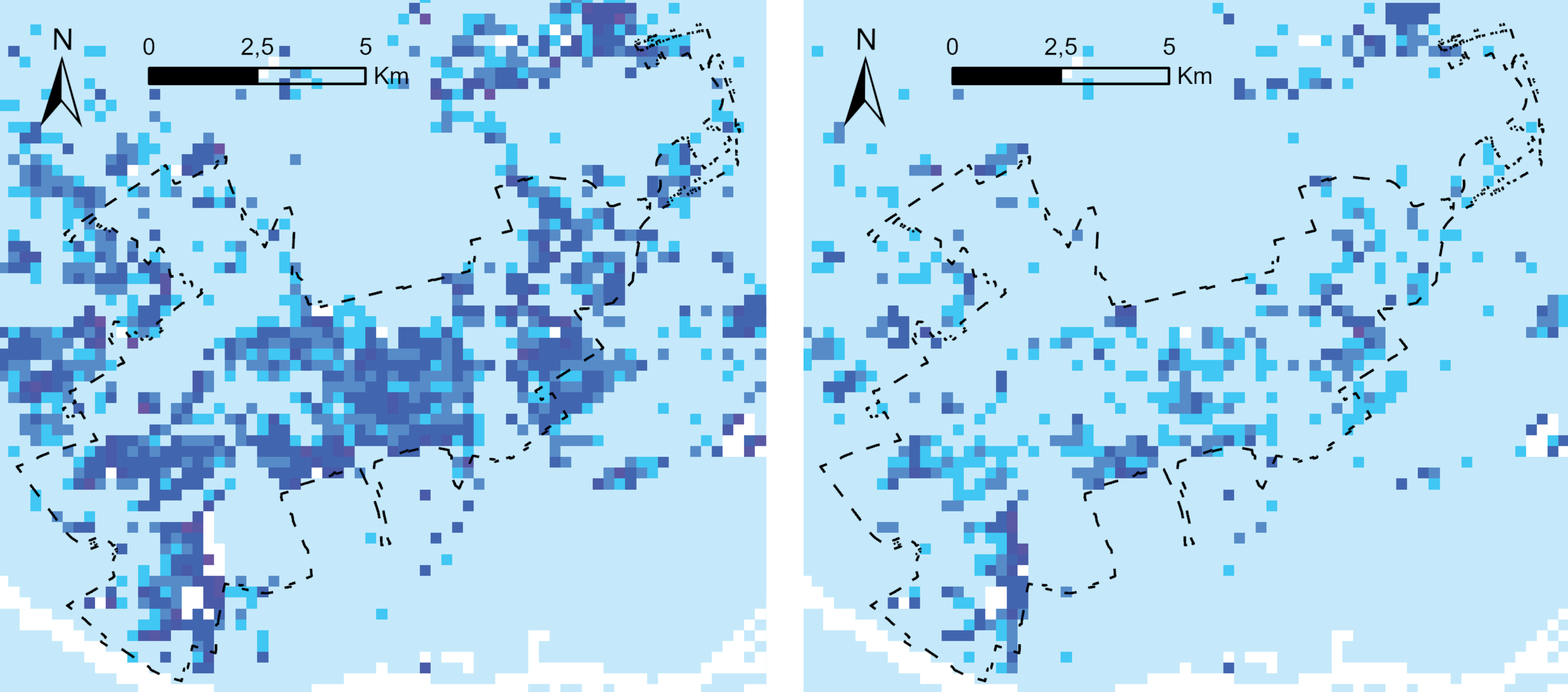


Figure 14 Feasibility analysis: required groundwater level elevation (left) towards -40cm (right) towards -20cm

Legend
Groundwater level elevation needed (cm)

- 0-5
- 5-10
- 10-20
- 20-40
- 40-50
- 50-60
- 60-70
- BPL Midden-Delfland

In the -20 cm map, only a few areas are within the reach of 40 cm to the -20 cm target dewatering level. However, significantly more areas are within 40 cm of the -40 cm target. These areas coincide with the lowest parts of the study area, which are often also the areas with peat, indicating that the peatland areas are already managed with a shallower groundwater level, but they have not yet reached the desired range of -40 to -20 cm.

However, it is important to interpret this map with caution. Actual groundwater levels throughout the year are often higher than those depicted in the dataset, particularly during wetter seasons or years. Because of this, the actual feasibility may be underestimated, and some locations may already meet or exceed the targeted levels for parts of the year. Although this dataset reflects historical conditions, future climate scenarios suggest an increase in the frequency and severity of dry summers. This implies that the extreme conditions shown in the map may become more common.

In summary, this feasibility analysis shows which areas currently have which groundwater levels and indicates the needed effort to reach the desired -20cm or -40cm. It also suggests that practical feasibility may be higher in some areas than this conservative dataset implies. These insights help define the spatial constraints within which groundwater level strategies and alternative land uses can be realistically implemented.

9.4.3 Desirability analysis

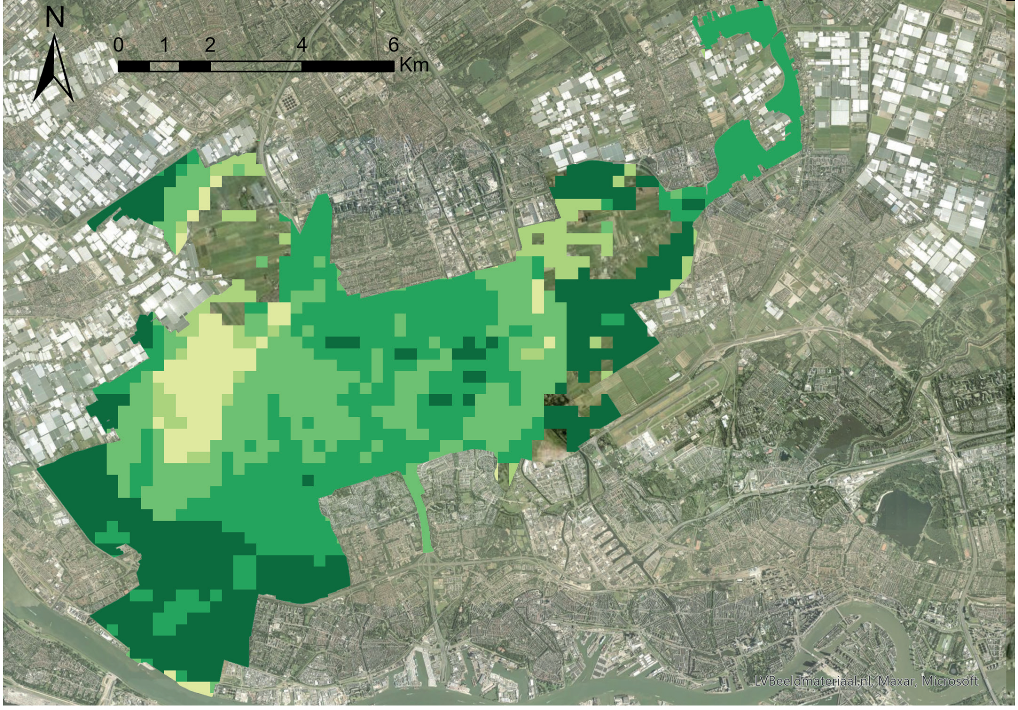
The desirability component of the analysis reflects spatially the preferred areas for groundwater elevation, guiding where this intervention is more socially or economically acceptable. This was carried out with the help of a Multi Criteria Decision Analysis, identifying areas where interventions may be resisted or welcomed.

The weights for the MCDA were determined using AHP with the help of expert input. Experts were asked to assign relative weights to a set of predefined criteria. Each expert only scored the categories for which they had relevant expertise. The assignment form and an overview of expert contributions are included in Appendix 1. The processing of the data in ArcGIS PRO can be found in Appendix 2.

Table 6 displays the relative scores for each criterion given, within the three categories of the conceptual framework. The differences between the scores are relatively small, all close to around what would be an equal distribution. Only minor deviations are visible, suggesting that the influence of each criterion is roughly balanced within the three categories.

Table 6 Relative scores for criteria agricultural viability, infrastructure resilience, environmental sustainability

Criterium	Relative score
Agricultural viability	
Crop-specific optimal groundwater level	22%
Crop tolerance to inundation	15%
Crop water demand (drought tolerance)	25%
Meadow bird areas	15%
Salinized agricultural areas	24%
Infrastructure resilience	
Sensitivity to water nuisance	26%
Foundation vulnerability	36%
Soil bearing capacity	38%
Environmental sustainability	
Peatland extent and carbon emissions	37%
Ecological network	25%
Areas at risk of salinization	38%

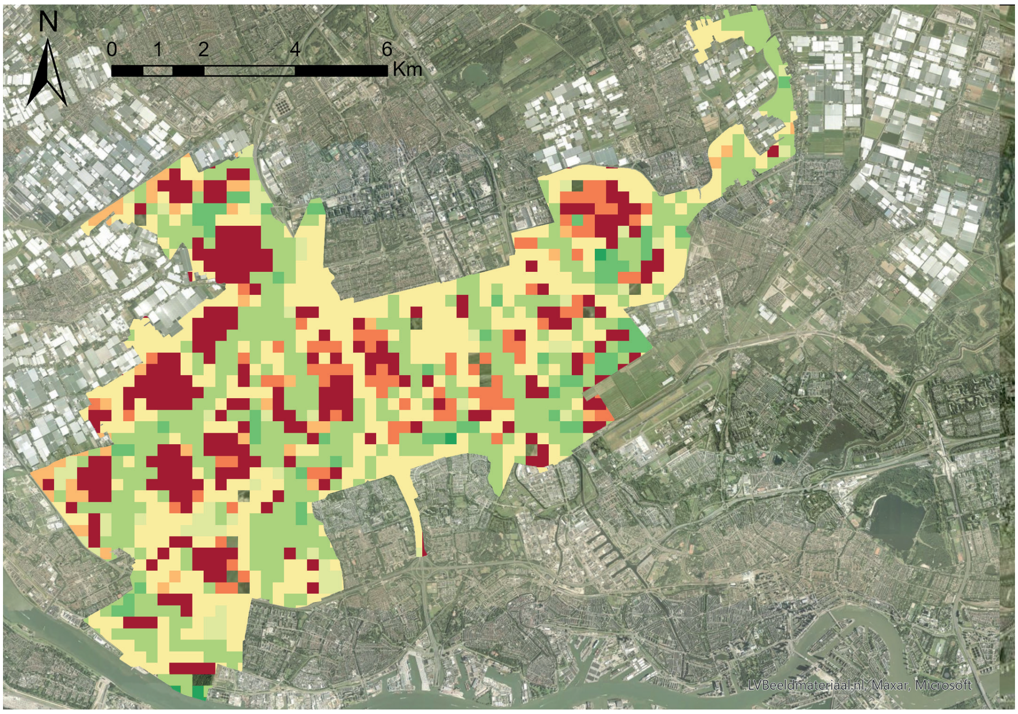


Class

1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10

Figure 15

Desirability analysis: MCDA
Environmental sustainability

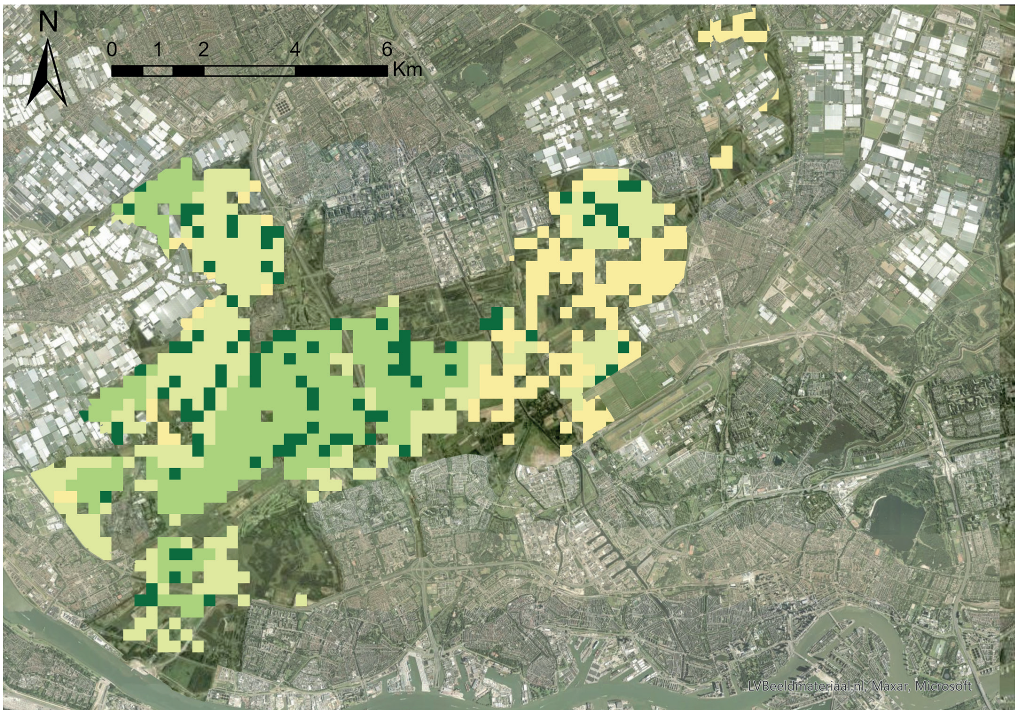


Class

1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10

Figure 16

Desirability analysis: MCDA
Infrastructure resilience



Class

1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10

Figure 17

Desirability analysis: MCDA
Agricultural viability

The map in Figure 18 displays the combined MCDA desirability analysis. The goal of the map is to identify quickly which areas react positively or negatively. However, the combined MCDA desirability map holds some challenges in interpretation. In general, a large part of the study area scores above class 5, indicating a relatively high desirability for groundwater level elevation. Zones that score below 5 are considered less desirable, as elevation may have negative impact on one or more aspects of the AV, IR, or ES categories.

Because of the consolidation of criteria, it is not everywhere retraceable which specific criterion is driving the positive or negative score in an area. Which makes it hard to know what specific factor to take into account when elevating groundwater levels in that area would be indicated as necessary and feasible in the previous analyses. The value of the combined map lies in the ability to cross-reference with the individual layer maps, which helps identify which criteria are dominant in driving the total desirability scores. Therefore, the individual MCDA for each layer is examined and visualized in Figures 15, 16, and 17.

Environmental Sustainability MCDA

From the ES perspective, areas with a high possibility for peat oxidation reduction and a high risk of salinization are among the most positively influenced zones. In addition, designated nature reserves and ecological zones also show high desirability for groundwater elevation. These areas often coincide with remaining peat soils, where substantial emission reduction can be achieved. This results in Figure 15, where the southwestern part of Midden-Delfland stands out as a priority area for intervention from an environmental sustainability standpoint.

Infrastructure Resilience MCDA

The IR criteria, particularly water nuisance sensitivity, tend to have a strong negative weight, which also appear in almost all raster cells in the study area. Because of this, the IR perspective often reduces the overall desirability score, even in zones with high ecological or agricultural potential. For example, roads and villages on peat soils are marked with lower desirability. However, as can be seen in Figure 16, rural and areas with mostly nature where infrastructure is limited appear as preferable areas for groundwater level elevation from the IR perspective.

Agricultural Viability MCDA

Looking at the agricultural zones it becomes visible that most areas experience slightly negative to neutral effects from groundwater elevation, although the impact varies significantly by crop type. The ability for groundwater elevation to have positive effects on the criterium of drought resistance, leads to a more favourable view. Moreover, salinized areas and areas designated for meadow bird habitat additionally respond positively. This is particularly the case in the western part of Midden-Delfland, where saline intrusion is already an issue. Compared to the eastern part of the region, the west appears significantly more desirable for groundwater elevation based on the combined AV criteria, which is visualized in Figure 17.

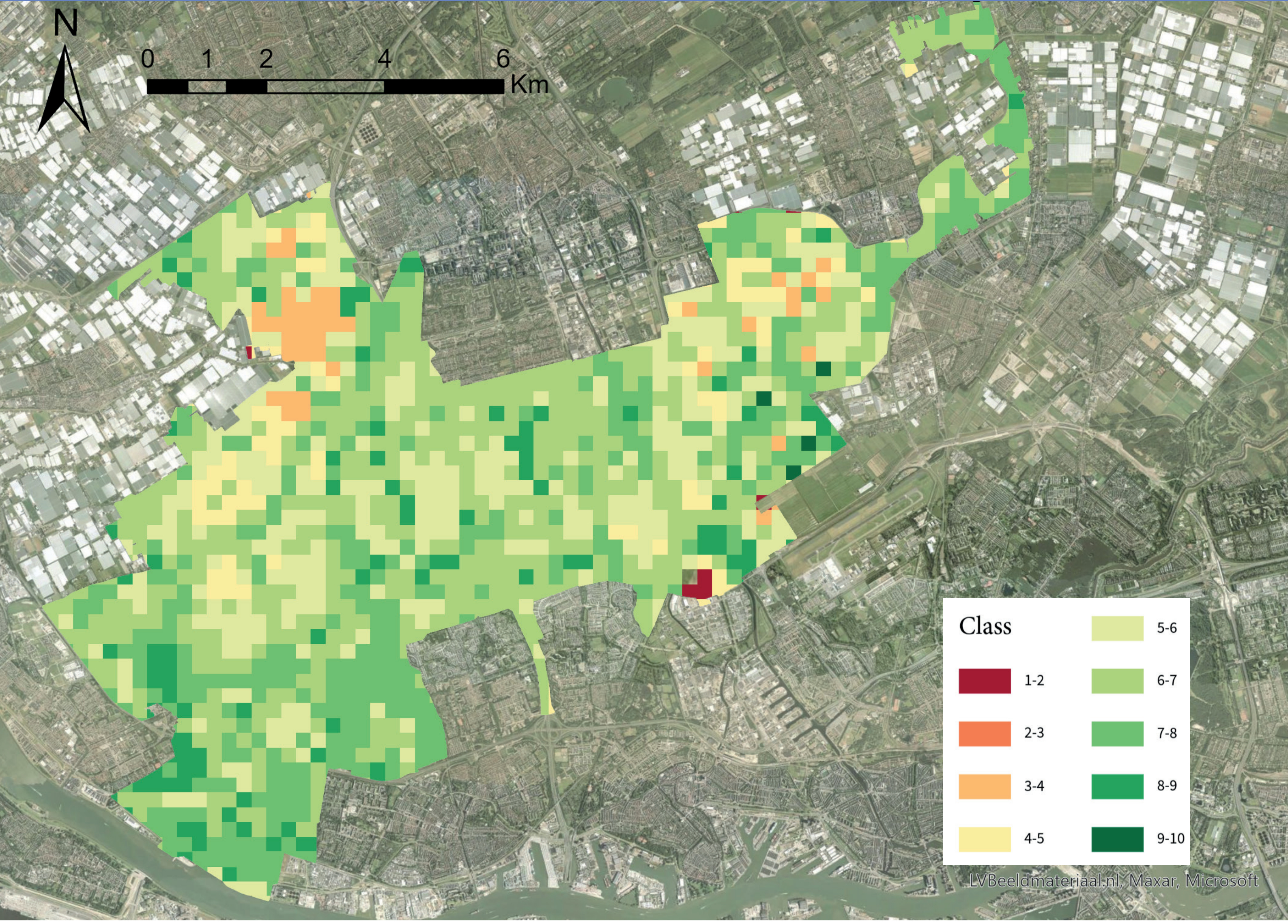


Figure 18

Desirability analysis: MCDA

9.5 Summary

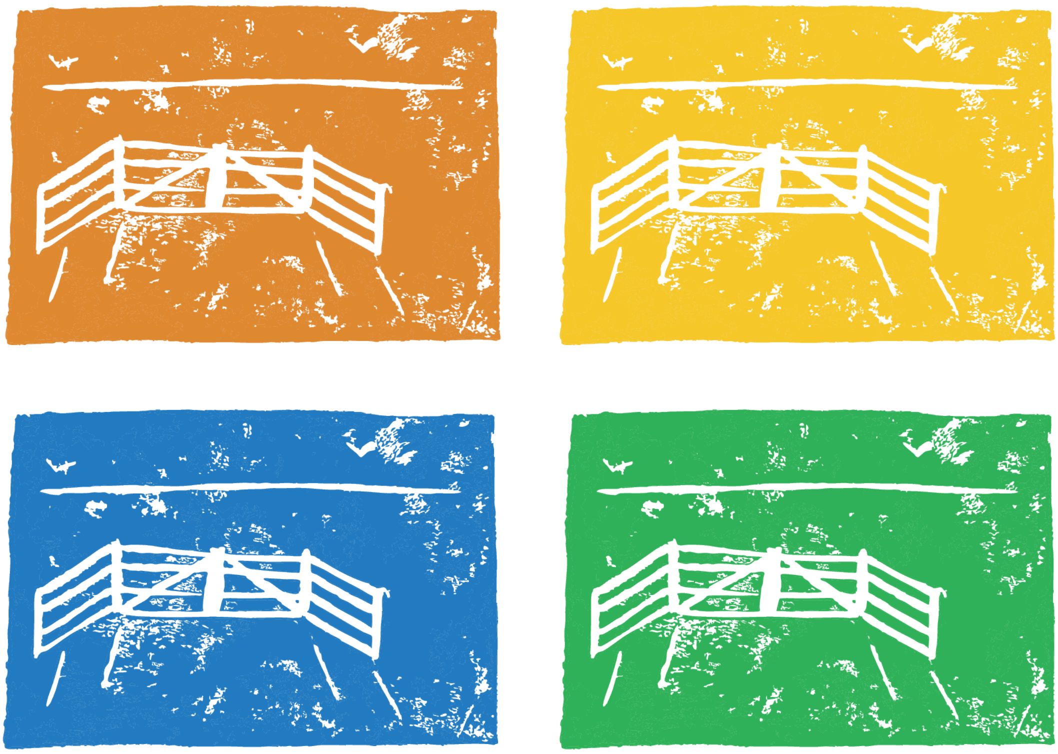
The MCDA and GIS analyses show where groundwater level elevation is necessary, where it is feasible, and where it is most desirable. Based on these outcomes, certain areas can be identified as priorities for intervention to make the areas more fit with a high groundwater level. The combination of necessity, feasibility, and desirability highlights various factors that determine the overall suitability of locations for groundwater level elevation.

Since the MCDA results are open to interpretation and discussion, they should be approached with caution. However, the underlying factors and classifications, separately, are valid and verified and will play an important role in informing the design component of this research.

Areas that are identified as most necessary for groundwater elevation but least desirable from a current land-use perspective are of particular interest in the context of transition. Overall, it can roughly be concluded that the desirability analysis from the three categories identifies nature areas, salinized agricultural zones, and less infrastructure dense landscapes, which point to areas particularly in the southwest of Midden-Delfland, as the most promising locations for raising groundwater levels. If groundwater levels are to be raised in these zones, existing land uses may need to be adapted or transformed to accommodate the new hydrological conditions.

Results Phase Three

Translate findings to spatial transitions



10. Results phase three

This chapter brings together all previously gathered insights and applies them to the case of Midden-Delfland. In the previous chapter, areas where groundwater elevation is necessary, feasible and desirable were identified. To optimise the potential of groundwater elevation for carbon reduction, some current land use functions need to be re-evaluated. The greatest impact can be made in the agricultural fields because the majority of the peatland is situated there. Building on the current challenges and the momentum created by national climate and environmental programs, this moment presents a window of opportunity for meaningful transition, therefore, the options for agricultural change to higher groundwater agriculture are explored.

