Developing a Framework for Combining Port Functions with Water Storage in the Netherlands

Application to the Amsterdam Houtrakpolder Case

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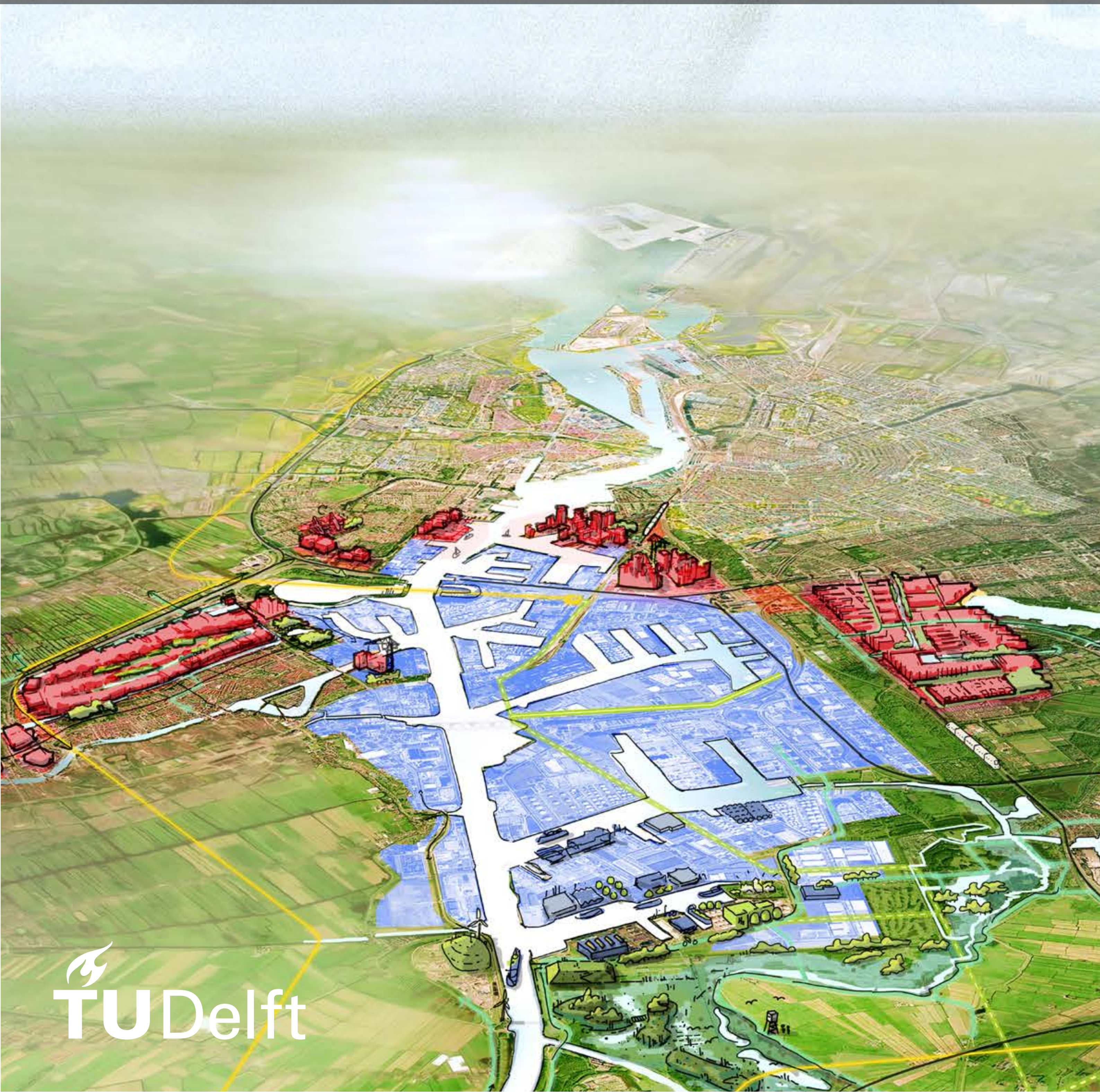

TU Delft

Developing a Framework for Combining Port Functions with Water Storage in the Netherlands

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by

T.O. Voorkamp

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Preface

It has been quite a journey. For seven months, I have been working hard on this project, which is the final step towards earning my Master's degree in Transport, Infrastructure & Logistics at TU Delft.