The chapter begins by analysing the current Midden-Delfland. Then it

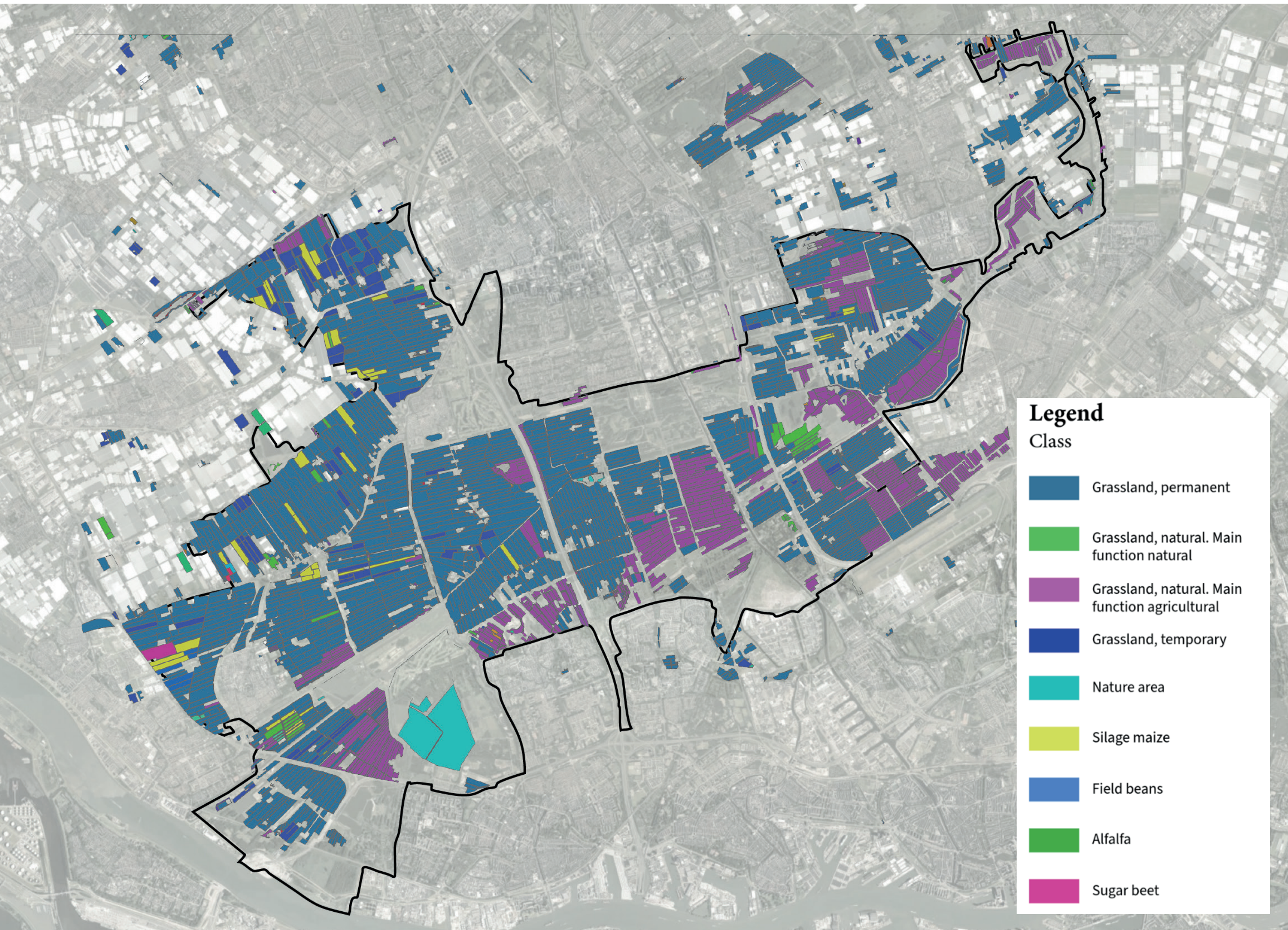


Figure 19 Current agricultural crops in Midden-Delfland. Adapted from PDOK (2022).

continues by outlining the goals for Midden-Delfland from the perspective of this research, based on policy ambitions, research findings, and expert interviews. This input will then be used to explore options for combining sustainable agriculture together with raising groundwater levels, examining what functions need to be placed where, and discussing how these characteristics would together translate into a spatial vision for 2050, for a climate-resilient Midden-Delfland.

10.1 The current agricultural landscape of Midden-Delfland

Before envisioning a future for agriculture under elevated groundwater levels, it is essential to understand the present situation. Midden-Delfland is known for its iconic Dutch peat meadow landscape, characterised by long, open polders with grazing cows. Currently, the agricultural sector in Midden-Delfland mainly consists of dairy farms, as shown on the crop indexation map from Figure 19, where the crop grassland reflects dairy farming. This landscape holds a strong cultural and emotional value in the Netherlands, which is reflected in legal protections aimed at maintaining its open character, as mentioned by experts in Chapter 8.

In addition, the openness of the landscape is a critical condition for meadow bird conservation, which remains a key pillar of regional nature policy (Provincie Zuid-Holland, 2019). Together, these cultural and ecological requirements make spatial transitions in the area particularly challenging. However, national debates surrounding climate change and nitrogen emissions have created a “window of opportunity” to reconsider land use in a more sustainable direction. This shift is also encouraged by regional policy documents such as the *Zuid-Hollands Programma Landelijk Gebied* (South Holland Programme for Rural Area) (Provincie Zuid-Holland, 2025).

10.1.1 The Dutch agricultural dairy system

Because of the prominent presence of dairy farming in Midden-Delfland, it is important to understand the dairy system. The intensive dairy industry as we know it today, embedded in this Dutch polder landscape, is largely the result of developments since the 1950s. Driven by rationalization, specialization, and upscaling, many small farms merged into fewer, larger operations (Aben et al., 2024). Supported by the use of fertilizers, mechanization, and pesticides, the system prioritized productivity, often at the expense of the natural environment.

Environmentally, the sector contributes to high nitrogen emissions, which pose a threat to protected Natura 2000 areas (European Union, 1992), while continued peat drainage results in significant greenhouse gas emissions. Additionally, biodiversity has declined due to the dominance of monocultures, and the runoff of fertilizers and pesticides continues to degrade both surface and groundwater quality (Blondeau et al., 2024; Eulenstein et al., 2016).
From a spatial perspective, agriculture now competes with other land uses such as housing, energy infrastructure, climate adaptation, nature conservation, and recreation, which together place growing demands on limited space (Ministerie van Landbouw Natuur en Voedselkwaliteit, 2020). Combined with its ecological footprint, these spatial pressures place the dairy sector under increasing scrutiny in today’s context.

10.1.2 Climate change and farmer perspectives

Climate change is already affecting farmers with local consequences such as drought, land subsidence, and crop failure. For instance, an agricultural expert noted that during a recent dry period, groundwater levels dropped by 30 cm in just over a month. While farmers are entrepreneurs focused on income and animal welfare, they are more and more confronted with the limits of the current agricultural model.

From an economic perspective, the path toward sustainability is hindered by market risks, a lack of long-term policy consistency, and the dependency of many farmers on subsidies, as highlighted by experts in Chapter 8. Changing farming models is financially uncertain, particularly because bank loans tend to favour conventional systems, whose revenues are more predictable due to the use of pesticides, fertilizers, and economies of scale (de Jong et al., 2021).

If groundwater levels are to be raised to the ideal range of -40 to -20 cm below surface level, current agricultural practices will become less viable. The conventional system based on heavy machinery and dairy farming cannot operate effectively above a groundwater level of around -50 cm (Evans et al., 2021). This calls for a shift toward alternative forms of agriculture and land management.

In areas where groundwater elevation is proposed, two main options emerge: either adapting existing agricultural practices or transitioning to alternative land uses, such as nature development. However, this shift requires moving away from the conventional model of agriculture as the standard business case and the associated typical Dutch landscape. Instead, it calls for a new system that continues to produce food while simultaneously enhancing biodiversity, supporting climate adaptation, and delivering broader societal value.

10.1.3 Agricultural practices in Midden-Delfland

Midden-Delfland already distinguishes itself through relatively sustainable agricultural practices. Nearly all farms in the region operate under an extensive model, using less fertilizer and fewer pesticides, and maintaining more grassland per cow. As of September 2022, 48 out of approximately 55 farmers were participating in the ‘circular agriculture working group’, which focuses on nutrient efficiency, reducing ammonia emissions, and increasing on-farm protein production. According to experts 4 and 7, farmers in the area demonstrate above-average environmental awareness, suggesting that the region holds strong potential for sustainable transformation. These experts also noted that many farmers diversify their income through activities such as educational services, farm shops, and event hosting.

The perception that Midden-Delfland farmers are already relatively sustainable is also supported by regional promotion through community magazines and local initiatives (Gemeente Midden-Delfland, 2024). Experts in biodiversity and agriculture emphasize that transparency, collaboration with researchers, and the open sharing of sustainability monitoring results, like soil and water quality data, have significantly increased farmer engagement. Most farmers are open to adaptation, especially when the measures benefit animal health and financial viability. As one biodiversity expert noted, “farmers also enjoy seeing dragonflies and butterflies.” This shows that willingness to adopt ecological measures is often influenced by both intrinsic motivations and the availability of subsidies. Ultimately, farmers remain entrepreneurs, looking for profitable operations and good living conditions for their livestock.

These insights indicate that higher groundwater levels may not be feasible across all current agricultural land. However, groundwater elevation in Midden-Delfland can be achieved through a limited number of effective methods, each with different spatial implications. According to experts, suitable techniques for peat areas like in Midden-Delfland are submerged drainage systems and furrow infiltration. In addition, alternative land uses, like nature, or sponge-like vegetation that retain winter water for use in drier months could enhance both sustainable water balance and ecological value. Raising surface water levels alone is not effective at this scale due to the high water demand and the limited impact on peat soils.

Figure 20 Landscape context of the study area.. Created by the author.

 Figure 21 Collage of the identity of Midden-Delfland according to the conceptual framework. Created by the author.

10.2 Towards a climate-resilient Midden-Delfland: the design objectives

To generate a future vision of the area of Midden-Delfland, the current characteristics, and its future goals need to be taken into account. What are the current strengths of the area and what contributions could a future Midden-Delfland with higher groundwater levels provide? To guide the design of this future vision, objectives were determined.

Firstly, the objectives are derived from the research aim. These objectives reflect a future proof design within the scope of current policy frameworks related to the research. These policy frameworks include the South-Holland Programme for Rural Areas and the aim to reduce 1 Mton of carbon emissions by 2030 in the Dutch Climate Agreement (Ministerie van Economische Zaken en Klimaat, 2019a; Provincie Zuid-Holland, 2025). Consequently, specific design objectives for this area were formed. These objectives are in line with the framework of agricultural viability, infrastructure resilience, and environmental sustainability to further enhance the valued current character of the study area while simultaneously making it more climate-resilient. These objectives originate from interviews conducted with various stakeholders, considering the spatial opportunities and constraints, and are supported by the vision of the BPL Midden-Delfland to protect and enhance the 1) natural landscape, 2) agricultural landscape, and 3) the recreational landscape, as its main ambition is "to strengthen its role as a green-blue oasis where nature, agriculture, and recreation coexist in balance." (BPL Midden-Delfland, n.d.). These current characteristics are visualised in Figure 21.

The specific areas selected for redesign are derived from the groundwater level elevation analysis in Chapter 9. The focus is specifically on areas currently used for agriculture, as these are most prominent on peat soils, and thus offer the greatest potential for reducing GHG emissions. Additionally, Midden-Delfland largely exists of agricultural land, this vision concentrates on the agricultural landscape to reduce CO_2 emissions and soil subsidence, while simultaneously enhancing ecological value, sustainability, and other regional objectives, such as recreation and community wellbeing. The goals the research aims to achieve are the following:

- **Reduce soil subsidence**
- **Minimize CO_2 emissions**

To which the following overall objectives, aligned with existing policies, guide the design in achieving this goal. These can be traced back to the backbone of the conceptual framework of this research, framed as *resilient groundwater management*:

- **Embrace water and soil as guiding principle**
    - making them the foundation for spatial decisions to ensure long-term environmental and functional resilience
- **Design for climate resilience: accommodating extreme weather events**
    - by shaping a multifunctional landscape that mitigates flooding, retains water during drought, and supports resilience

Framework specific design objectives:

- **Enviromental sustainability: Strengthening ecological connections**
    - Reconnect the different parts of the area to nature by restoring green-blue corridors, enhancing biodiversity in agricultural and natural zones, and supporting a resilient landscape mosaic adapted to water and soil dynamics.
- **Infrastructure resilience: Maintaining and enriching the recreational character of the area**
    - Preserve Midden-Delfland's accessible identity while enriching its recreational value through adventurous new routes and nature-based experiences.
- **Agricultural viabilty: Advancing Midden-Delfland's sustainable agricultural practices**
    - Strengthen Midden-Delfland's role as a frontrunner in sustainable (circular) farming by piloting new land use models, and creating a living laboratory for regenerative, peat-compatible agriculture.

Figure 22 The design objectives for the area, aligned with conceptual framework. Created by the author.

All in all, this combines into the following vision of the area, depicted in Figure 23:

By 2050, Midden-Delfland is a climate-resilient region with healthy peat soils, rich biodiversity, and future-proof agriculture. Strengthened ecological connections, a thriving recreational landscape, and sustainable farming practices together ensure a vibrant, multifunctional area that buffers water, supports life, and protects future generations.

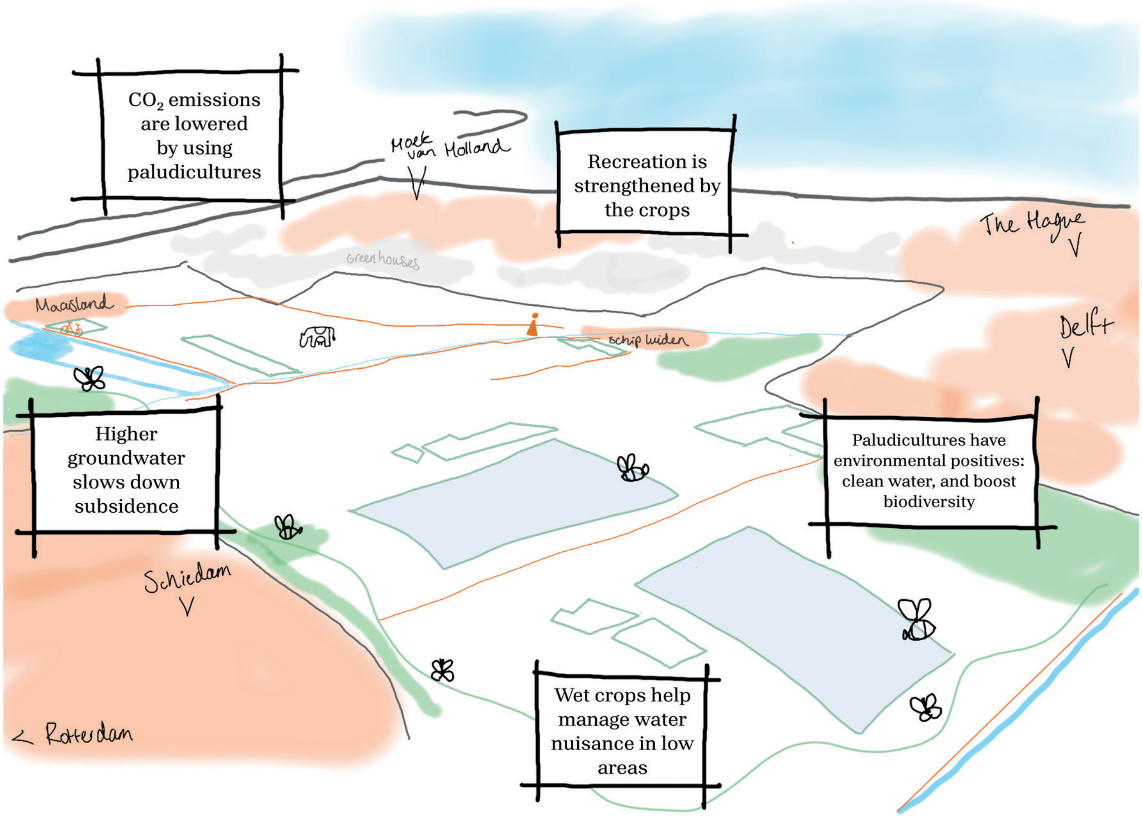


Figure 23 Vision map for Midden-Delfland

10.3 The future agricultural landscape of Midden-Delfland

This section explores agricultural practices that respond positively to elevated groundwater levels. It examines land use options that align with climate adaptation goals and the design objectives previously mentioned and concludes with assessing their advantages and disadvantages for the Midden-Delfland region. The insights are used as a foundation for the development of the future spatial vision.

10.3.1 Sustainable agriculture for high groundwater levels

To reduce CO_2 emissions and slow peat oxidation, it is essential to transform the current low-groundwater-level dairy farming system into agricultural practices that are compatible with higher groundwater levels. According to Marselis et al. (2024), different land use types are promising for peat landscapes. The most economically viable options, are explored below.

1. **Peat moss**

Peat moss

Peat moss has the ability to store water, prevents CO_2 emissions, and even stores CO_2. Additionally, it catalyses peat formation, which results in the ground level elevating with 1 cm per 10 years (Daun et al., 2023). This type of agriculture is already used frequently in peatland areas in Germany. The harvested peat moss is used in the horticultural sector, particularly as a substrate for potting new plants. For optimal growth, peat moss requires groundwater levels close to the surface (between -5 and +5 cm) and has sponge-like properties, allowing it to absorb and store large amounts of water (Pouliot et al., 2015). As a result, it can act as a natural water buffer during heavy rainfall and provide moisture to the crop during dry periods. However, this cultivation requires clean water and currently offers limited financial returns. From an economic perspective, farmers may be more willing to adopt peat moss cultivation if adequate compensation for yield loss is given.

2. **Cranberries**

Cranberry

Cranberries achieve optimal yields at a groundwater level between -40 and -20 cm, which also aligns with conditions favourable for reducing greenhouse gas emissions (Balode & Blumberga, 2024). While yields are initially low, typically generating no income in the first two to three years for the crop to grow big enough, several farms in the Netherlands have demonstrated its viability, with approximately five cranberry farms currently in operation. Near village edges or along busy recreational routes, cranberry cultivation could serve a multifunctional purpose by offering recreational value, such as selling products on-site and welcoming visitors to the farm.

3. **Cattail**

Cattail offers a multifunctional solution that combines water purification, water storage, and soil restoration. The plant absorbs nutrients such as phosphorus and nitrogen, which have accumulated in the soil and water due to decades of intensive agricultural practices (de Jong et al., 2021). By taking up these excess nutrients, originally added in the form of (artificial) fertilizers, cattail helps to rebalance and purify nutrient-rich peat soils,

which also makes it viable for nature areas on the long term.
Cattail tolerates a wide range of water levels, from -10 cm to +25 cm, and is resilient to fluctuating water conditions (de Jong et al., 2021). This makes it particularly suitable for water retention strategies in peatland areas. In addition to its ecological benefits, the crop can be processed into animal feed or bio-based building and insulation materials. This presents promising opportunities for the Dutch housing market, which increasingly seeks local and sustainable construction materials.
While cattail supports water filtration and storage, methane emissions from too high groundwater levels remain a concern (Evans et al., 2021). Currently, the crop is not yet competitive with dairy production, primarily due to high cultivation costs and low returns. However, with economies of scale and a growing market for bio-based materials, its viability can improve over time, as is demonstrated in Germany (de Jong et al., 2021). In the Netherlands, several pilot projects are underway to explore cattail cultivation, but large-scale production has not yet been realized. In eastern Germany, however, entire villages have already been constructed using cattail as a circular building material, to demonstrate its long-term potential (de Jong et al., 2021).

Cattail

4. Reed

Reed tolerates groundwater levels ranging from 20 cm above to 20 cm below the surface. Reed cultivation supports both emission reduction and biodiversity. It also plays a positive role in water quality, the same way cattail does, by directly by absorbing nutrients, and indirectly by creating habitats for aquatic species (Wichmann, 2017; Wichmann & Köbbing, 2015). It can be used in various ways, including chopped biomass for biogas production, bales for direct combustion, and thatching material for roofs.
In the Netherlands, there are around 100 reed growers managing approximately 4,500 hectares, mainly in the eastern part of the Netherlands. However, this is not sufficient to meet domestic demand, as 75% of the reed used in the Netherlands is imported (de Jong et al., 2021).

Reed

Figure 24 Images of paludicultures. Created by the author.

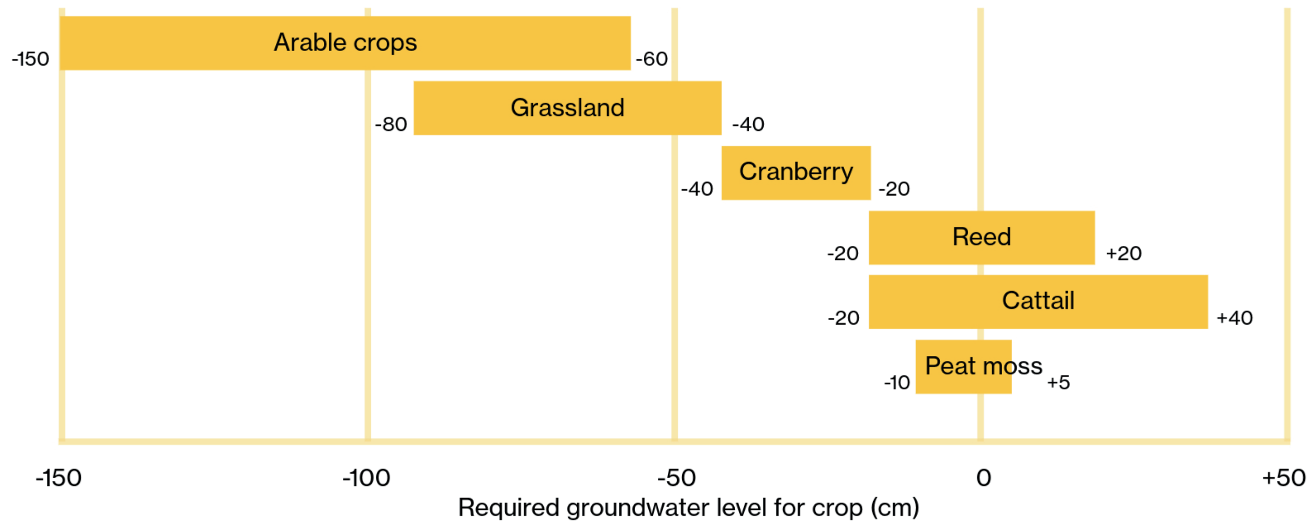


Figure 25 Types of agriculture and paludiculture possible at different groundwater levels. Created by the author.

10.3.2 Synthesis sustainable agriculture alternatives

Based on the assessment of these different agricultural species align with the conceptual framework and design objectives, the following conclusions can be drawn.

Resilient groundwater management

Cattail and reed have the highest water retention capacity, as they tolerate a groundwater level above the ground level. This is then followed by peat moss, which can still store a reasonable amount of water, but has a slightly lower groundwater level. Cranberries, however, only add little value in this regard, as the crop can be grown with the lowest groundwater level of all proposed crops.

Environmental sustainability

Peat moss offers the most positive effect on greenhouse gas (GHG) reduction. In addition to emitting less CO_2, it can also actively sequester carbon. Reed follows, contributing to reduced emissions due to elevated groundwater levels. However, as water is above the surface level, methane emissions may disregard some of the benefits. Moreover, cattail ranks slightly lower due to even higher water levels that further increase methane emissions. Cranberries perform least effectively in this category, as they require groundwater levels between 40 and 20 cm below the surface, offering minimal GHG savings compared to current land use.

Additional environmental benefits are seen with reed and cattail, both of which help purify water through nutrient uptake. In the longer term, the reed and cattail areas could transition into ecological wetland areas, particularly after nutrient extraction has been completed. Additionally, peat moss has added value for biodiversity as is is home to diverse plant and animal species, many of which are uniquely adapted to these wetland environments

Infrastructure resilience

When looking at the recreational value of each crop cranberry cultivation shows strong potential for multifunctional land use. It requires manual harvesting, currently in the Netherlands often supported by volunteers, making locations near villages particularly suitable. This also offers potential for farms to include visitor experiences such as farm shops or pick-your-own events.

For cattail and reed, recreational potential is limited. These crops grow tall and dense, creating a closed landscape that limits in-field recreation. Educational purposes, such as small museums explaining their processing and uses, may be possible.

Peat moss offers more recreational opportunities. For example, adventurous walking paths could be created across peat moss fields, varying from accessible moss-covered areas in dry conditions to wetland trails after rain. While recreation may slightly reduce yields, it can significantly increase public acceptance, given it does not interfere with regular farm operations. A practical solution could be a designated experience field not used for harvest.

Agricultural viability

Peat moss is ecologically the most effective crop in terms of CO_2 reduction, but its yield is relatively low and the business model has yet to be fully developed in the Netherlands. However, in Germany, commercial applications already exist, showing profitability starting at approximately 30 hectares. Cattail also demonstrates strong market potential, yet the Dutch market for this crop remains underdeveloped. If more producers were to engage in cultivation, economies of scale could be achieved, with profitability estimated from 20 to 30 hectares, as is already experienced in Germany. Reed benefits from a more established market, as 75% of Dutch reed is currently imported. It is economically viable from 10 hectares. Cranberries occupy a niche market but have proven viable as several cranberry farms are already active in the Netherlands, many of which combine farming with visitor experiences such as farm shops. These operations have shown to become profitable at around 18 hectares in the Netherlands. These practical conditions have been incorporated into the spatial plan.

Unique characteristics per crop

Each crop offers unique benefits, but also presents drawbacks, in the transition toward a sustainable peatland landscape, summarized in Table 7.

Table 7 Proposed crops and their characteristics. Created by the author.

Crop	Height	Range groundwater level (cm)	GHG reduction	Biodiversity potential	Water storage	Water purifying	Characteristic
Peat moss	15 cm	-10+5	++	++	+	++	‘original’ landscape, open
Cranberries	20 cm	-40-20	+	0	0	0	Recreational opportunities, open
Cattail	2-3m	-20+40	-	+	++	++	Closed, high crop
Reed	1-3m	-20+20	+	+	++	++	Closed, high crop

- Peat moss is the most powerful option for CO_2 mitigation and has strong biodiversity potential, although it comes with the trade-off of low productivity.
- Cranberries, while offering only moderate climate benefits, present strong potential for recreational use and therefore strengthening of the identity of Midden-Delfland as a recreational area.
- Cattail offers fewer benefits for direct CO_2 reduction, but holds significant potential as a circular construction material, urgently needed in the housing sector. However, the market for cattail-based building materials is still very small in the Netherlands.
- Reed is comparatively easier to integrate, produces relatively low methane emissions, and contributes to water purification and biodiversity enhancement.

In conclusion, these various crops each have different consequences for the spatial plan. Peat moss has the greatest flexibility in spatial placement and can be used across a wide range of conditions, including areas with thinner peat layers and short-to-ground level dewatering depths. Cattail, on the other hand, is most effective in locations with thick peat layers and currently low groundwater levels. Reed requires a slightly less deep dewatering depth.

Cranberries, while less critical for greenhouse gas reduction and ecological development, still have a valid role to play. Their economic model and recreational appeal make them particularly well-suited to areas near villages or cycling and walking routes in the area.

The economic viability of wetland crops remains a significant variable, with current data suggesting that reed and cranberries hold the most promising market outlook, followed by cattail and peat moss. Peat moss, while less profitable, provides the strongest ecological advantages. Cranberry farms located near villages offer promising opportunities for integrating landscape identity, recreation, and water management.

In conclusion, a future-proof Midden-Delfland depends on strategic spatial zoning. Some areas should continue to support adapted dairy farming, while others transition toward wetland crops or even ecological restoration. A mix of land uses, aligned with groundwater conditions, environmental potential, and surrounding landscape functions, will guide this planning process.

10.4 Shaping the transition with Theory of Change

To ensure that the proposed spatial transition in Midden-Delfland is both effective and socially acceptable, this part will apply the Theory of Change (ToC) as a strategic planning tool. The ToC supports visioning and transition planning by clarifying how and why change is expected to occur within a specific context (Deutsch et al., 2021). It helps to reflect systematically on the barriers, preconditions, stakeholders, and assumptions involved in reaching the long-term vision for the region (Mayne, 2017). By embedding the outcomes of the GIS analysis, expert consultations, and policy review into the ToC framework, the resulting strategy will become more robust, executable, and fits well in the context, by incorporating the tensions and uncertainties in the plan.

The goal
The main goal is that by 2050, Midden-Delfland is a climate-resilient region, where peat oxidation is halted or reversed, CO_2 emissions are significantly reduced, biodiversity is thriving, and agriculture is both ecologically and economically future-proof. The region's landscape should function as a sponge that buffers and purifies water, absorbs climate shocks, and contributes to a healthy environment for all inhabitants.

The intermediate outcomes
To realise the 2050 vision for Midden-Delfland, a combination of policy reforms, behavioural shifts, land-use changes, and ecological restoration is necessary, based on the previous findings from this study.

- **CO_2 emissions must be reduced in line with the Climate Agreement**

  Peat oxidation in the region is a significant source of greenhouse gas emissions. Emission levels must be reduced in accordance with the Dutch Climate Agreement (2019), which targets a 49% reduction in greenhouse gases by 2030 compared to 1990 levels, of which 1 Mton reduction is achieved from peatland carbon reduction.

- **Structural elevation of groundwater levels**

  In peatland areas, groundwater levels need to be structurally raised to between 20 and 40 cm below surface level (Ministerie van Algemene Zaken, 2022). This is critical for slowing or stopping peat degradation and soil subsidence.

- **Sustainable agricultural practices**

  Farmers farming on peat soils must transition toward (agricultural) practices more compatible with higher water levels and contribute to long-term soil preservation.

- **Shift from rapid drainage to water retention**

  Current water management is primarily designed to remove excess water as quickly as possible. A transition is needed to retain water in the landscape, allowing it to function as a sponge during both dry and wet periods.

- **Aligned systems with peat conservation**

  Water management and land-use permits must be restructured to prioritise peat preservation over maximum agricultural output.

- **Improved water quality**

  Buffer zones and landscape redesign must reduce nutrient runoff and pesticide pollution from agricultural land to protect ecosystems and drinking water.

- **Recognition and valuation of ecosystem services**

  Services such as carbon storage, flood mitigation, and biodiversity should be financially rewarded as it often comes at the cost of yield. Rewetting should be seen not as a burden, but as a public service to society, worth compensation.

Interventions to get to the goal

To achieve the required changes and goals, a few are proposed to be necessary steps:

- **Establishing pilot areas**

  Pilot zones for high water retention and wet agriculture should be designated in low-lying peat zones with minimal existing infrastructure. For example, areas near recreational routes could be suitable, as they are already frequently visited by cyclists and walkers. These pilots should include crops like cattail or peat moss and be designed to demonstrate landscape change and feasibility of these crops to both farmers and visitors. For this, neutral entities like universities or research institutes could undertake independent research to demonstrate the effectiveness of the proposed climate-resilient solutions to convince all stakeholders.

- **Education and communication**

  Education is important for both farmers and local residents, as well as for people advocating for the preservation of the current peat landscape, is education. This can be done via pilot zones. Pioneering farmers in the area, beginning with paludiculture pilots, could act as peer-educators or ambassadors within the existing ‘circular farming Midden-Delfland’ programme. This will build understanding of the benefits of rewetting and help reduce resistance to change. For educating and informing visitors, information panels and interactive farm days could be organised to introduce the public to relatively unfamiliar crops. Another approach is to link this communication to recreation, to get the message to reach visitors more effectively.

- **Facilitating dialogue between stakeholders**

  Structured dialogue is necessary between stakeholders who may be negatively impacted by higher groundwater levels, such as landowners, and those who benefit, such as nature advocacy groups. The goal is not to blame anyone, but to find common ground. With good communication, people can work together to find fair solutions, to get to a shared compromise that is necessary to achieve a climate-resilient Midden-Delfland.

- **Implementation of fitting water management and infiltration systems**

  Waterboards must revise water level decisions to reflect new priorities for peat protection and climate resilience. Additionally, technical measures to facilitate groundwater elevation need to be applied or additional ones need to be made in the field. These measurements can be furrow infiltration, subsurface infiltration pipes (WIS) or new sluices for example, as explained in Chapter 4.2.

- **Development of ecosystem service payment schemes**

  A compensation framework must be introduced to reward farmers and landowners for climate and water management services. These methods are already being developed for peatlands in the province of Friesland, and could be adjusted to serve the research purpose in the province of Zuid-Holland (Wetterskip Fryslân, 2024). Additionally, places that are less profitable, such as natural areas or unproductive lands, must be redefined as valuable ecological assets and incorporated into ecosystem services payment schemes.

- **Policy reform at the provincial level**

  Provincial spatial policy must move away from traditional ideals of productive peat landscapes and support multifunctional, wet, and nature-inclusive uses. For instance, the ‘open peat meadow’ should no longer be binding in policies if it would delay the change to a climate-proof region.

Assumptions and risks

The success of the proposed transition relies on several assumptions and involves certain risks:

- **Public institutions are willing to collaborate**

  The province and waterboard are expected to recognise the urgency of the problem (as reflected in national policy) and to support spatial and regulatory reforms.

- **Stakeholders acknowledge the urgency**

  Both farmers and citizens are assumed to increasingly recognise the impacts of climate change and the importance of acting on GHG emissions from peat oxidation.

- **The government is willing to fund the transition**

  Without strong financial support, particularly for farmers, a voluntary and just transition will be nearly impossible, ecosystem service compensation of some sorts must be guaranteed.

- **Resistance to land-use change**

  A high risk is the unwillingness from both landowners to transform land use, and residents opposing changes in the current landscape. Clear incentives and proven alternative business models are essential to overcome this.

- **Farmers are open to sustainability**

  Many farmers are already involved in a local circular agriculture program. However, sustainability must be framed as a viable business case, and clarity and certainty on future prospects in order for people to be fully committed.

- **Water-related transitions are more prone to support**

  People may at first resist (land-use) change, but are often positively inclined toward water in the landscape, especially when linked to recreation, nature, or residential quality.

Actors

Looking at the different steps which are needed, mentioned above, the actors for the proposed spatial transition in Midden-Delfland are farmers, the waterboard, the province, national government and nature conservation organisations. In this region, also local initiatives have big influence. These organisations are Vockestaert, the agri-environmental Association for Midden-Delfland and PUUUR Midden-Delfland, a platform of entrepreneurs, local organisations, and stakeholders from agriculture, nature, tourism, recreation, and hospitality sectors active in Midden-Delfland. The cooperation and influence of these organisations are needed for implementing and maintaining this transition and they should be involved from the start.

With the Theory of Change, the proposed vision for Midden-Delfland can be translated into a grounded transition plan, which highlights both the potential and the complexity of realising a climate-resilient future for this region.

10.5 The design proposal

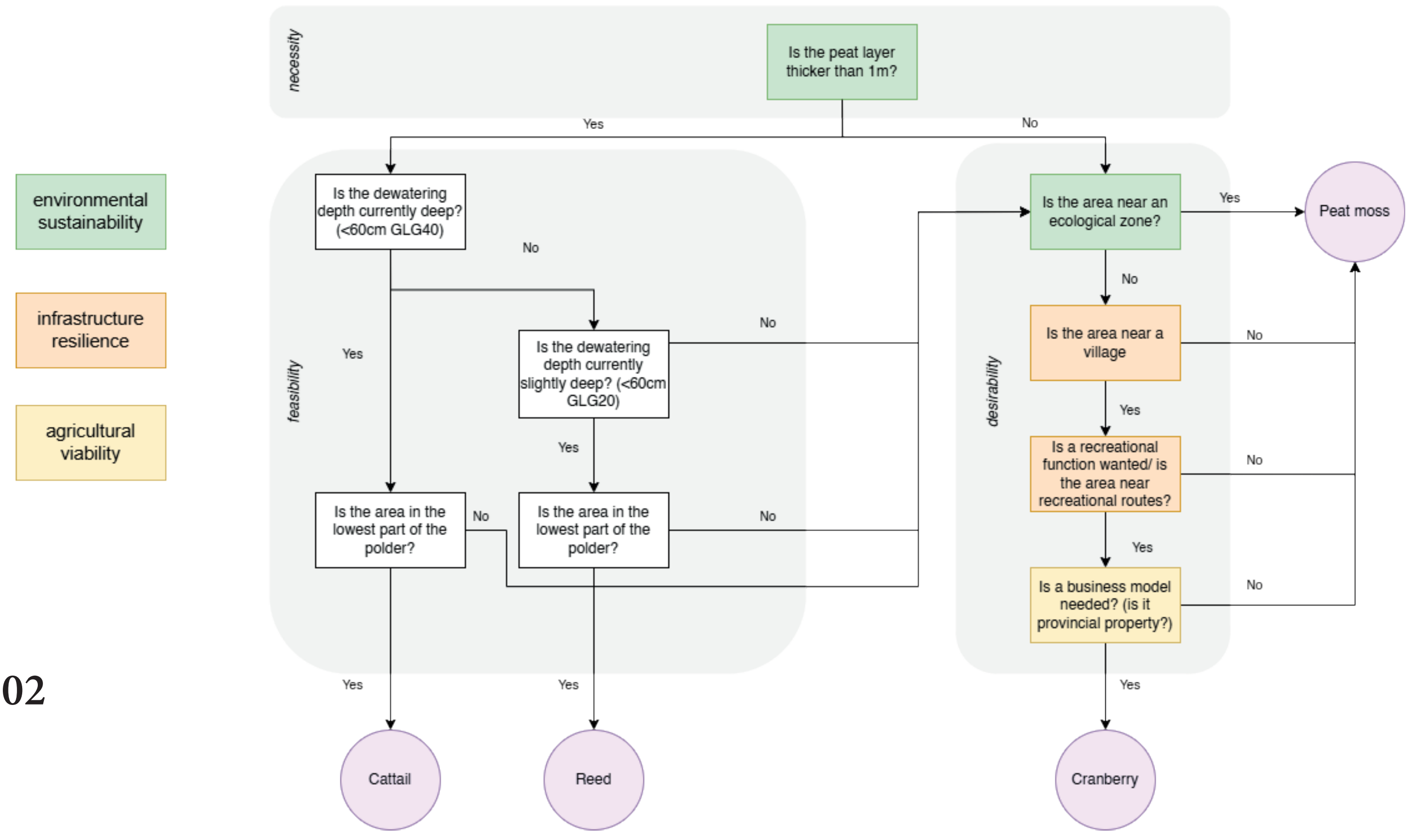
To support the spatial choices in the transition toward sustainable agricultural practices in peatland areas, a decision tree was developed. This decision tree, shown in Figure 26, serves as a practical guide following the structure based on necessity, feasibility, and desirability, discussed in Chapter 9, and the conceptual framework.

Since the various sustainable crops discussed previously each require specific conditions to thrive, the decision tree starts by evaluating the most demanding but also potentially most impactful options: cattail and reed. These crops have a high potential to reduce greenhouse gas (GHG) emissions, but they also carry a risk of increasing emissions if the groundwater level goes above -20 cm. Therefore, the first step focuses on the current CO_2 emissions of an area, determined by the thickness of the peat layer and the existing dewatering depth. This approach ensures that the potential disadvantages, which are the risk of methane emissions linked to the relatively high groundwater levels required for these crops (+10 to +20 cm), are only accepted in areas where the potential for GHG reduction is significant.

The next step is to assess whether a stable, high groundwater level can be maintained, an essential condition for these crops, which is indicated by a low surface elevation. If these conditions are not met, cattail and reed are excluded due to their limited suitability in the spatial context and the risk of increased GHG emissions.

The next options considered are peat moss and cranberry. While peat moss has relatively low economic returns, cranberries offer the least GHG reduction potential among the four options. These two are then evaluated based on the categories defined in the conceptual framework, which align with the design objectives introduced at the start of the chapter. Based on this comparative analysis, either peat moss or cranberry is selected as the preferred crop, depending on their respective characteristics and alignment with sustainability goals, as outlined in the synthesis, and where in the area it could help achieve or strengthen the different design objectives.

Figure 26 Decision tree to guide spatial choices for paludiculture. Created by the author.



10.5.1 The decision tree applied

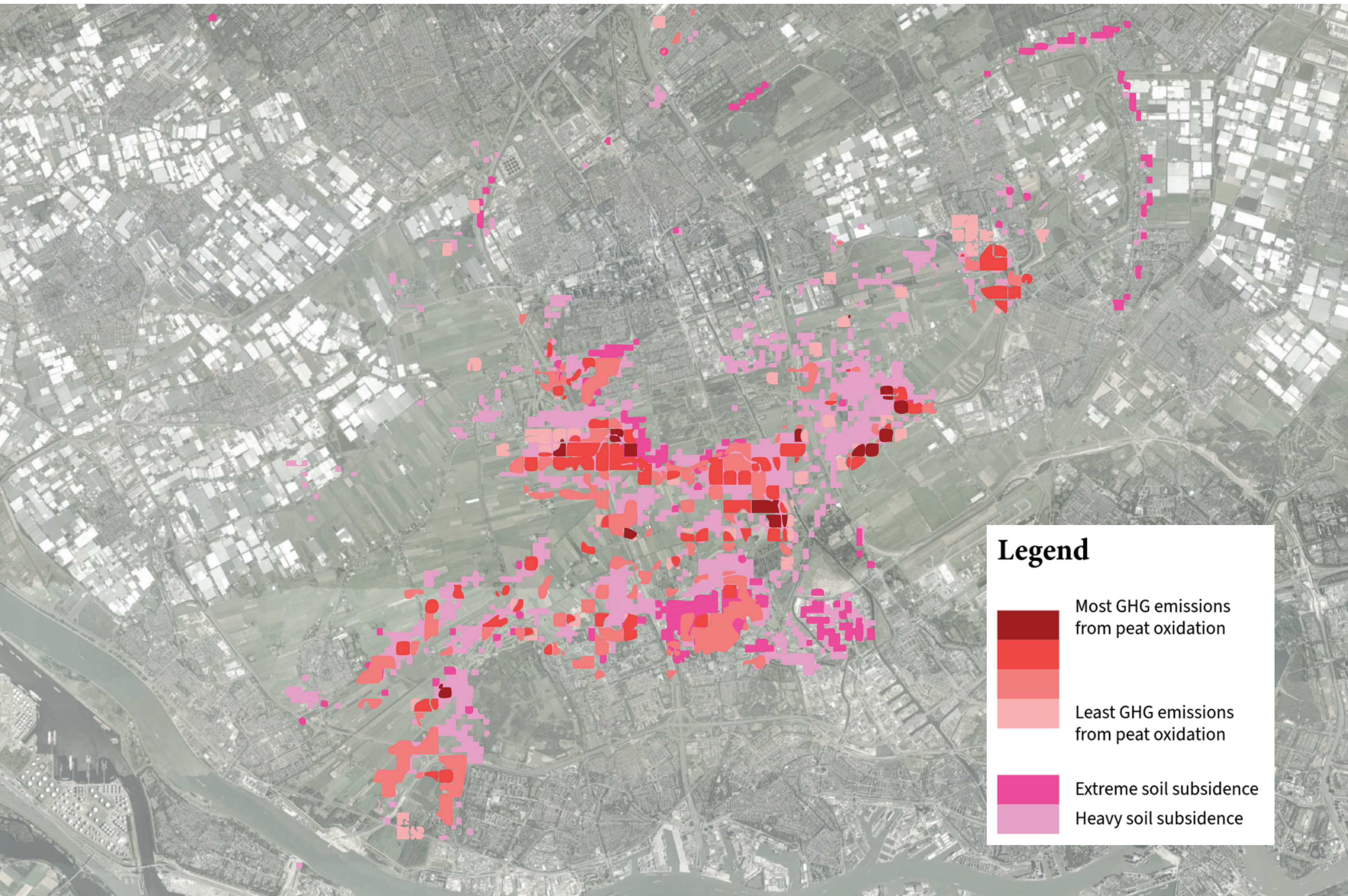
The necessity map, derived from the necessity analysis in Chapter 9, serves as the starting point for identifying which areas are eligible for groundwater level elevation. The necessity map is translated into the map in Figure 27 to find identify quickly the areas where most GHG emissions from peatland can be reduced.

The ecological and recreational systems were mapped, visualized in Figure 30 and 31, and the lowest areas in the region were identified using AHN elevation data (AHN, 2023), visible in Figure 32. The feasibility maps produced in Chapter 9 were then used for the feasibility check and determined which locations need to transition and in what way, according to the method in the decision tree mentioned above.

From the desirability analysis, the results were analysed per criterion for the desirability analysis to be useful for spatial planning at a parcel level, mainly focusing on which areas would benefit most from groundwater elevation and which would benefit least. The western part of the region appeared to benefit the most, leading to the recommendation to raise groundwater levels across nearly all peatland areas in the west, resulting in a transition to alternative crops. In the eastern part of the area, more distinctions were made, and not all peatland areas were considered to be suitable for groundwater level elevation, also partly to serve other goals, with freshwater scarcity being a significant driver.

This all led to the development of an initial spatial vision, after which all proposed crop types were aligned with the existing agricultural plots to enable practical implementation for farmers. The proposed crops were then scaled to a size that would be economically viable for each crop.

Figure 27 Necessity map. Created by the author.



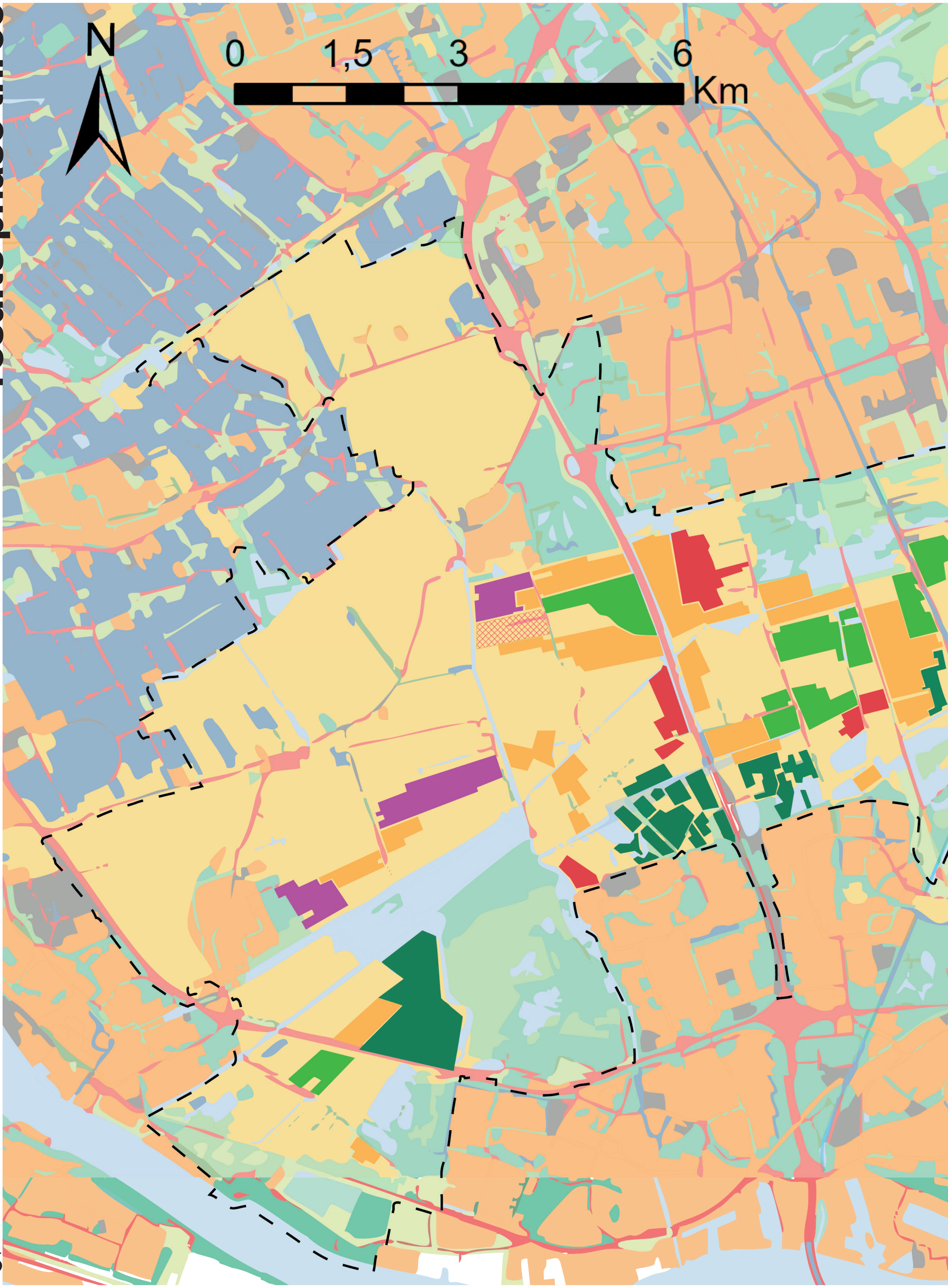
10.5.2 The proposed vision plan for 2050

In Figure 28, the vision is conceptually visualised how the current landscape can be transformed into a more climate-resilient one. It involves not just viewing it as an agricultural landscape, but also incorporating other factors to make it multifunctional and, consequently, more resilient to climate change.

In Figure 29 this vision is translated into the proposed spatial transition plan.

Figure 28 Visual representation of transition for Midden-Delfland. Created by the author.

results phase three


N
0
1,5
3
6
Km

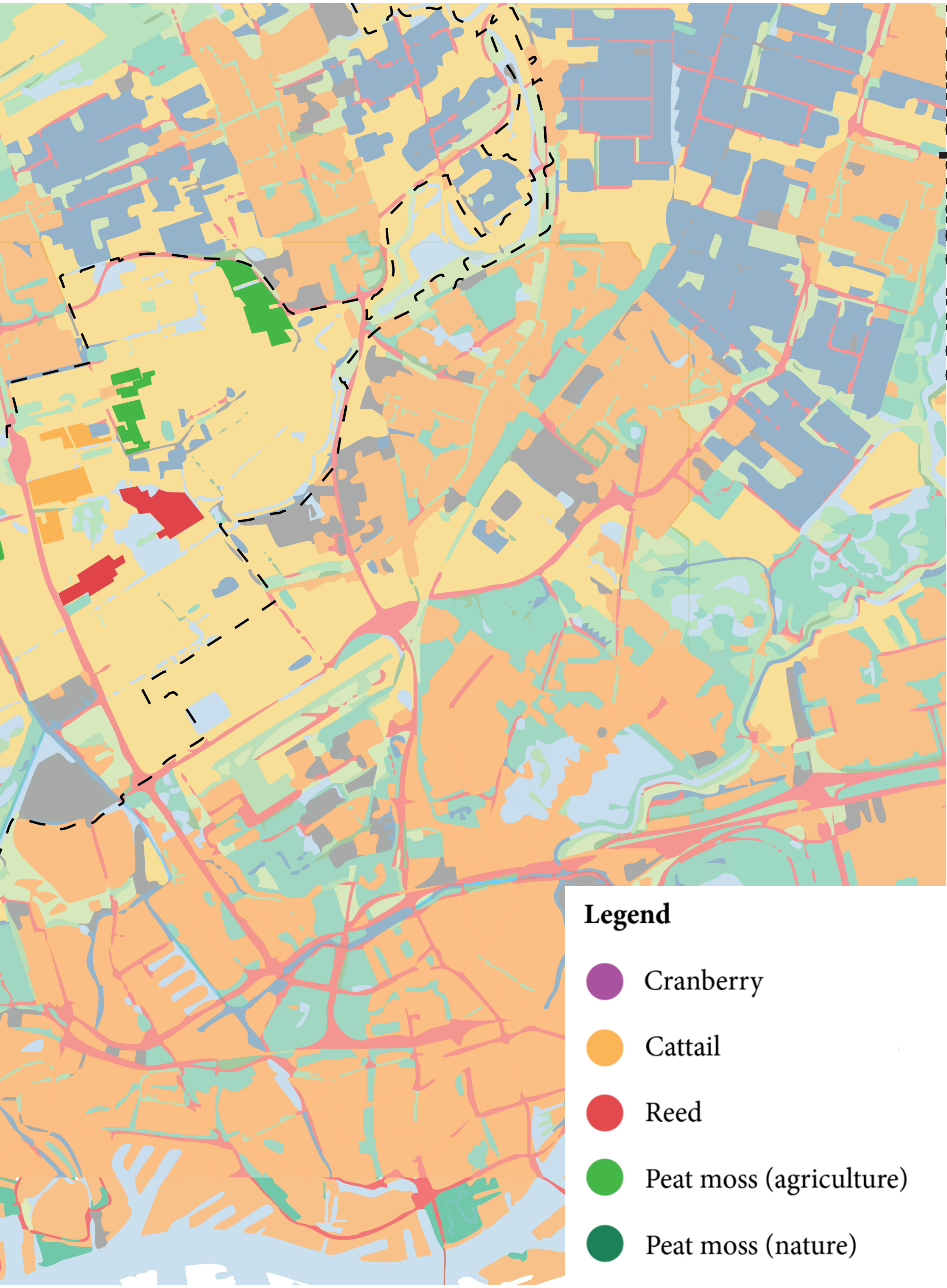


Figure 29 Proposed spatial crop transition plan Midden-Delfland. Created by the author.

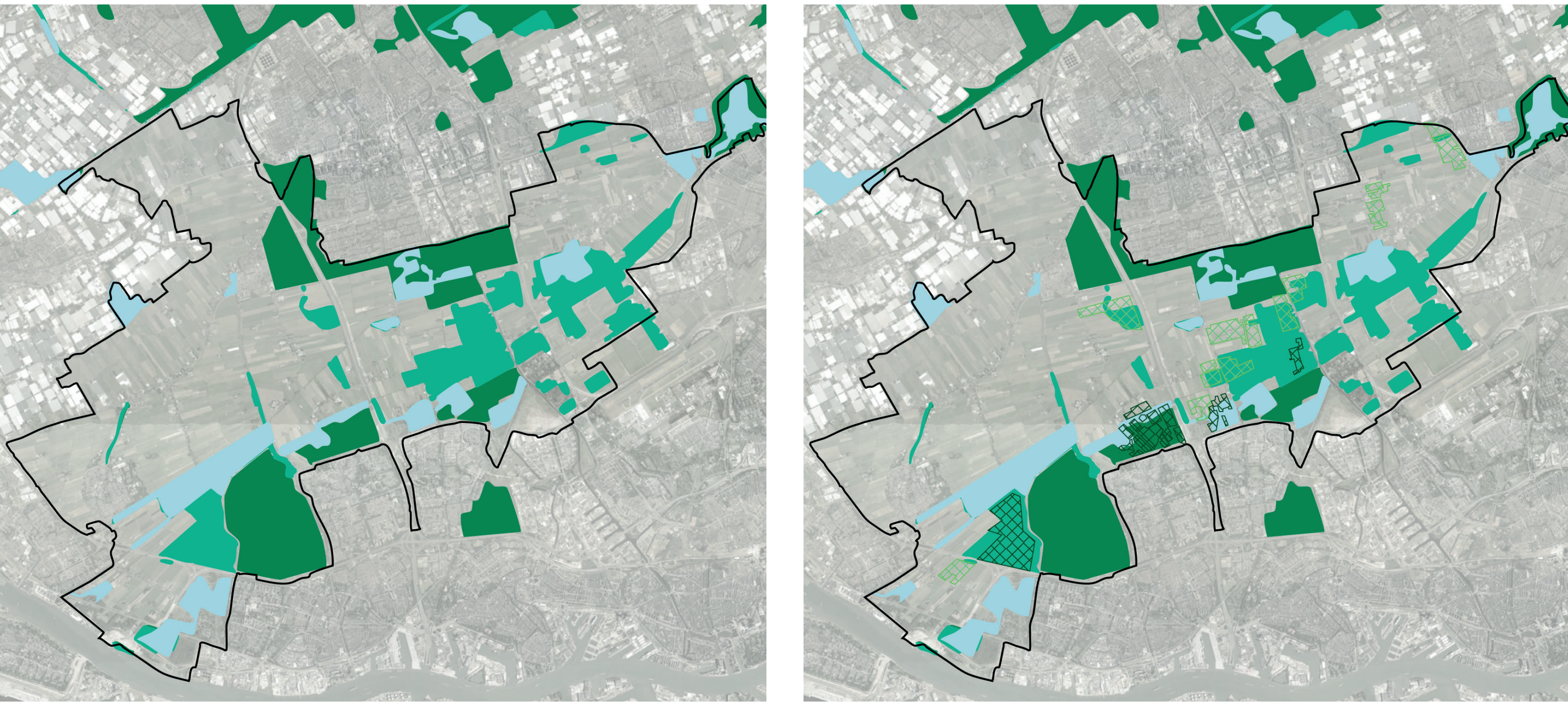


Figure 30 Connection to ecological network. Own work.

Legend

Nature Network Netherlands (NNN)

Important biodiversity zones

Wet ecological zones

Possibilities for strengthening eco network

Crops

Peat moss (agriculture)

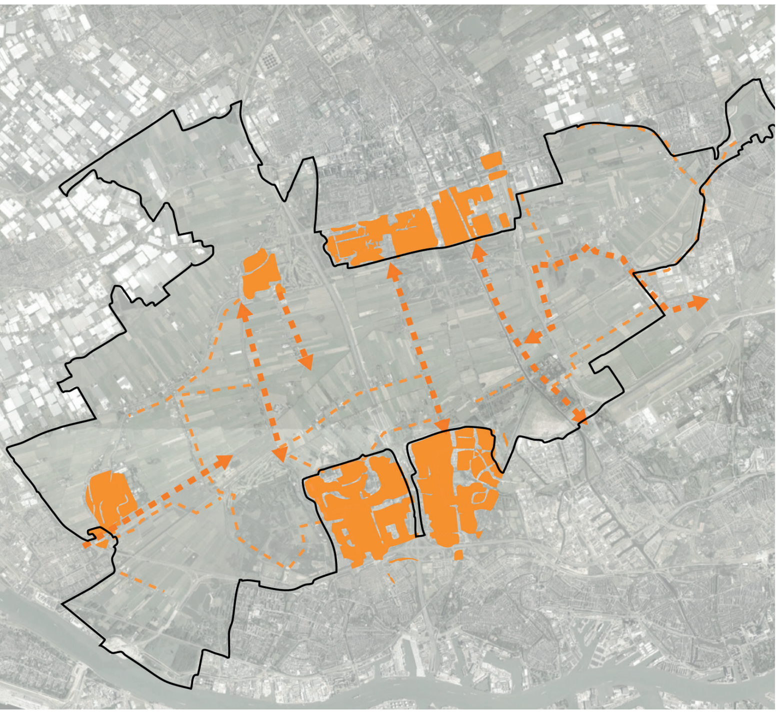
Peat moss (nature)

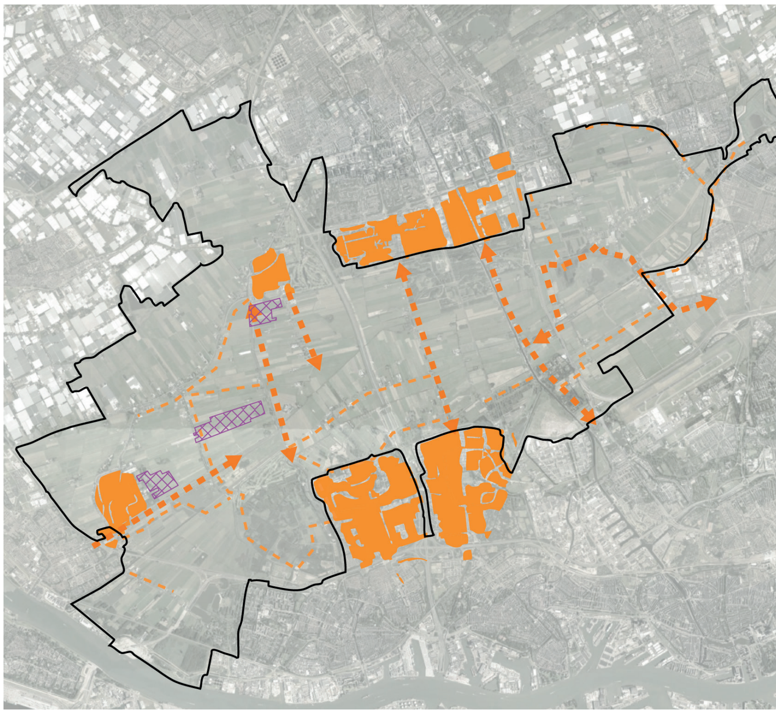
Embeddedness of the vision in the networks of the region

With the ability of peat moss to strengthen biodiversity and enhance both the existing ecological network, peat moss is placed nearby these areas. Figure 30 illustrates how the final placement of this crop can support current green structures and their ecological functions. Peat moss is divided into two types: peat moss cultivated for agricultural purposes and natural peat moss, which could combine with recreational functions, such as walking paths.

Crops with recreational potential and the ability to enhance the existing recreational network, as identified in the previous analysis, are connected to current recreational areas, as shown in Figure 31, to maximize their recreational value.

In Figure 32, the areas located more than 3 metres below sea level (NAP) are highlighted. These represent the lowest parts of the region and are therefore most suitable for water retention purposes. In the figure on the right, the crops from the proposed transition plan are shown to indicate which areas will be used for additional water buffering could be implemented.





Legend

Villages in/surrounding study area

Main bicycle routes

Main walking routes

Crops

Cranberry

Peat moss (nature)

Figure 31 Connection to recreational network. Own work.

Legend

Areas below -3m NAP

Crops

Cranberry

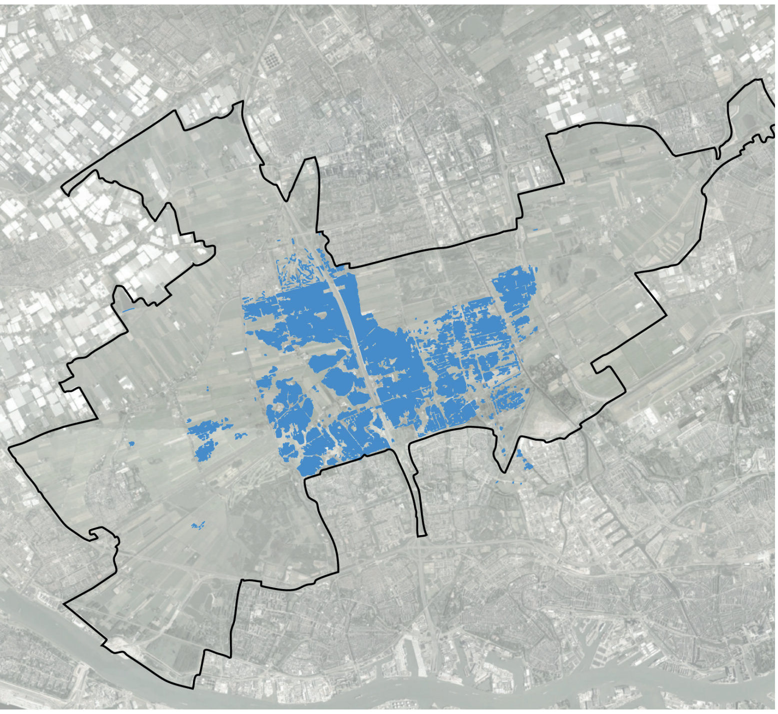
Cattail

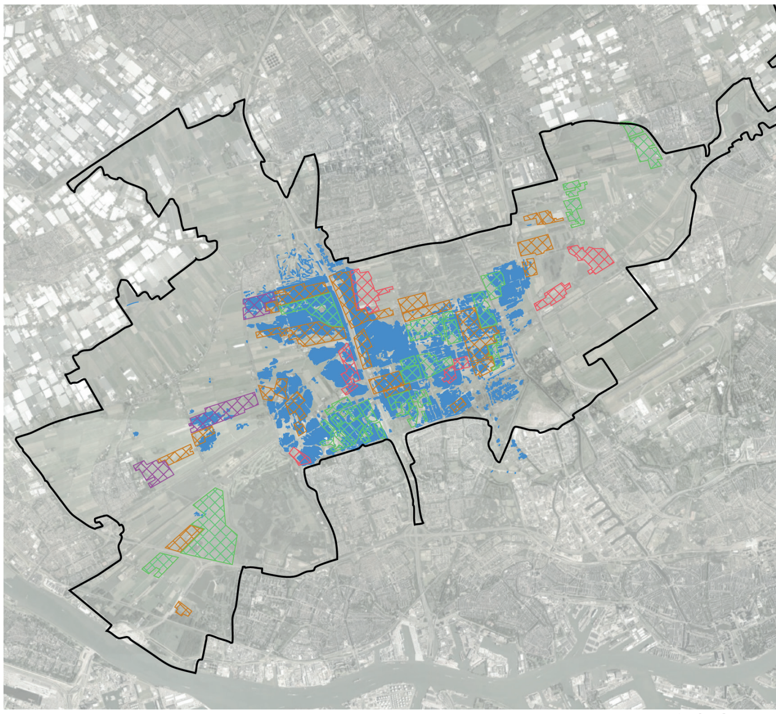
Reed

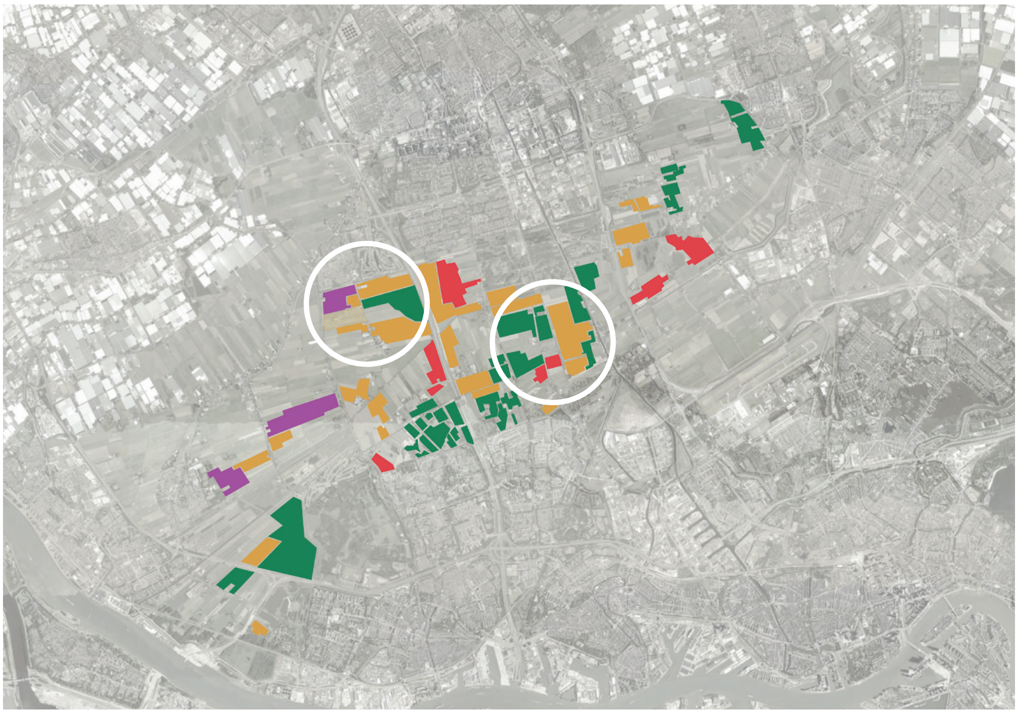
Peat moss (agriculture)

Peat moss (nature)

Figure 32 Crop possibilities for water retention areas. Connection to ecological network. Own work.







The zoom-ins explain the characteristics of each crop in the immediate surroundings. They show how the crops work in practise and what they require. Additionally, the zoom-ins explain how the theory of change is incorporated into the spatial plan.

Cranberry
Food and Drink

Harvesting with help of volunteers or small machinery

Cooling Space to store the yield temporarily

Food and Drink Production small scale Processing Areas on Site

Farm Shop for income and visitor purpose

Transport to Factories and larger producers

Reed
Roofing Material

shipment by truck To Craftsman for usage

Storage and Drying Warehouse

Shared Machine storage with cattail)

Cattail
Insulation Material

transport to Regional Factory for regional house production

Shared Machine storage with reed)

Peat moss
potting soil substrate for horticulture

Temporary Storage and Drying Barn

Transport to Factory near Horticulture Center

Machine storage shared with multiple owners for cost efficiency and it is possible

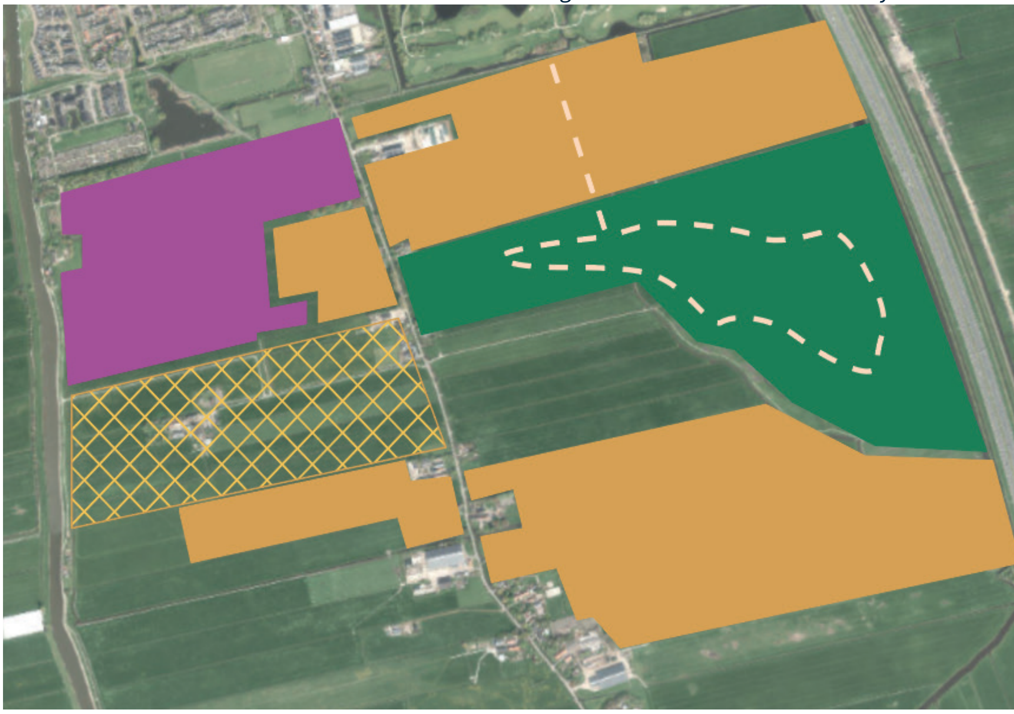
Legend

- Cranberry
- Cattail
- Reed
- Peat moss (agriculture)
- Peat moss (nature)

Education and communication

The walkway through the natural peat moss plot introduces visitors to new types of crops. Cranberry cultivation offers opportunities for community involvement, as it requires volunteer support during the harvest season. By adding recreational and educational value to the landscape, local residents are positively engaged, helping with acceptance of the transition.

Figure 33 Zoom in one. Created by the author.



Establishing pilot areas

The first step of the transition plan starts with setting up a pilot area to demonstrate the effectiveness of rewetting and increase willingness among local farmers to participate.

Education and communication

The processed cattail and reed are used as local, biobased building materials for new homes in the area. This shows local residents to see what these crops can be used for, helping to increase awareness and reduce resistance to land-use change

Figure 34 Zoom in two. Created by the author.

Figure 35 Impression of a peat moss landscape and its characteristics according to conceptual framework. Created by the author.

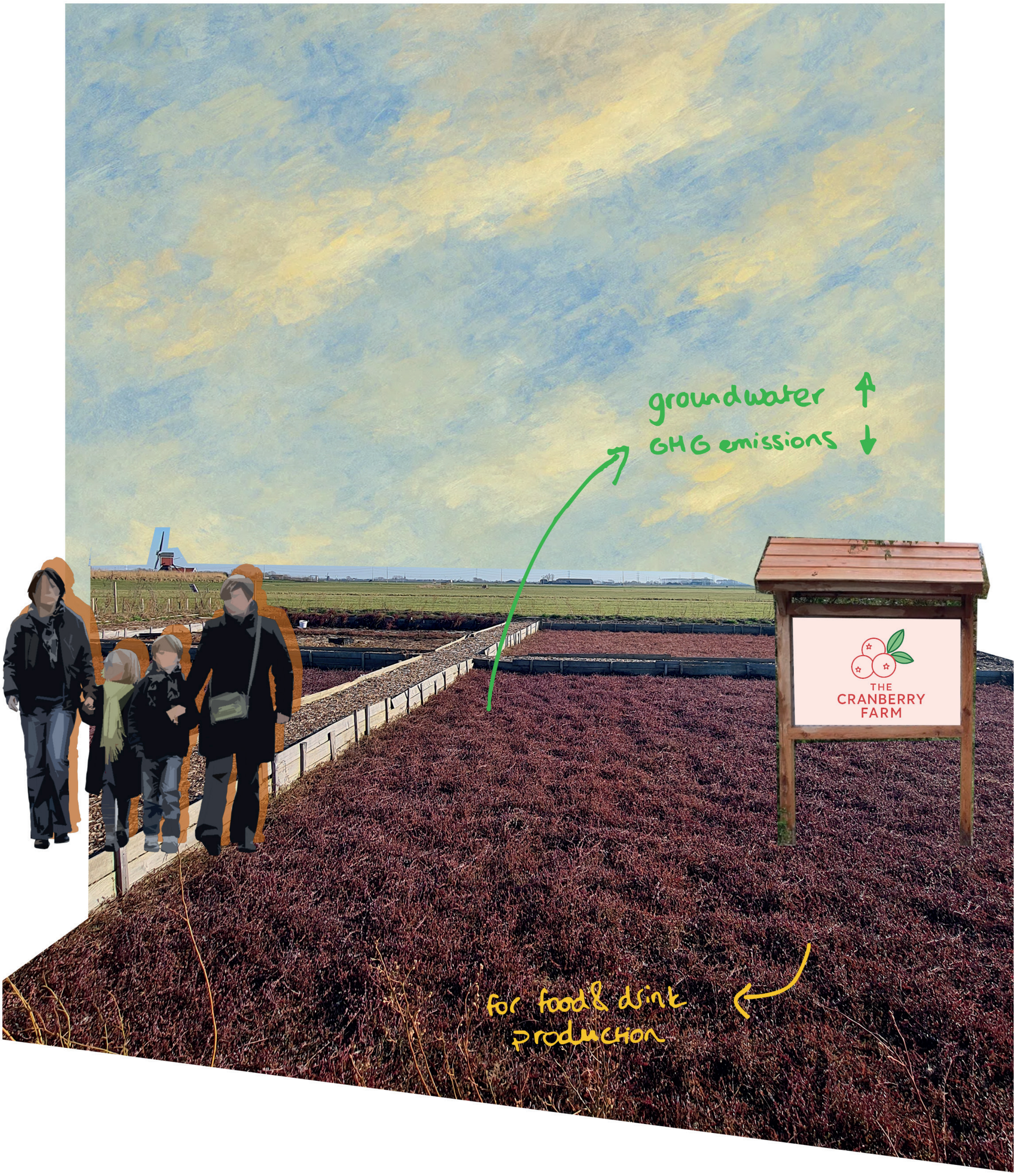
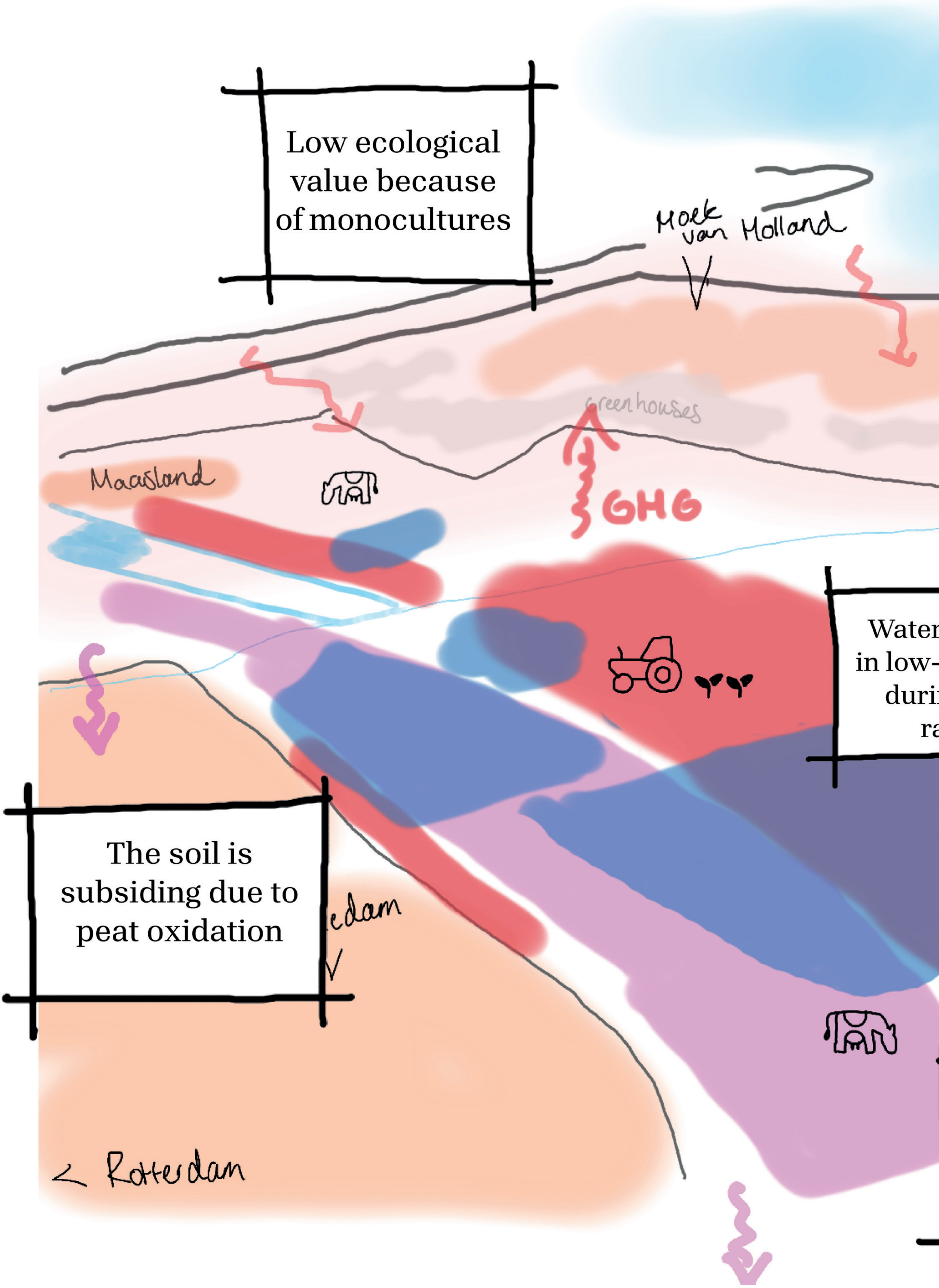


Figure 36 Impression of a cranberry landscape and its characteristics according to conceptual framework. Created by the author



Low ecological value because of monocultures
Hoek van Holland
greenhouses
Maasland
GHG
The soil is subsiding due to peat oxidation
Rotterdam

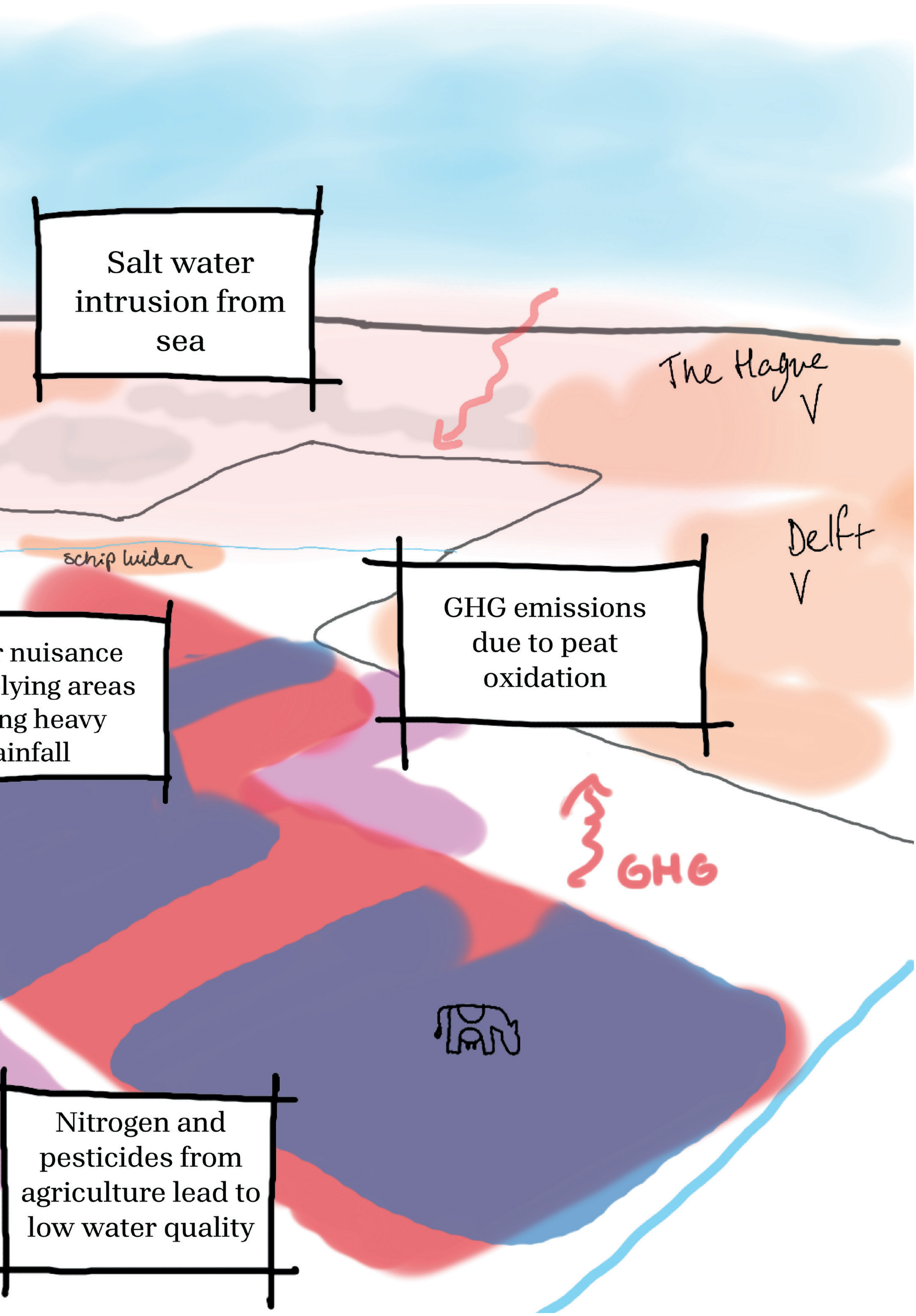
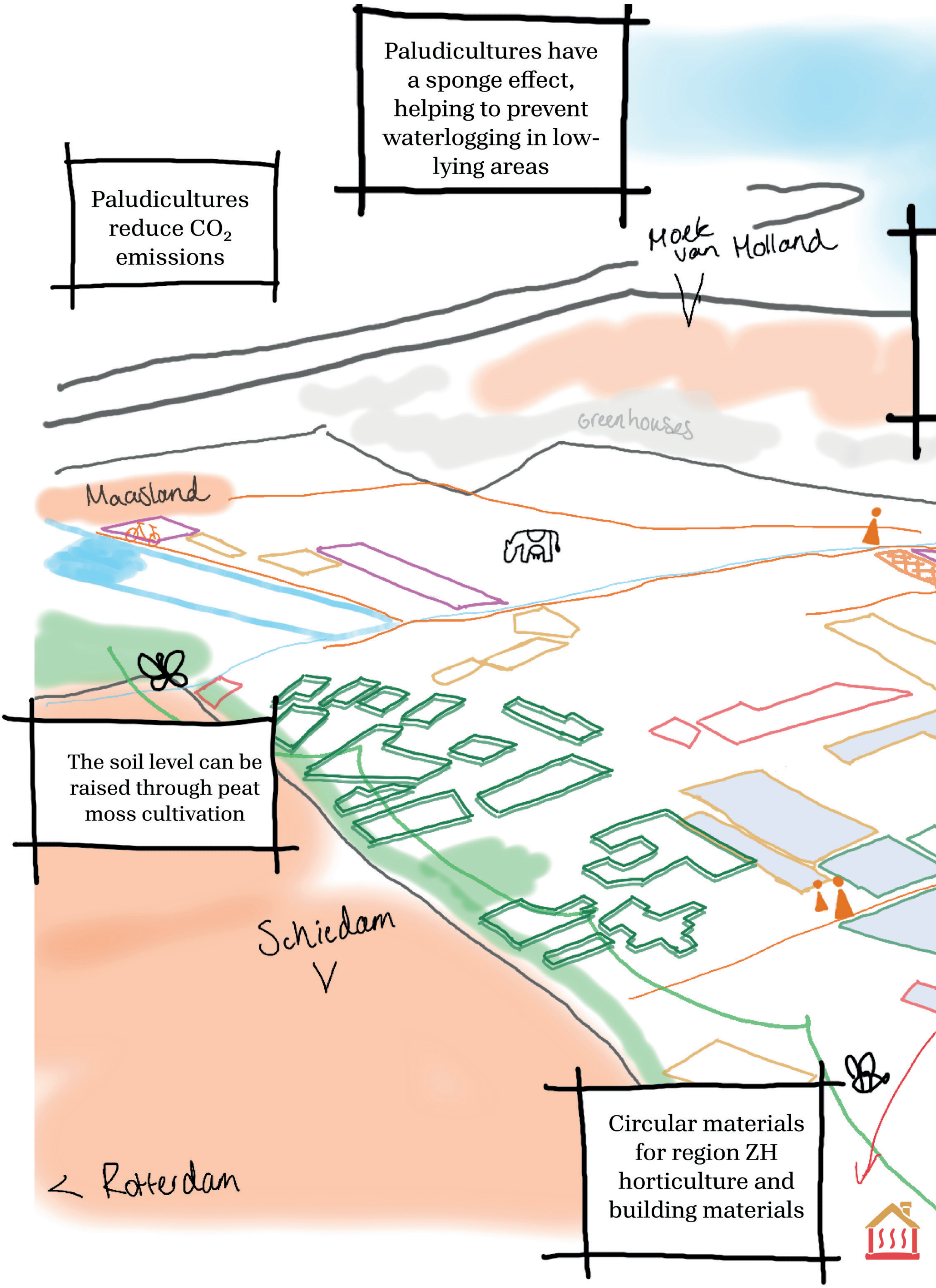


Figure 37 Problem identification Midden-Delfland. Created by the author.


Paludicultures reduce CO_2 emissions
Paludicultures have a sponge effect, helping to prevent waterlogging in low-lying areas
Hoek van Holland
greenhouses
Maasland
The soil level can be raised through peat moss cultivation
Schiedam
< Rotterdam
Circular materials for region ZH horticulture and building materials

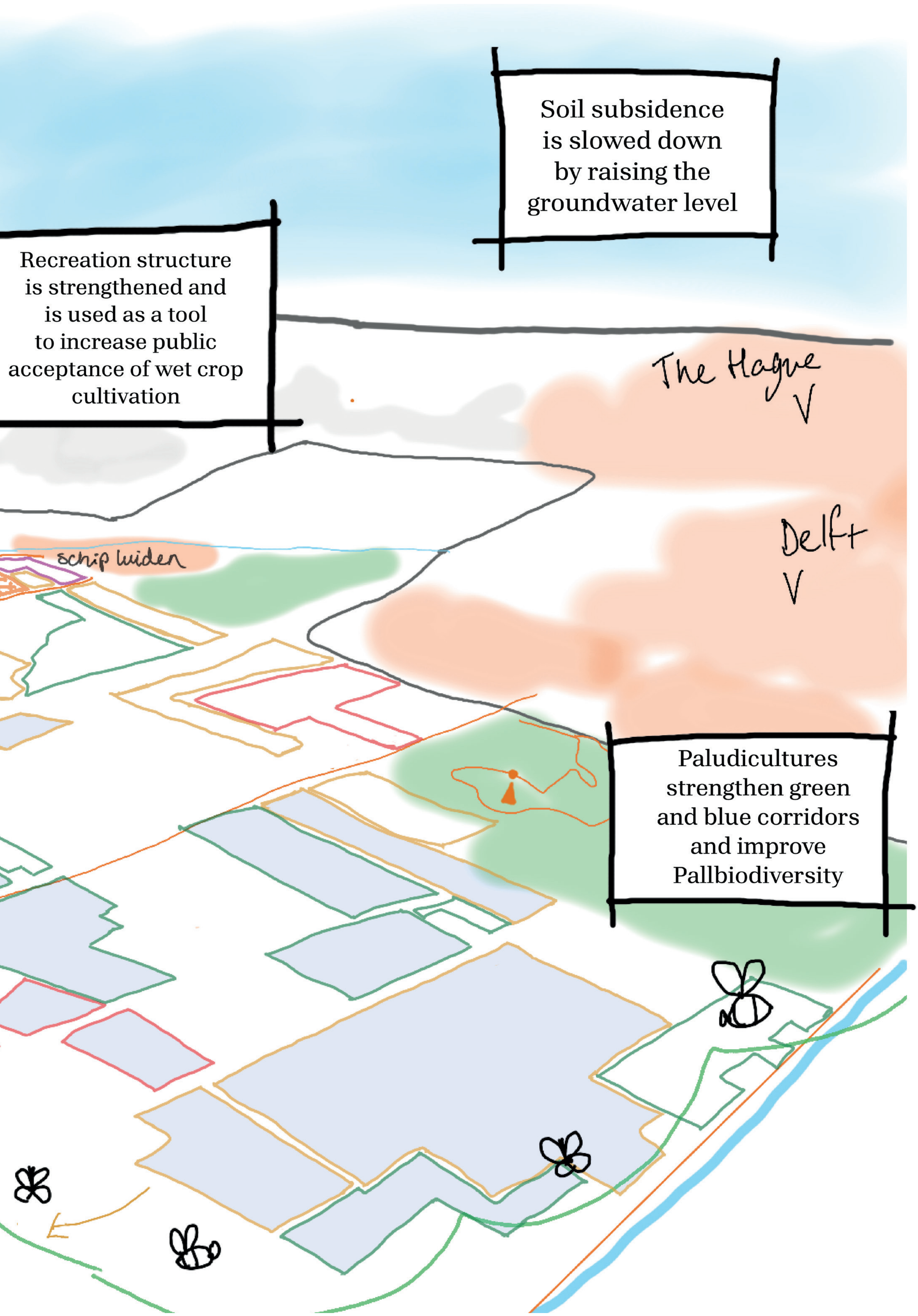


Figure 38 Spatial transition applied in Midden-Delfland. Created by the author.

10.6 Summary

Due to freshwater scarcity, raising groundwater levels cannot and should not be applied throughout the whole area of Midden-Delfland. In some areas, the negative consequences outweigh the benefits. Therefore, groundwater elevation should be targeted at the most necessary locations, where it can be used effectively for climate mitigation through water storage and buffering. These areas can be designed for multifunctional use, combining agriculture with recreation or nature when needed or can contribute positively.

The crops listed below are recommended because they support these objectives, but each also has its restrictions:

1. **Peat moss** is the most effective choice for CO_2 mitigation and offers strong biodiversity advantages. However, financial returns are limited.
2. **Reed** has a strong business case, produces relatively low methane emissions, and helps purify water.
3. **Cattail** is less efficient at reducing CO_2 but has significant potential as a sustainable building material like insulation.
4. **Cranberries** provide moderate climate benefits but offer high potential for recreational use. This supports the identity of Midden-Delfland as a leisure and tourism area.

These crops will enhance but also reshape the current landscape of Midden-Delfland. They can supply materials for local construction, support circular horticulture in South Holland, and boost local food systems. With these short supply chains, the community can see what is being grown and produced, fostering public support.

To begin this transition, the message is: just start. This is a long-term journey, and it will take time for people to adapt to new landscapes and unfamiliar crops. Support systems, such as ecosystem payment schemes, will also need time to be fully developed. Nonetheless, funding opportunities are already available for innovative farmers eager to pioneer these practices. As visible progress appears, like better water retention during dry seasons or increased biodiversity, momentum will most likely grow and accelerate the sustainability transition.

In conclusion, a future-proof Midden-Delfland requires strategic spatial zoning. Some areas can continue dairy farming, while others shift toward paludicultures. A mix of land uses, tailored to groundwater conditions, ecological potential, and landscape function, will create a climate-resilient region.

Discussion

11. Discussion

The current chapter presents several points that will be discussed regarding interpretation, relevance, theoretical implications, and limitations in relation to other literature and practice to reflect on the findings of this study and placing them in a broader perspective.

11.1 Interpretations of the findings

This research aimed to find the necessity, and spatially evaluate the feasibility and desirability of groundwater level elevation in Midden-Delfland. The results offer meaningful insights into how the peatland landscape can transition to be more climate-resilient.

The necessity analysis identified zones where peat oxidation and soil subsidence pose the highest risk, which pointed in particular at areas with deep, unprotected peat. These results present a solid basis for prioritizing groundwater level elevation and investment in specific locations to reduce greenhouse gas emissions and prevent soil subsidence.

The feasibility analysis shows that in many areas, raising groundwater levels to -40 cm is most likely technically achievable. Under the conservative assumptions, -20 cm is only possible in very few areas, but these areas do align with the ones where it is also necessary. This indicates that rewetting is practically possible in substantial parts of the region, where rewetting is also necessary.

The desirability analysis, combining environmental sustainability, infrastructure resilience, and agricultural viability through MCDA, showed the complexity of spatial decision-making. The eleven criteria used strongly reflect the guiding principles from literature and practice and were validated by the experts. The results showed that few areas perform highly on all three layers simultaneously, but that but notable overlaps do exist.

Overall, natural areas rank positively across all three layers, whereas most urban areas rank negatively on all three layers. Other regions show varied scores across different layers, indicating that implementing groundwater level elevation would most likely mean modification of current land use characteristics. This points to the need for area specific strategies, some areas may focus on wet cultivation and ecosystem services, while others maintain essential agricultural production or infrastructure stability.

Building on these findings, a spatial plan was developed that envisions Midden-Delfland as a multifunctional peatland landscape, where land use is changed based on the ecological conditions, following societal and economic values. Instead of focussing only on the existing dairy monoculture, the plan proposes a mosaic of functions: all different types of high groundwater level farming combined with nature, recreation or water storage. This spatial vision respects the cultural landscape of Midden-Delfland while adapting to future challenges. It shows that groundwater level elevation can be a catalyser for climate-adaptive landscape transformation.

It is important to note that expert interviews confirmed that planning decisions are shaped not only by spatial logic but also by institutional roles, political interests, and subjective values. The desirability map, should therefore not be seen as a strict plan, but as tools for negotiation and dialogue in participatory planning.

Finally, the study presents that spatial planning must embrace uncertainty and adaptability. Soil variation, climate extremes, and socio-political dynamics cannot always be predicted or mapped. Nevertheless, these findings provide directional guidance for action. A flexible and iterative approach is essential to address the uncertainties of agricultural peatland transition.

11.2 Implications for research and practice

The study provides both theoretical insights and practical tools. It contributes to academic debates by operationalizing the following frameworks in a real-world case: the Dutch Layers Approach, Ecosystem Services, and Theory of Change. It also proposes a decision tree for spatial planning that can guide future policy and design.

Practitioners can use the findings to understand under what conditions groundwater elevation may be necessary, feasible, and desirable. The research also highlights that no single solution will fit all. Spatial decisions in this region will ultimately depend on stakeholder engagement, as the same technical analysis may lead to different outcomes in different regions depending on local priorities and values.

The study further underscores the importance of grounding spatial design in the physical geography of an area, as also advocated in the Water and Soil Guiding Policy Brief. Only by designing in accordance with local geographical conditions can greenhouse gas emissions from peat soils be effectively and purposefully reduced.

Moreover, the study presents that transformative visions must remain adaptive and iterative. Transition is not a fixed end state, but a pathway that continues to change. While technical solutions can support change, they should not create path dependencies that reduce flexibility. Therefore, planning should embrace experimentation, pilots, and space for failure. Only then a flexible way for future developments is guaranteed.

11.3 Theoretical contributions

The theoretical framework used in this research, consisting of the Dutch Layers Approach, Ecosystem Services, and Theory of Change, shaped both the methodology and the interpretation of the results.

The Dutch Layers Approach (van Schaick & Klaasen, 2011) played a central role throughout the analysis and design phases. Traditionally, spatial planning in the Netherlands began from the top layer (occupation), but this research, and developments the past years, reversed that logic by prioritizing the subsoil and water systems. This bottom-up perspective proved valuable in framing groundwater as a determining factor in spatial transitions. Results, particularly Chapter 8, underscored the interdependence and connectedness of the three layers, validating the strength of this framework as a conceptual hierarchy. However, the approach also has its limitations. It can unintentionally overemphasize one layer when others are equally relevant, potentially limiting triangulation and integrated thinking. Moreover, while the framework was helpful in structuring the findings, successful spatial planning requires the ability to design across layers, not just within them.

The Ecosystem Services (ES) (Assis et al., 2023; Vagge et al., 2024)framework provided a functional perspective for evaluating trade-offs between environmental sustainability, infrastructure resilience, and agricultural viability. By providing a structured way to link ecological processes with societal needs, it helped integrate the different conceptual layers of the research and complemented the Dutch Layers Approach effectively. The research operationalized ES such as water purification, food production, and climate regulation. The spatial component of the study focused on how connectivity between ecological and agricultural zones could enhance this ES delivery. These findings confirmed literature insights, showing that spatial form can directly influence the performance of ES like biodiversity but also agricultural viability. The results also support the need for spatial planning to optimize both supply and demand of ES through connectivity and multifunctionality. The GIS-based MCDA proved valuable by providing a method to assess these trade-offs in a spatially explicit manner.

The Theory of Change (ToC) (Piras et al., 2022)framework helped clarify the sequential logic behind spatial transitions. It provided a useful overview of the steps needed in a transition, from identifying problems to envisioning long-term goals and building in monitoring and feedback loops. The interviews confirmed that many elements of ToC were already implicitly recommended or used in practice. That said, the framework was limited in capturing the temporal dynamics of transition, particularly which actions must precede others and how momentum is built over time. Additionally, the approach is limited by the perspective of the researcher. More valid results could be obtained when the analysis is done with multiple people from different backgrounds. The interviews confirmed that integrating ToC with scenario planning could definitely improve its applicability to real-world spatial change.

Reflecting on these frameworks, the specific combination was what made the study appropriate and effective. Each offered unique value: Dutch Layers for structural analysis, ES for functional justification and connecting the layers, and ToC for strategic design. Future research could benefit from a tight integration between the frameworks, particularly by explicitly linking the layers of landscape forms (Dutch Layers Approach) with its functions (ES) and processes (ToC).

11.4 Limitations of the study

The research faced limitations in time, scope, and data availability. The expert group mainly consisted of professionals from the water sector, which led to an overrepresentation of hydrological perspectives. No farmers were interviewed directly, however, their views were obtained through secondary sources, which were valid but possibly biased through the lens of water experts.

The GIS analysis only captures what can be made spatially explicit, several relevant social and ecological aspects, like water quality and opinions of residents, were not incorporated due to data limitations or lack of expert input.

The MCDA was constrained by the limited number of participants and variation in their understanding of the concepts and the weighting exercise. Additionally, the data used could have been more recent. Due to time constraints, mostly readily available or easily adaptable datasets were used. This resulted in some limitations, such as relying on the lowest average groundwater level dataset instead of more accurate, current groundwater levels. Another example is the use of peat thickness data from 2016, even though peat is an organic material and its thickness is likely to change within a few years and peat thickness also significantly affects GHG emissions, as mentioned in Chapter 4. These limitations emphasise the need for recent, high-resolution datasets in future studies to improve the accuracy and relevance of spatial strategies.

Furthermore, the outcome of the MCDA depends significantly on how the input layers were scored and combined. Although classifications were grounded in literature and partially verified by experts, additional expert feedback could have strengthened the reliability and justification of the classifications. In particular, not all criteria may have been equally balanced across the three domains (agricultural viability, environmental sustainability, and infrastructure resilience). For example, some scores within the agricultural viability category may have been overly optimistic relative to others, potentially reducing the comparability of layers.

There is also a degree of uncertainty associated with the AHP weighting process. Experts may have been either overly cautious or optimistic in their responses, leading to potential bias in the assigned weights. In some cases, participants may not have been fully aware of how weights across the three categories related proportionally to one another, which could have resulted in over- or underemphasis of specific themes.

Another limitation lies in the spatial resolution of several input datasets. Layers such as roads or localised water nuisance may have lost important detail when aggregated to the analysis scale. The water nuisance layer, for instance, may not be suitable for MCDA at this resolution due to the loss of spatial precision. More reliable results could have been achieved by including only those criteria that retained relevance at the applied resolution.

Finally, while the MCDA successfully highlights broader spatial patterns and supports strategic decision-making, it is not suitable for use at the parcel level. The varying reliability and scale compatibility of input layers require that results be interpreted cautiously and used primarily as a basis for further analysis and stakeholder discussion, rather than as definitive spatial recommendations.

Subjectivity is an inherent limitation in this study. As a researcher with a strong commitment to environmental sustainability, it is recognized that this perspective influenced the design criteria and prioritization. While this may be a source of bias, it also served as a strength by providing a clear normative direction.

11.5 Recommendations for future research

This study highlights several advices for further research, particularly in bridging the gap between strategic spatial design and policy implementation.

Further research is needed to obtain specific data on GHG emissions related to different land use options. In particular, detailed studies on the CO_2, CH_4, and N_2O emissions of each proposed crop are essential. Although some research has already been conducted, it is acknowledged that most of these crops require longer-term studies to fully understand how they respond to elevated groundwater tables their GHG emissions. Additionally, it would be valuable to assess the long-term environmental and economic costs of maintaining a low water table and allowing peat oxidation to continue. Quantifying these emissions and trade-offs could support more informed and balanced decision-making in spatial planning and land management.

Second, the development of effective and concrete policy recommendations in this field remains crucial, for the outcomes to be useful and integrated in real-world context. Current policies often lack clarity, coherence and are sometimes conflicting, and future research could focus on creating robust frameworks that help policy makers navigate the trade-offs between environmental goals and spatial realities. Such research should emphasize practical feasibility and provide tools that are actionable and adaptable.

An open question lies in how we deal with landscape and heritage value in the face of climate change. The cultural and historical importance of the peat meadow landscape is widely acknowledged, but research is needed to explore when and how policy should adapt if conserving heritage landscapes comes at the expense of climate goals.

Moreover, a broader spatial optimization approach of this research could consider caloric yield per crop type or land unit to rethink agricultural land use distribution across the Netherlands. Future studies might explore what minimum spatial functions must be maintained, and how spatial planning can ensure food security while meeting climate targets.

In addition, research should focus on collaborative transition strategies with all stakeholders, including farmers. While this study derived agricultural perspectives through secondary sources, direct engagement and co-design with farmers is necessary to ensure practical support and long-term success. Such engagement would deepen understanding of what support systems (financial, regulatory, technical) are most effective.

Stakeholder participation more broadly deserves attention. Future studies should explore multi-stakeholder governance models that bring together residents, farmers, water boards, municipalities, provinces, nature organizations, and policymakers. This inclusive process is essential to prevent fragmented or conflicting strategies. The tendency for policy to be drafted exclusively by professionals should be countered with participatory design to ensure it fits the context.

While not the scope of this thesis, spatial claims of the energy transition also need to be incorporated into future research agendas. Solar fields, wind turbines, and energy networks are increasingly shaping the rural landscape and compete with ecological and agricultural functions and it therefore deserves attention in the rural transition.

Finally, applied research into the implementation of groundwater elevation strategies is required. What practical steps must be taken to revise water management plans, and how can technical solutions be scaled? Though not all of this falls under academic research, the operationalisation of such plans is crucial to move from vision to practice.

In conclusion, while the study is limited in scope and depth due to practical constraints, it offers a valuable contribution by integrating theoretical insights with spatial and policy relevance. It invites further experimentation, dialogue, and iteration in designing a climate-adaptive Midden-Delfland and similar peat meadow landscapes.

12. Conclusion

This chapter concludes the thesis by answering the main research question, summarising the key findings of each sub-question, and formulating a final reflection on the research on groundwater elevation as a climate adaptation strategy in Midden-Delfland.

The research questions together provide a thorough understanding of how the transition toward groundwater elevation can be most effectively achieved and highlight how the agricultural transition can be seen as an opportunity for implementing groundwater elevation and, in doing so, help achieve broader climate adaptation goals.

12.1 Main research question

How can spatial planning in Midden-Delfland adapt to rising groundwater levels while balancing the trade-offs between agricultural viability, environmental sustainability, and infrastructure resilience in the face of climate change?

Based on quantitative and qualitative research, this research shows that a transition towards groundwater level elevation in Midden-Delfland is possible if specific spatial, environmental, and social conditions are met. When combined with systemic changes in land use, policy, and agricultural practices, groundwater elevation can support an environmentally, socially, and economically viable future for the region.

The following six recommendations establish the foundation for viewing the agricultural transition as an opportunity for groundwater elevation, and thus, climate adaptation.

1. **Focus on water retention**
   Prioritise water buffering strategies to raise groundwater levels and build resilience against increasing drought and freshwater scarcity.

2. **Multifunctional land use**
   Encourage a mosaic landscape where agriculture, nature, recreation, and water management are combined to improve efficient use of space.

3. **Transition requires both direction and support**
   Farmers cannot lead this transition alone. Ensure consistent policy frameworks, long-term visions, and participatory planning processes for governmental institutions.

4. **Reward ecosystem services fairly**
   Compensate farmers for both production and reward them for their contributions to biodiversity, CO_2 reduction, and water storage, to recognise their public value.

5. **Redefine the cultural landscape**
   Allow for new land uses, such as wet crops and nature-based recreation, that align with climate goals while respecting landscape identity.

6. **Dare to start**
   Don't wait for complete certainty. Initiate well-thought measures and learn by doing, climate adaptation requires timely action.

Agricultural viability can be preserved, but in new forms. This adaptation will require shifting toward crops and practices that are compatible with higher groundwater levels, such as different types of paludicultures, crops compatible with high groundwater levels. These transitions must be supported through fair compensation and clear, stable policies. Without public investment, especially regarding temporary income losses, farmers cannot be expected to lead this transition alone.

Infrastructure resilience will be safeguarded by implementing groundwater elevation where it poses no harm, or where the climate benefits, such as CO_2 reduction, clearly outweigh the risks. Additionally, the recreational values of the region should be protected and enhanced, contributing to Midden-Delfland's character as an open and accessible area.

Environmental sustainability is strengthened by reconnecting and restoring ecological zones with green-blue corridors, and limiting GHG emissions. Elevating groundwater in priority peat areas can significantly lower CO_2 emissions while creating space for biodiversity. A mosaic of land uses, nature, wet crops, recreational functions, can form the basis of a new, climate-adaptive landscape identity.

This research envisions a future in which Midden-Delfland grows from a monocultural dairy region to a multifunctional peatland landscape where nature-inclusive farming, water retention, education, and wet crop cultivation coexist. Crops such as reed, cattail, peat moss, and cranberries will enrich the landscape, but also change it. These crops can supply materials for local construction, circular horticulture in the South-Holland region, and support the regional food systems. This future respects the cultural heritage of the landscape but also adapts it to the climate challenges ahead.

12.2 Findings from sub-questions

Sub-question 1: What are the main barriers and enabling conditions contributing to the successful implementation of groundwater elevation measures?

The main barrier to successful groundwater elevation is freshwater scarcity. Without adequate freshwater, raising groundwater levels is not feasible. Land uses that rely on groundwater drainage, such as conventional agriculture, also conflict with elevation goals. Policy contradictions also barricade progress. For instance, subsidies can support 'unsustainable' agricultural practices incompatible with elevated groundwater levels, and shifting political agendas create uncertainty for farmers considering sustainable measures. Moreover, provincial policies aimed at preserving cultural landscapes may unintentionally restrict land-use innovation such as agroforestry or wet crops.

On the other hand, enabling conditions include clear, consistent policy frameworks regarding the sustainability transition in the agriculture sector. Additionally, participatory planning processes help the proposed land-use transitions to be locally supported and manageable in practice. Equally important is fair compensation for potential yield losses and financial recognition for the ecosystem services farmers provide. Biodiverse or climate-friendly measures may take up productive land or require time before new crops reach full yield, so support is necessary to make the transition economically viable. Groundwater elevation can create a sustainable agricultural landscape with a climate-resilient water system. However, these barriers and conditions need to be considered.

Sub-question 2: Which spatial and environmental factors determine the suitability of groundwater elevation in peatland areas, given spatial tensions and opportunities?

Spatially, suitability is highest in low-lying zones with thick peat layers, creating high CO_2 emissions, and well-developed surface water infrastructure. Environmental factors include the potential for biodiversity restoration and carbon sequestration, but risks such as nutrient leaching and methane emissions associated with a high groundwater level must be weighed.

These factors can be divided into three levels. Factors determining the necessity, feasibility and desirability of groundwater elevation. Necessity depends on whether groundwater elevation is needed to prevent peat degradation. Feasibility is determined by current groundwater levels, peat distribution, and water infrastructure. Last, desirability depends on the local priorities and functions of the area. These combined factors help identify where groundwater elevation is both practical and beneficial.

Sub-question 3: In which areas of Midden-Delfland are higher groundwater levels contributing positively to environmental sustainability, infrastructure resilience, and agricultural viability, and where does it lead to negative impacts?

The spatial MCDA shows spatial variation in suitability. Positive contributions are seen in areas with high peat thickness, low elevation, and potential to strengthen biodiversity. Negative impacts arise near infrastructure and where groundwater elevation reduces crop yields. The analysis shows that a tailored approach at the scale of a parcel is needed when examining the different positive and negative impacts. Trade-offs can only be chosen per situation with each different spatial and environmental factors.

Sub-question 4: Which agricultural alternatives are suitable for areas where groundwater levels are elevated as a climate adaptation measure?

Several alternatives have been identified as viable under higher groundwater levels. This resulted in the following crops: reed, cattail, peat moss, and cranberries. These crops vary in economic value and ecological benefit, and each fits specific contexts depending on the need for water retention, ecological and recreational opportunities, and land use goals. A decision tree was developed to guide appropriate crop selection, balancing necessity, feasibility, and desirability.

Sub-question 5: What is the envisioned spatial transition needed to achieve a climate-resilient Midden-Delfland through groundwater level elevation?

The envisioned spatial transition for a climate-resilient Midden-Delfland is a shift from monocultural dairy farming toward a multifunctional peatland landscape. Only by combining functions can the area meet ecological, agricultural, and social needs. In this vision, land use balances the multiple objectives by integrating agricultural function with nature, water storage, and recreation. Such a landscape can maintain the cultural identity of the region, but adapts it to the realities of climate change.

12.3 Concluding thoughts

The research reveals significant tensions: between heritage preservation and environmental urgency, between short-term ecological results and long-term environmental stability, and between fragmented policy domains.

Yet, these same challenges present an opportunity. Since agriculture remains the dominant land use, with most of the region's peat lying beneath it, this is where the greatest impact can be made. The agricultural transition can be a significant opportunity for climate adaptation, but the government must demonstrate, financially and with clear policy, what climate adaptation and mitigation are worth to them.

When considering potential future scenarios, future visions should not be judged against the current state but against the likely future of the status quo. Current land use decisions often seem more appealing simply because the future consequences of inaction are invisible. By comparing interventions not to today's baseline but to the projected future of the status quo, the urgency and importance of change become more evident, and action is more likely to be taken sooner.

Progress begins by taking the first step. Many innovations and transitions are delayed because of the tendency to wait until every detail has been researched or unanimous support is reached before moving forward. But climate adaptation and mitigation do not have the luxury of time. Progress needs to start somewhere, and imperfect steps, taken with right intentions, are better than not starting at all.

If this research teaches anything, it is that landscapes tell stories. Midden-Delfland's story began when the Dutch started dewatering the peatland for agricultural use. Let the next chapter be about how the Netherlands responded to climate change. While the cultural form of the landscape can be respected, not every element needs to be preserved in its original state. A transition for a climate-resilient Midden-Delfland is both necessary and feasible, if we are willing to begin.

13. References

Aben, R. C. H., van de Craats, D., Boonman, J., Peeters, S. H., Vriend, B., Boonman, C. C. F., van der Velde, Y., Erkens, G., & van den Berg, M. (2024). CO_2 emissions of drained coastal peatlands in the Netherlands and potential emission reduction by water infiltration systems. *Biogeosciences*, *21*(18), 4099–4118. https://doi.org/10.5194/bg-21-4099-2024

Ahmad, S., Liu, H., Günther, A., Couwenberg, J., & Lennartz, B. (2020). Long-term rewetting of degraded peatlands restores hydrological buffer function. *Science of The Total Environment*, *749*, 141571. https://doi.org/10.1016/j.scitotenv.2020.141571

AHN. (2023). *AHN Viewer* [Pagina]. AHN; AHN. https://www.ahn.nl/ahn-viewer

Arcadis, Haskoning, & Sweco. (2024). *Impactstudie verhogen grondwaterstand veenweiden*.

Arets, E. J. M. M., Baren, S. A. van, Hendriks, C. M. J., Kramer, H., Lesschen, J. P., & Schelhaas, M. J. (2023). *Greenhouse gas reporting of the LULUCF sector in the Netherlands: Methodological background, update 2023*. https://doi.org/10.18174/588942

Assis, J. C., Hohlenwerger, C., Metzger, J. P., Rhodes, J. R., Duarte, G. T., da Silva, R. A., Boesing, A. L., Prist, P. R., & Ribeiro, M. C. (2023). Linking landscape structure and ecosystem service flow. *Ecosystem Services*, *62*, 101535. https://doi.org/10.1016/j.ecoser.2023.101535

Balode, L., & Blumberga, D. (2024). Comparison of the Economic and Environmental Sustainability for Different Peatland Strategies. *Land*, *13*(4), Article 4. https://doi.org/10.3390/land13040518

Basisregistratie Ondergrond. (2024). *Home* [Overzichtspagina]. Basisregistratie Ondergrond. https://basisregistratieondergrond.nl/

Becker, B., Reichel, F., Bachmann, D., & Schinke, R. (2022). High groundwater levels: Processes, consequences, and management. *WIREs Water*, *9*(5), e1605. https://doi.org/10.1002/wat2.1605

Blondeau, E., Velthof, G. L., Heinen, M., Hendriks, R. F. A., Stam, A., van den Akker, J. J. H., Weghorst, M., & van Groenigen, J. W. (2024). Groundwater level effects on greenhouse gas emissions from undisturbed peat cores. *Geoderma*, *450*, 117043. https://doi.org/10.1016/j.geoderma.2024.117043

Born, G. J. van den, Kragt, F., Henkens, D., Rijken, B., Bemmel, B. van, Sluis, S. van der, Polman, N., Bos, E. J., Kuhlman, T., Kwakernaak, C., Akker, J. van den, Diogo, V., Koomen, E., Lange, G. de, Bakel, J. van, & Brinke, W. B. M. ten. (2016). *Dalende bodems, stijgende kosten: Mogelijke maatregelen tegen veenbodemdaling in het landelijk en stedelijk gebied: beleidsstudie*. https://research.wur.nl/en/publications/dalende-bodems-stijgende-kosten-mogelijke-maatregelen-tegen-veenb

BPL Midden-Delfland. (n.d.). *Bijzonder Provinciaal Landschap Midden-Delfland*. Retrieved 21 May 2025, from https://www.bplmiddendelfland.nl/

Bryman, A. (2016). *Social Research Methods*. Oxford University Press.

Carter, J. G. (2007). Spatial planning, water and the Water Framework Directive: Insights from theory and practice. *The Geographical Journal*, *173*(4), 330–342. https://doi.org/10.1111/j.1475-4959.2007.00257.x

Centraal Bureau voor de Statistiek. (2021). *Hoe gebruiken we ons water?* [Webpagina]. Centraal Bureau voor de Statistiek. https://www.cbs.nl/nl-nl/dossier/dossier-milieu-en-economie/hoe-gebruiken-we-ons-water-

Centraal Bureau voor de Statistiek. (2024). *Inwoners per gemeente* [Webpagina]. Centraal Bureau voor de Statistiek. https://www.cbs.nl/nl-nl/visualisaties/dashboard-bevolking/regionaal/inwoners

Cherney, A., Povey, J., Head, B., Boreham, P., & Ferguson, M. (2012). What influences the utilisation of educational research by policy-makers and practitioners?: The perspectives of academic educational researchers. *International Journal of Educational Research*, *56*, 23–34. https://doi.org/10.1016/j.ijer.2012.08.001

CLO. (2020, July 30). *Europese Kaderrichtlijn Water | Compendium voor de Leefomgeving*. https://www.clo.nl/indicatoren/nl141205-europese-kaderrichtlijn-water

Connell, J., & Kubisch, A. C. (1998). *Applying a Theory of Change Approach to the Evaluation of Comprehensive Community Initiatives: Progress, Prospects, and Problems*. https://www.semanticscholar.org/paper/Applying-a-Theory-of-Change-Approach-to-the-of-and-Kubisch/b5ae8eceb15ffaf10e2268af2a045c62b4e13f51

Daun, C., Huth, V., Gaudig, G., Günther, A., Krebs, M., & Jurasinski, G. (2023). Full-cycle greenhouse gas balance of a *Sphagnum* paludiculture site on former bog grassland in Germany. *Science of The Total Environment*, *877*, 162943. https://doi.org/10.1016/j.scitotenv.2023.162943 de Jong, M., van Hal, O., Pijlman, J., van Eekeren, N., & Junginger, M. (2021). Paludiculture as paludifuture on Dutch peatlands: An environmental and economic analysis of *Typha* cultivation and insulation production. *Science of The Total Environment*, *792*, 148161. https://doi.org/10.1016/j.scitotenv.2021.148161

Deltares, & TNO. (2021). *Bodemdalingsvoorspellings-kaarten*. ArcGIS StoryMaps. https://storymaps.arcgis.com/stories/89c12cdd9f54453ead3b9d85e71f8bdc

Deltares, & WENR. (2019). *Nationaal Water Model* [Webpagina]. Informatiepunt Leefomgeving; Rijkswaterstaat. https://iplo.nl/thema/water/applicaties-modellen/watermanagementmodellen/nationaal-water-model/

Deutsch, L., Belcher, B., Claus, R., & Hoffmann, S. (2021). Leading inter- and transdisciplinary research: Lessons from applying theories of change to a strategic research program. *Environmental Science & Policy*, *120*, 29–41. https://doi.org/10.1016/j.envsci.2021.02.009

Duin, F. van. (2025, March 19). *Polderlab Veldbezoek* [Interview]. https://polderlab.org/wetenschappers

Erkens, G., & Kooi, H. (2018). *Verkenning bodemdaling in Midden-Delfland*.

Eulenstein, F., Saparov, A., Lukin, S., Sheudshen, A. K., Mayer, W. H., Dannowski, R., Tauschke, M., Rukhovich, O. V., Lana, M., Schindler, R., Pachikin, K., Drechsler, H., & Cremer, N. (2016). Assessing and Controlling Land Use Impacts on Groundwater Quality. In L. Mueller, A. K. Sheudshen, & F. Eulenstein (Eds.), *Novel Methods for Monitoring and Managing Land and Water Resources in Siberia* (pp. 635–665). Springer International Publishing. https://doi.org/10.1007/978-3-319-24409-9_29

European Commission. (n.d.). *Water Framework Directive*. Retrieved 12 April 2023, from https://environment.ec.europa.eu/topics/water/water-framework-directive_en

European Union. (1992). *Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora*. https://eur-lex.europa.eu/legal-content/EN/LSU/?uri=oj:JOL_1992_206_R_0007_006

European Union. (2009). *Directive 2009/147/EC on the conservation of wild birds*. https://eur-lex.europa.eu/legal-content/EN/LSU/?uri=oj:JOL_2010_020_R_0007_01

Evans, C. D., Peacock, M., Baird, A. J., Artz, R. R. E., Burden, A., Callaghan, N., Chapman, P. J., Cooper, H. M., Coyle, M., Craig, E., Cumming, A., Dixon, S., Gauci, V., Grayson, R. P., Helfter, C., Heppell, C. M., Holden, J., Jones, D. L., Kaduk, J., … Morrison, R. (2021). Overriding water table control on managed peatland greenhouse gas emissions. *Nature*, *593*(7860), 548–552. https://doi.org/10.1038/s41586-021-03523-1

Gemeente Midden-Delfland. (2024). *Magazine Duurzaam Boer Blijven* [Pagina]. Gemeente Midden-Delfland; Gemeente Midden-Delfland. https://www.middendelfland.nl/magazine-duurzaam-boer-blijven

Goodland, R. (1995). The Concept of Environmental Sustainability. *Annual Review of Ecology and Systematics*, *26*, 1–24.

Greene, R., Devillers, R., Luther, J. E., & Eddy, B. G. (2011). GIS-Based Multiple-Criteria Decision Analysis. *Geography Compass*, *5*(6), 412–432. https://doi.org/10.1111/j.1749-8198.2011.00431.x

Hendriks, D., Passier, H., Marsman, A., Levelt, O., Lamers, N., Valstar, J., Hoogvliet, M., Louw, P. de, Rozemeijer, J., Ven, F. van de, Linge, J. M. van, & Hu, X. (2023). *Integrale Grondwaterstudie Nederland: Module 1: landelijke analyse*. https://research.wur.nl/en/publications/integrale-grondwaterstudie-nederland-module-1-landelijke-analyse

Hilasvuori, E., Akujärvi, A., Fritze, H., Karhu, K., Laiho, R., Mäkiranta, P., Oinonen, M., Palonen, V., Vanhala, P., & Liski, J. (2013). Temperature sensitivity of decomposition in a peat profile. *Soil Biology and Biochemistry*, *67*, 47–54. https://doi.org/10.1016/j.soilbio.2013.08.009

Hurlimann, A. C., & March, A. P. (2012). The role of spatial planning in adapting to climate change. *WIREs Climate Change*, *3*(5), 477–488. https://doi.org/10.1002/wcc.183

IAEA. (2025, February 12). *Groundwater: How Scientists Study its Pollution and Sustainability* [Text]. IAEA. https://www.iaea.org/newscenter/news/pollution-and-sustainability-of-groundwater

KNMI. (2025, January 30). *KNMI - De staat van ons klimaat 2024: Weer een recordwarm jaar*. https://www.knmi.nl/over-het-knmi/nieuws/de-staat-van-ons-klimaat-2024

Lavoie, R., Joerin, F., & Rodriguez, M. J. (2014). Incorporating groundwater issues into regional planning in the Province of Quebec. *Journal of Environmental Planning and Management*, *57*(4), 516–537. https://doi.org/10.1080/09640568.2012.751019

Liu, L., & Jensen, M. B. (2018). Green infrastructure for sustainable urban water management: Practices of five forerunner cities. *Cities*, *74*, 126–133. https://doi.org/10.1016/j.cities.2017.11.013

Liu, M., Wei, H., Dong, X., Wang, X.-C., Zhao, B., & Zhang, Y. (2022). Integrating Land Use, Ecosystem Service, and Human Well-Being: A Systematic Review. *Sustainability*, *14*(11), Article 11. https://doi.org/10.3390/su14116926

Loisel, J., & Gallego-Sala, A. (2022). Ecological resilience of restored peatlands to climate change. *Communications Earth & Environment*, *3*(1), 1–8. https://doi.org/10.1038/s43247-022-00547-x

LTO. (2023, June 28). *Dit zijn de standpunten van LTO Noord op het Zuid-Hollandse PPLG (ZH-PLG)*. https://www.ltonoord.nl/regios-en-provincies/regio-west/zuid-holland/actueel/dit-zijn-de-standpunten-van-lto-noord-op-het-zuid-hollandse-pplg

Ma, L., Zhu, G., Chen, B., Zhang, K., Niu, S., Wang, J., Ciais, P., & Zuo, H. (2022). A globally robust relationship between water table decline, subsidence rate, and carbon release from peatlands. *Communications Earth & Environment*, *3*(1), 1–14. https://doi.org/10.1038/s43247-022-00590-8

Marselis, S. M., Hannula, S. E., Trimbos, K. B., Berg, M. P., Bodelier, P. L. E., Declerck, S. A. J., Erisman, J. W., Kuramae, E. E., Nanu, A., Veen, G. F. (Ciska), van 't Zelfde, M., & Schrama, M. (2024). The use of living labs to advance agro-ecological theory in the transition towards sustainable land use: A tale of two polders. *Environmental Impact Assessment Review*, *108*, 107588. https://doi.org/10.1016/j.eiar.2024.107588

Mayne, J. (2017). Theory of Change Analysis: Building Robust Theories of Change. *Canadian Journal of Program Evaluation*, *32*(2), 155–173. https://doi.org/10.3138/cjpe.31122

Mays, L. W. (2013). Groundwater Resources Sustainability: Past, Present, and Future. *Water Resources Management*, *27*(13), 4409–4424. https://doi.org/10.1007/s11269-013-0436-7

Ministerie van Algemene Zaken. (2022, November 25). *Kabinet maakt water en bodem sturend bij ruimtelijke keuzes—Nieuwsbericht—Rijksoverheid.nl* [Nieuwsbericht]. Ministerie van Algemene Zaken. https://www.rijksoverheid.nl/actueel/nieuws/2022/11/25/kabinet-maakt-water-en-bodem-sturend-bij-ruimtelijke-keuzes

Ministerie van Economische Zaken en Klimaat. (2019a, August 6). *Het Akkoord—Klimaatakkoord* [Webpagina]. Ministerie van Economische Zaken en Klimaat. https://www.klimaatakkoord.nl/klimaatakkoord

Ministerie van Economische Zaken en Klimaat. (2019b, August 6). *Landbouw en landgebruik—Klimaatakkoord* [Webpagina]. Ministerie van Economische Zaken en Klimaat. https://www.klimaatakkoord.nl/landbouw-en-landgebruik

Ministerie van Infrastructuur en Waterstaat. (2019). *Water management in the Netherlands*.

Ministerie van Infrastructuur en Waterstaat. (2022). *Reactie LTO Nederland op laatste versie Water en Bodem Sturend versie 7 november 2022—Rapport—Rijksoverheid.nl* [Rapport]. Ministerie van Algemene Zaken. https://www.rijksoverheid.nl/documenten/rapporten/2023/05/03/bijlage-2-analyse-lto-water-en-bodem-sturend-versie-7-november-2022

Ministerie van Infrastructuur en Waterstaat. (2024, October 22). *Kamerbrief over de visie op water en bodem—Kamerstuk* [Kamerstuk]. Ministerie van Algemene Zaken. https://doi.org/10/22/brief-water-en-bodem-naar-aanleiding-van-het-tweeminutendebat-water-8-oktober-2024

Ministerie van Infrastructuur en Waterstaat. (2025a). *Verdeling water bij droogte* [Webpagina]. https://www.rijkswaterstaat.nl/water/waterbeheer/droogte-en-watertekort/verdeling-water-bij-droogte

Ministerie van Infrastructuur en Waterstaat. (2025b). *Wat is het nationaal Deltaprogramma? - Deltaprogramma* [Webpagina]. Ministerie van Infrastructuur en Waterstaat. https://www.deltaprogramma.nl/deltaprogramma

Ministerie van Landbouw Natuur en Voedselkwaliteit. (2020). *Niet alles kan overal—Rapport—Rijksoverheid.nl* [Rapport]. Ministerie van Algemene Zaken. https://www.rijksoverheid.nl/documenten/rapporten/2020/06/08/niet-alles-kan-overal

Ministerie van Landbouw Natuur en Voedselkwaliteit. (2024, October 15). *Antwoorden op Kamervragen over schrappen NPLG - Kamerstuk—Rijksoverheid.nl* [Kamerstuk]. Ministerie van Algemene Zaken. https://doi.org/10/15/beantwoording-kamervragen-over-schrappen-nplg

Ministry of the Interior and Kingdom Relations. (2024). *De economie van de toekomst begint bij de delta—Publicatie—College van Rijksadviseurs* [Publicatie]. Ministerie van Binnenlandse Zaken. https://www.collegevanrijksadviseurs.nl/adviezen-publicaties/publicatie/2024/06/28/economie-van-de-toekomst

Minkkinen, K., Ojanen, P., Koskinen, M., & Penttilä, T. (2020). Nitrous oxide emissions of undrained, forestry-drained, and rewetted boreal peatlands. *Forest Ecology and Management*, *478*, 118494. https://doi.org/10.1016/j.foreco.2020.118494

Oukes, C., Leendertse, W., & Arts, J. (2022). Enhancing the Use of Flood Resilient Spatial Planning in Dutch Water Management. A Study of Barriers and Opportunities in Practice. *Planning Theory & Practice*, *23*(2), 212–232. https://doi.org/10.1080/14649357.2022.2034921

Page, S. E., & Baird, A. J. (2016). Peatlands and Global Change: Response and Resilience. *Annual Review of Environment and Resources*, *41*(Volume 41, 2016), 35–57. https://doi.org/10.1146/annurev-environ-110615-085520

Paris Agreement. (2015). *Paris Agreement to the United Nations Framework Convention on Climate Change* (No. T.I.A.S. No. 16-1104). https://treaties.un.org/pages/viewdetails.aspx?src=treaty&mtdsg_no=xxvii-7-d&chapter=27&clang=_en

Paul, S., Ammann, C., Wang, Y., Alewell, C., & Leifeld, J. (2024). Can mineral soil coverage be a suitable option to mitigate greenhouse gas emissions from agriculturally managed peatlands? *Agriculture, Ecosystems & Environment*, *375*, 109197. https://doi.org/10.1016/j.agee.2024.109197

Piras, S., Tobiasz-Lis, P., Currie, M., Dmochowska-Dudek, K., Duckett, D., & Copus, A. (2022). Spatial justice on the horizon?

A combined Theory of Change scenario tool to assess place-based interventions. *European Planning Studies*, *30*(5), 952–973. https://doi.org/10.1080/09654313.2021.1928057

Pouliot, R., Hugron, S., & Rochefort, L. (2015). *Sphagnum* farming: A long-term study on producing peat moss biomass sustainably. *Ecological Engineering*, *74*, 135–147. https://doi.org/10.1016/j.ecoleng.2014.10.007

Provincie Zuid-Holland. (n.d.). *Deelgebied Midden-Delfland* [Overzichtspagina]. Provincie Zuid-Holland; Zuid-Holland. Retrieved 2 July 2025, from https://www.zuid-holland.nl/onderwerpen/natuur-landschap/zuid-hollands-programma-landelijk-gebied/zh-plg-kerngebied-veenweiden/deelgebied-midden-delfland/

Provincie Zuid-Holland. (2019). *Actieplan Boerenlandvogels 2019-2027* [Webpagina]. Zuid-Holland. https://www.zuid-holland.nl/onderwerpen/natuur-landschap/actieplan-boerenlandvogels/

Provincie Zuid-Holland. (2025). *Ingekomen stukken Programmering projecten Maatregelenpakket Zuid-Hollands Programma Landelijk Gebied Provincie Zuid-Holland (PZH)*. https://pzh.notubiz.nl/modules/1/Ingekomen%20stukken/1014670

Pryn, M. R., Cornet, Y., & Salling, K. B. (2015). Applying sustainability theory to transport infrastructure assessment using a multiplicative ahp decision support model. *Transport*, *30*(3), Article 3. https://doi.org/10.3846/16484142.2015.1081281

Purvina, D., Licite, I., Butlers, A., Lazdins, A., Saule, G., Turks, A., & Prysiazhniuk, L. (2023). Evaluation of peat layer thickness effect on soil GHG fluxes. *22nd International Scientific Conference 'Engineering for Rural Development': Proceedings: [Jelgava, Latvia], May 24-26, 2023*, 454–460.

Raad voor de leefomgeving en de infrastructuur. (2024, June). *Ruimtelijke ordening in een veranderend klimaat*. https://www.rli.nl/publicaties/2024/advies/ruimtelijke-ordening-in-een-veranderend-klimaat

Rozemeijer, J., Klein, J., Hendriks, D., Borren, W., Ouboter, M., & Rip, W. (2019). Groundwater-surface water relations in regulated lowland catchments; hydrological and hydrochemical effects of a major change in surface water level management. *Science of The Total Environment*, *660*, 1317–1326. https://doi.org/10.1016/j.scitotenv.2019.01.110

Ruppert, T., Dambruch, J., Krämer, M., Balke, T., Gavanelli, M., Bragaglia, S., Chesani, F., Milano, M., & Kohlhammer, J. (2015). Visual Decision Support for Policy Making: Advancing Policy Analysis with Visualization. In M. Janssen, M. A. Wimmer, & A. Deljoo (Eds.), *Policy Practice and Digital Science: Integrating Complex Systems, Social Simulation and Public Administration in Policy Research* (pp. 321–353). Springer International Publishing. https://doi.org/10.1007/978-3-319-12784-2_15

Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*.

Safeeq, M., & Fares, A. (2016). Groundwater and Surface Water Interactions in Relation to Natural and Anthropogenic Environmental Changes. In A. Fares (Ed.), *Emerging Issues in Groundwater Resources* (pp. 289–326). Springer International Publishing. https://doi.org/10.1007/978-3-319-32008-3_11

Santoni, S., Garel, E., Gillon, M., Marc, V., Miller, J., Babic, M., Simler, R., Travi, Y., Leblanc, M., & Huneau, F. (2021). Assessing the hydrogeological resilience of a groundwater-dependent Mediterranean peatland: Impact of global change and role of water management strategies. *Science of The Total Environment*, *768*, 144721. https://doi.org/10.1016/j.scitotenv.2020.144721

Srivastav, A. L., Dhyani, R., Ranjan, M., Madhav, S., & Sillanpää, M. (2021). Climate-resilient strategies for sustainable management of water resources and agriculture. *Environmental Science and Pollution Research*, *28*(31), 41576–41595. https://doi.org/10.1007/s11356-021-14332-4

Stead, D. (2014). Urban planning, water management and climate change strategies: Adaptation, mitigation and resilience narratives in the Netherlands. *International Journal of Sustainable Development & World Ecology*, *21*(1), 15–27. https://doi.org/10.1080/13504509.2013.824928

Stuyt, L. C. P. M., Blom-Zandstra, M., & Kselik, R. a. L. (2016). *Inventarisatie en analyse zouttolerantie van landbouwgewassen op basis van bestaande gegevens*. https://doi.org/10.18174/391931

Tiemeyer, B., Frings, J., Kahle, P., Köhne, S., & Lennartz, B. (2007). A comprehensive study of nutrient losses, soil properties and groundwater concentrations in a degraded peatland used as an intensive meadow – Implications for re-wetting. *Journal of Hydrology*, *345*(1), 80–101. https://doi.org/10.1016/j.jhydrol.2007.08.002

TNO, & Deltares. (2021). *Bodemdalingskaart 2.0*. https://bodemdalingskaart.portal.skygeo.com/portal/bodemdalingskaart/u2/viewers/basic/

Unie van Waterschappen. (2023, March 31). Visie op Grondwater. *Unie van Waterschappen*. https://unievanwaterschappen.nl/waterkwantiteit/grondwater/

Vagge, I., Chiaffarelli, G., Pirola, L., Gibelli, M. G., Sgalippa, N., Vagge, I., Chiaffarelli, G., Pirola, L., Gibelli, M. G., & Sgalippa, N. (2024). *Landscape Ecology and Ecosystem Services as Landscape Analysis and Assessment Tools for Ecological Landscape Planning*. IntechOpen. https://doi.org/10.5772/intechopen.1006355

Vamvakeridou-Lyroudia, L. S., Chen, A. S., Khoury, M., Gibson, M. J., Kostaridis, A., Stewart, D., Wood, M., Djordjevic, S., & Savic, D. A. (2020). Assessing and visualising hazard impacts to enhance the resilience of Critical Infrastructures to urban flooding. *Science of The Total Environment*, *707*, 136078. https://doi.org/10.1016/j.scitotenv.2019.136078

van der Hilst, F., Dornburg, V., Sanders, J. P. M., Elbersen, B., Graves, A., Turkenburg, W. C., Elbersen, H. W., van Dam, J. M. C., & Faaij, A. P. C. (2010). Potential, spatial distribution and economic performance of regional biomass chains: The North of the Netherlands as example. *Agricultural Systems*, *103*(7), 403–417. https://doi.org/10.1016/j.agsy.2010.03.010

van der Laan, A., van Dijk, J., Rebel, K. T., & Wassen, M. J. (2024). Rewet without regret? Nutrient dynamics in fen peat exposed to different rewetting degrees. *Biogeochemistry*, *167*(5), 705–721. https://doi.org/10.1007/s10533-024-01139-x

van Oort, P. A. J., Timmermans, B. G. H., Schils, R. L. M., & van Eekeren, N. (2023). Recent weather extremes and their impact on crop yields of the Netherlands. *European Journal of Agronomy*, *142*, 126662. https://doi.org/10.1016/j.eja.2022.126662

van Schaick, J., & Klaasen, I. (2011). The Dutch Layers Approach to Spatial Planning and Design: A Fruitful Planning Tool or a Temporary Phenomenon? *European Planning Studies*, *19*(10), 1775–1796. https://doi.org/10.1080/09654313.2011.614387

van Tilburg, A. J., & Hudson, P. F. (2022). Extreme weather events and farmer adaptation in Zeeland, the Netherlands: A European climate change case study from the Rhine delta. *Science of The Total Environment*, *844*, 157212. https://doi.org/10.1016/j.scitotenv.2022.157212

Wang, Y., Paul, S. M., Jocher, M., Espic, C., Alewell, C., Szidat, S., & Leifeld, J. (2021). Soil carbon loss from drained agricultural peatland after coverage with mineral soil. *Science of The Total Environment*, *800*, 149498. https://doi.org/10.1016/j.scitotenv.2021.149498

Wang, Z., Li, M., Shen, L., & Wang, J. (2022). Incorporating clay as a natural and enviro-friendly partial replacement for cement to reduce carbon emissions in peat stabilisation: An experimental investigation. *Construction and Building Materials*, *353*, 128901. https://doi.org/10.1016/j.conbuildmat.2022.128901

Wei, Y., Chen, Y., Cao, X., Xiang, M., Huang, Y., & Li, H. (2024). A Critical Review of Groundwater Table Fluctuation: Formation, Effects on Multifields, and Contaminant Behaviors in a Soil and Aquifer System. *Environmental Science & Technology*, *58*(5), 2185–2203. https://doi.org/10.1021/acs.est.3c08543

WENR. (2016). *Dikte Oxideerbaar Veen Open-dataportaal Zuid-Holland*. https://opendata.zuid-holland.nl/geonetwork/srv/dut/catalog.search#/metadata/42739CF5-9D7E-46E7-B032-62B94E7DD81E

Wetterskip Fryslân. (2024). *Breed gedragen compensatie-aanpak voor hogere peilen in veenweide* [Nieuwsbericht]. Wetterskip Fryslân. https://www.wetterskipfryslan.nl/news/breed-gedragen-compensatie-aanpak-voor-hogere-peilen-in-veenweide

Wichmann, S. (2017). Commercial viability of paludiculture: A comparison of harvesting reeds for biogas production, direct combustion, and thatching. *Ecological Engineering*, *103*, 497–505. https://doi.org/10.1016/j.ecoleng.2016.03.018

Wichmann, S., & Köbbing, J. F. (2015). Common reed for thatching—A first review of the European market. *Industrial Crops and Products*, *77*, 1063–1073. https://doi.org/10.1016/j.indcrop.2015.09.027

Zhang, M., Singh, H. V., Migliaccio, K. W., & Kisekka, I. (2017). Evaluating water table response to rainfall events in a shallow aquifer and canal system. *Hydrological Processes*, *31*(22), 3907–3919. https://doi.org/10.1002/hyp.11306

14. Appendices

Appendix 1: AHP Weighting and Results

The form for participating experts

The following form was send in Dutch to all participants.

Weighting of criteria for raising the groundwater level

You only have to enter a score in the red cells.

Do not give the scores until you can assess all criteria within a category. For each category, it is briefly explained what it entails and the individual criteria are explained. After reading, you can assign a score to the different criteria for each category.

Background information

To assess the spatial suitability of raising the groundwater level in Midden-Delfland, a set of criteria has been developed, divided into the categories: **ecology**, **climate-resilient infrastructure** and **agricultural management**. The goal is to identify locations where raising the groundwater level would have the most positive impact.

For each category, it is assessed which criterion **weighs most heavily compared to the other criteria within the same category**.

Agricultural business operations

General explanation:

The agricultural management dimension looks at the positive and negative effects of raising the groundwater level on agricultural activities. The aim is to identify areas where agriculture can benefit from, or be limited by, higher groundwater levels.

Criteria:

- **Crop-specific optimal groundwater level**
  Various crops have an ideal groundwater level; grassland tolerates higher water levels better than, for example, potatoes.
- **Tolerance of crops to inundation**

  Some crops can tolerate flooding better than others; Sensitivity to flooding determines the risks of raising the water level.
- **Water requirements of crops (drought tolerance)**
  Crops such as maize and alfalfa benefit from higher groundwater levels during dry periods because their irrigation needs decrease.
- **Meadow bird areas**

  In these areas, high groundwater levels are already being worked with during the breeding season; This offers opportunities for nature-inclusive agriculture and cooperation with water managers.

- **Salinized agricultural areas**

  In areas where salinization occurs, raising the groundwater can reduce the salt pressure and thus protect agricultural land and crops.

Giving scores for agricultural business category

Scales to give scores:

Value	Meaning
1	Both criteria are **equally important**
3	One criterion is **somewhat more important** than the other
5	One criterion is **clearly more important**
7	One criterion is **much more important**
9	One criterion is **extremely important**
2,4,6,8	An **intermediate value** between two choices mentioned above

If the **second** criterion is more important than the first, enter the **inverted** number.

*For example: if criterion B is clearly more important than A → enter **1/5** for "A vs B".*

Fill in the red cells below with a score

The question you have to ask yourself is: **which aspect contributes more to agricultural business operations with a higher groundwater level?**

Example

Compare "Crop-specific optimal groundwater level" with "Tolerance of crops to inundation": **which aspect contributes more to agricultural management with a higher groundwater level?** Rate the importance on a scale of 1 to 9, or use a fraction if the second aspect is more important.

Comparison of criteria	**Score (to be filled in by expert)**	**Any comments**
Crop-specific optimal groundwater level **vs** Tolerance of crops to inundation		
Crop-specific optimal groundwater level **vs** Water requirements of crops (drought tolerance)		
Crop-specific optimal groundwater level **vs** Meadow bird areas		
Crop-specific optimal groundwater level **vs** Salinized agricultural areas		
Tolerance of Crops to Inundation **vs** Water Requirement of Crops (Drought Tolerance)		
Tolerance of crops to inundation **vs** Meadow bird areas		
Tolerance of crops to inundation **vs** Salinized agricultural areas		
Water requirements of crops (drought tolerance) **vs** Meadow bird areas		
Water Requirements of Crops (Drought Tolerance) **vs** Salinized Agricultural Areas		
Meadow bird areas **vs** Salinized agricultural areas		

Climate-resilient infrastructure

General explanation:
The climate-resilient infrastructure category examines the sensitivity of buildings, underground networks and technical systems to higher groundwater levels. The aim is to identify areas where infrastructure could benefit from stabilisation or is at risk of damage.

Criteria:

- **Susceptibility to flooding**

  In areas where infiltration capacity is limited, a higher groundwater level can increase the risk of flooding.

- **Vulnerability of foundations**

  Older buildings (before 1970) with wooden piles are susceptible to damage at low groundwater levels; Higher positions can actually protect foundations.

- **Bearing capacity of the soil**

  On peat and clay, a higher groundwater level can limit further subsidence, but on sandy soils it can actually cause instability.

Giving scores for climate-resilient infrastructure category

Scales to give scores:

Value	Meaning
1	Both criteria are **equally important**
3	One criterion is **somewhat more important** than the other
5	One criterion is **clearly more important**
7	One criterion is **much more important**
9	One criterion is **extremely important**
2,4,6,8	An **intermediate value** between two choices mentioned above

If the **second** criterion is more important than the first, enter the **inverted** number.

*For example: if criterion B is clearly more important than A → enter **1/5** for "A vs B".*

Fill in the red cells below with a score

The question you have to ask yourself is: **which aspect contributes more to climate-proof infrastructure with a higher groundwater level?**

Example

Compare "Peat soil and carbon storage" with "Ecological network": **which aspect contributes more to the climate-resilient infrastructure with a higher groundwater level?** Rate the importance on a scale of 1 to 9, or use a fraction if the second criterion is more important.

Comparison of criteria	Score (to be filled in by expert)	Any comments
Sensitivity to flooding **vs** Vulnerability of foundations		
Sensitivity to flooding **vs** Carrying capacity of the soil		
Vulnerability of foundations **vs** Bearing capacity of the soil		

Ecology

General explanation:
The ecology category focuses on reducing environmental damage and improving natural systems. The aim is to find areas where raising the groundwater level most promotes nature development.

Criteria:

- **Peat areas and carbon emissions**

  Thick peat layers emit a lot of CO_2 during oxidation; By raising the groundwater level, these emissions are slowed down and soil subsidence is reduced.

- **Ecological network**

  Higher groundwater levels help to restore nature reserves and ecological connections by improving the moisture balance.

- **Areas at risk of salinisation**
  Salinisation threatens freshwater nature; a higher groundwater level can help to combat salinisation and protect vulnerable ecosystems.

Giving scores for ecology category

Scales to give scores:

Value	Meaning
1	Both criteria are **equally important**
3	One criterion is **somewhat more important** than the other
5	One criterion is **clearly more important**
7	One criterion is **much more important**
9	One criterion is **extremely important**
2,4,6,8	An **intermediate value** between two choices mentioned above

If the **second** criterion is more important than the first, enter the **inverted** number.

*For example: if criterion B is clearly more important than A → enter **1/5** for "A vs B".*

Fill in the red cells below with a score

The question you have to ask yourself is: **which aspect contributes more to the ecology with a higher groundwater level?**

Example

Compare "Peat soil and carbon storage" with "Ecological network": **which aspect contributes more to ecology with a higher groundwater level?** Rate the importance on a scale of 1 to 9, or use a fraction if the second criterion is more important.

Comparison of criteria	Score (to be filled in by expert)	Any comments
Peat areas & Carbon Emissions **vs** Ecological Networks		
Peat areas & Carbon Emissions **vs** Areas at Risk of Salinization		
Ecological networks **vs** Areas at risk of salinization		

All results from filled in form

1.1.1.1 *Agrarische bedrijfsvoering*

Comparison of criteria	3	4	6	7	8	9	10
Crop-specific optimal groundwater level **vs** Tolerance of crops to inundation	7	1/7	5	1/3	1/6	7	7
Crop-specific optimal groundwater level **vs** Water requirements of crops (drought tolerance)	1/3	1/7	3	1/5	5	5	1
Crop-specific optimal groundwater level **vs** Meadow bird areas	5	1/7	9	7	5	1	1/5
Crop-specific optimal groundwater level **vs** Salinized agricultural areas	1	1/7	5	3	1	1	1
Tolerance of Crops to Inundation **vs** Water Requirement of Crops (Drought Tolerance)	1/5	3	1/3	3	1/5	1	1/5
Tolerance of crops to inundation **vs** Meadow bird areas	3	1	3	7	1/6	1	3
Tolerance of crops to inundation **vs** Salinized agricultural areas	1/5	1	1	5	1/6	1/3	1/9
Water requirements of crops (drought tolerance) **vs** Meadow bird areas	9	1/5	5	7	1	1	7
Water Requirements of Crops (Drought Tolerance) **vs** Salinized Agricultural Areas	1	1/3	5	3	1	1	5
Meadow bird areas **vs** Salinized agricultural areas	1/7	3	1	1	1/5	3	1/7

1.1.1.2 *Klimaatbestendige infrastructuur*

Comparison of criteria	1	2	3	4	6	8	9
Sensitivity to flooding **vs** Vulnerability of foundations	5	7	1/7	1/7	1	3	1/5
Sensitivity to flooding **vs** Carrying capacity of the soil	4	5	1/5	1/7	5	3	1/5
Vulnerability of foundations **vs** Bearing capacity of the soil	1	1/3	5	1	5	1/3	5

1.1.1.3 *Ecologie*

Comparison of criteria	1	3	4	6	7	8	9
Peat areas & Carbon Emissions **vs** Ecological Networks	5	7	7	1/5	7	1/4	1/5
Peat areas & Carbon Emissions **vs** Areas at Risk of Salinization	4	7	3	1/3	9	1/3	1/5
Ecological networks **vs** Areas at risk of salinization	1	1/5	1	5	3	1	1/5

Calculations of the AHP normalization and consistency ratio

Geometric mean and normalization

Agricultural viability

Geometric mean

	Crop-specific optimal groundwater level	Crop tolerance to inundation	Crop water demand (drought tolerance)	Meadow bird areas	Salinized agricultural areas
Crop-specific optimal groundwater level	1,00	1,52	1,03	1,26	0,89
to inundation	0,66	1,00	0,69	1,40	0,41
Crop water demand (drought tolerance)	0,98	1,46	1,00	1,90	1,26
reas	0,79	0,71	0,53	1,00	0,85
ultural areas	1,13	2,42	0,79	1,17	1,00
sum	4,56	7,11	4,03	6,73	4,41

Normalization

	Crop-specific optimal groundwater level	Crop tolerance to inundation	Crop water demand (drought tolerance)	Meadow bird areas	Salinized agricultural areas	Sum normative values	Relative score
Crop-specific optimal groundwater level	0,22	0,21	0,25	0,19	0,20	1,08	22%
to inundation	0,14	0,14	0,17	0,21	0,09	0,76	15%
Crop water demand (drought tolerance)	0,21	0,20	0,25	0,28	0,29	1,23	25%
reas	0,17	0,10	0,13	0,15	0,19	0,75	15%
ultural areas	0,25	0,34	0,20	0,17	0,23	1,19	24%
sum	1,00	1,00	1,00	1,00	1,00	5,00	1,00

Infrastructure resilience

Geometric mean

	Sensitivity to water nuisance	Foundation vulnerability	Soil bearing capacity
Sensitivity to water nuisance	1,00	0,70	0,68
Foundation vulnerability	1,42	1,00	0,92
Soil bearing capacity	1,47	1,09	1,00
sum	3,89	2,79	2,60

Normalization

	Sensitivity to water nuisance	Foundation vulnerability	Soil bearing capacity	Sum normative values	Relative score
Sensitivity to water nuisance	0,26	0,25	0,26	0,77	26%
Foundation vulnerability	0,37	0,36	0,35	1,08	36%
Soil bearing capacity	0,38	0,39	0,38	1,15	38%
sum	1,00	1,00	1,00	3,00	

Environmental sustainability

Geometric mean

	Peatland extent and carbon emissions	Ecological network	Areas at risk of salinization
Peatland extent and carbon emissions	**1,00**	1,23	1,17
Ecological network	0,81	**1,00**	0,54
Areas at risk of salinization	0,86	1,86	**1,00**
sum	2,67	4,09	2,70

	Peatland extent and carbon emissions	Ecological network	Areas at risk of salinization
Peatland extent and carbon emissions	**1,00**	1,23	1,17
Ecological network	0,81	**1,00**	0,54
Areas at risk of salinization	0,86	1,86	**1,00**
sum	2,67	4,09	2,70

Normalization

	Peatland extent and carbon emissions	Ecological network	Areas at risk of salinization	Sum normative values	Relative score
Peatland extent and carbon emissions	0,37	0,30	0,43	1,11	37%
ork	0,30	0,24	0,20	0,75	25%
salinization	0,32	0,46	0,37	1,15	38%
sum	1,00	1,00	1,00	3,00	

1.1.1.4 *Consistency ratio*

Lambda max, consistency index CI, randomness Index RI and consistency ratio are calculated according to Saaty (1980).

If CR is less than 0.10, the matrix passes the consistency test and is considered consistent.

AV

λ_max ≈ 5.104

CI ≈ 0.0261

CR ≈ 0.0233

= <0.10 = consistent

IR

λ_max ≈ 3.000

CI ≈ 0.0002

CR ≈ 0.0003

= <0.10 = consistent

ES

λ_max ≈ 3.037

CI ≈ 0.0187

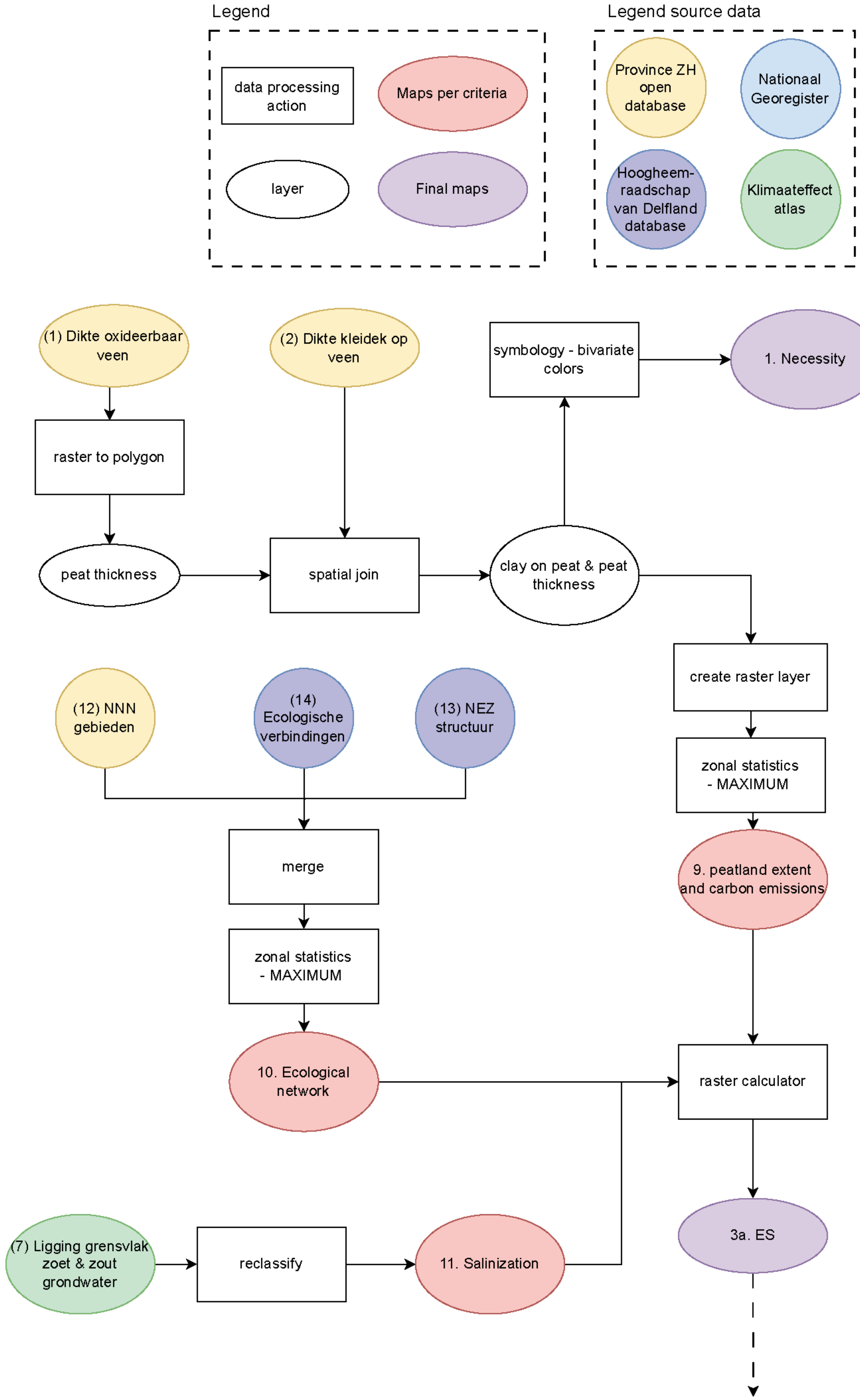
CR ≈ 0.0322

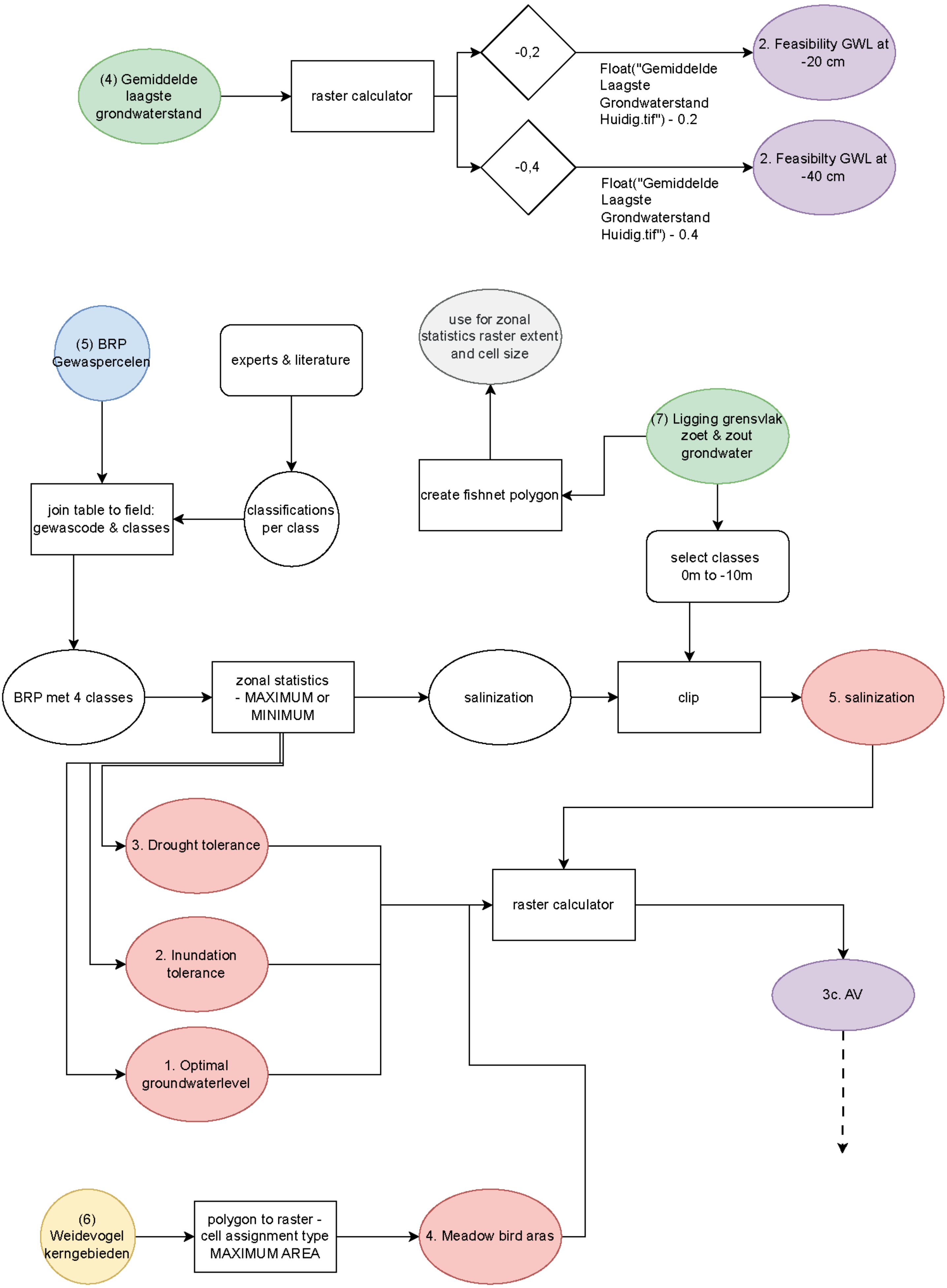
= <0.10 = consistent

Appendix 2: Data Process Model

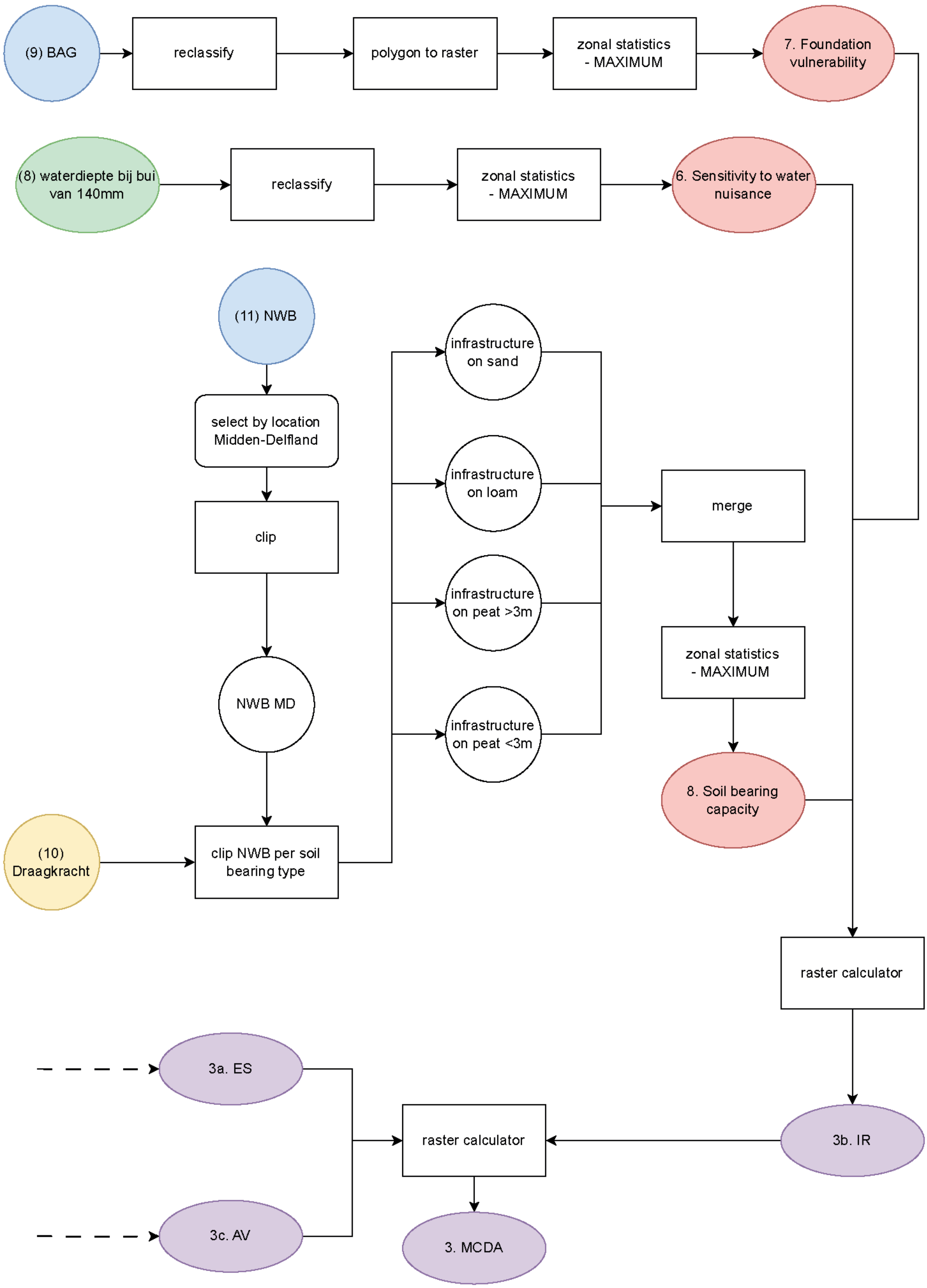
Reclassification was done with the classes identified in Table 5, Chapter 9.3.4.

The expressions used for Raster Calculator can be found in Appendix 3.





(4) Gemiddelde laagste grondwaterstand
raster calculator
-0,2
-0,4
Float("Gemiddelde Laagste Grondwaterstand Huidig.tif") - 0.2
Float("Gemiddelde Laagste Grondwaterstand Huidig.tif") - 0.4
2. Feasibilty GWL at -20 cm
2. Feasibilty GWL at -40 cm
(5) BRP Gewaspercelen
experts & literature
use for zonal statistics raster extent and cell size
(7) Ligging grensvlak zoet & zout grondwater
create fishnet polygon
join table to field: gewascode & classes
classifications per class
select classes 0m to -10m
BRP met 4 classes
zonal statistics - MAXIMUM or MINIMUM
salinization
clip
5. salinization
3. Drought tolerance
raster calculator
2. Inundation tolerance
3c. AV
1. Optimal groundwaterlevel
(6) Weidevogel kerngebieden
polygon to raster - cell assignment type MAXIMUM AREA
4. Meadow bird aras



(9) BAG
reclassify
polygon to raster
zonal statistics
- MAXIMUM
7. Foundation
vulnerability
(8) waterdiepte bij bui
van 140mm
reclassify
zonal statistics
- MAXIMUM
6. Sensitivity to water
nuisance
(11) NWB
select by location
Midden-Delfland
clip
NWB MD
infrastructure
on sand
infrastructure
on loam
infrastructure
on peat >3m
infrastructure
on peat <3m
merge
zonal statistics
- MAXIMUM
8. Soil bearing
capacity
(10)
Draagkracht
clip NWB per soil
bearing type
raster calculator
3a. ES
3b. IR
raster calculator
3c. AV
3. MCDA

Appendix 3: Raster calculator expressions

Expression for criteria 1 to 5

```
(
  Con(IsNull("criterium_1"), 0, "criterium_1") * 0.22 +
  Con(IsNull("criterium_2"), 0, "criterium_2") * 0.15 +
  Con(IsNull("criterium_3"), 0, "criterium_3") * 0.25 +
  Con(IsNull("criterium_4"), 0, "criterium_4") * 0.15 +
  Con(IsNull("criterium_5"), 0, "criterium_5") * 0.23
)
/
(
  Con(IsNull("criterium_1"), 0, 0.22) +
  Con(IsNull("criterium_2"), 0, 0.15) +
  Con(IsNull("criterium_3"), 0, 0.25) +
  Con(IsNull("criterium_4"), 0, 0.15) +
  Con(IsNull("criterium_5"), 0, 0.23)
)
```

Expression for criteria 6 to 8

```
(
  Con(IsNull("criterium_6"), 0, "criterium_6") * 0.26 +
  Con(IsNull("criterium_7"), 0, "criterium_7") * 0.36 +
  Con(IsNull("criterium_8"), 0, "criterium_8") * 0.38
)
/
(
  Con(IsNull("criterium_6"), 0, 0.26) +
  Con(IsNull("criterium_7"), 0, 0.36) +
  Con(IsNull("criterium_8"), 0, 0.38)
)
```

Expression for criteria 9 to 11

```
(
  Con(IsNull("criterium_9"), 0, "criterium_9") * 0.37 +
  Con(IsNull("criterium_10"), 0, "criterium_10") * 0.25 +
  Con(IsNull("criterium_11"), 0, "criterium_11") * 0.38
)
/
(
  Con(IsNull("criterium_9"), 0, 0.37) +
  Con(IsNull("criterium_10"), 0, 0.25) +
  Con(IsNull("criterium_11"), 0, 0.38)
)
```

Expression for final combination: ES, IR, AV

```
(
  Con(IsNull("ES"), 0, "ES") * 0.33 +
  Con(IsNull("IR"), 0, "IR") * 0.33 +
  Con(IsNull("AV"), 0, "AV") * 0.33
)
/
(
  Con(IsNull("ES"), 0, 0.33) +
  Con(IsNull("IR"), 0, 0.33) +
  Con(IsNull("AV"), 0, 0.33)
)
```