I started my academic journey with a bachelor's degree in International Business Administration at the Erasmus University in Rotterdam. When I transferred to the Technical University of Delft, I faced some challenges in getting up to speed with the mathematics and programming involved. But I have come a long way since then, and I am now confident to use my techno-economic academic background in the professional world.

I owe a big thank you to Drs. A. Blikman from the Ministry of Infstructure & Water Management (IenW), who was my supervisor. He has been a great mentor, helping me to understand our case study, connecting me with various specialists and stakeholders, and teaching me about the politics involved. I would also like to thank Wouter Pietersma, Alexia Michel and my other colleagues at the Seaports Department of the Ministry of IenW. In our weekly meetings they shared their knowledge and insights on how seaports are managed in the Netherlands, which was incredibly interesting.

I would also like to thank Dr J.H.R. van Duin, who was my daily supervisor at TU Delft and who gave me very clear guidance in our bi-weekly meetings. I really appreciated his invitation to the kick-off day of the Floating Future research project, where I was able to see the potential future impact of this field of study. The chair of the committee, Prof. dr. ir. D.L. Schott, was also very helpful with her suggestions regarding the structure of the research.

Finally, I would like to thank my roommates, Berend van der Sijde and Joris Lammers, for their support. Berend cooked amazing dinners for us every night and Joris was always there to cheer me on when things got tough. This thesis is the result of a lot of hard work and support from many people. I am grateful to everyone who has helped me along the way and I am excited to see where this journey takes me next.

T.O. Voorkamp
Delft, June 2024

Summary

To address major spatial challenges, the Dutch national government outlines three guiding principles in the National Environmental Vision (NOVI): prioritising multifunctionality, focusing on regional characteristics and avoiding burden shifting, with an emphasis on the steering role of the water system in environmental planning. This study develops a framework for integrating water storage functions with port terminal functions to form a dual-function system. The framework, which focuses on the technical feasibility and stakeholder interests of dual-function solutions, is validated by applying it to the case of the Amsterdam Houtrakpolder. The framework focuses on water retention over drainage, four types of port terminals, without considering the upgrading of existing infrastructure, and is applied to the unique water management challenges of the Netherlands.

An in-depth analysis of the different types of port terminals shows that each type has highly specialised operations and equipment tailored to the cargo handled. A functional distinction between sea, yard and landside operations is used to analyse and compare in detail the specific sub-functions inherent in each type of terminal. Container terminals use specialised facilities for efficient transshipment, handling and storage, relying on yards, cranes and automated equipment. Liquid bulk terminals handle liquid and gaseous cargoes with loading arms, hoses and pumps, and emphasise strict safety measures. Dry bulk terminals handle bulk materials with infrastructure such as stackers and reclaimers, and implement dust control measures. Offshore wind energy terminals require facilities for the assembly and shipment of large components, storage space, high-capacity quays, manufacturing facilities and repair workshops.

Water storage functions in the Dutch water management system are multifaceted, including stock, seasonal, peak, and emergency storage. These functions serve different needs, ranging from water scarcity mitigation to flood prevention, while their implementation is linked to a variety of water management systems and storage design models, limited by the landscape type of the area. Stock storage focuses on local rainfall retention, using widened watercourses or flexible water level management. Seasonal storage bridges seasonal variations in water availability with storage basins or new ponds. Peak storage, essential for flood control, uses temporary solutions like inlet or inner polders. Emergency storage prevents disasters with main system adaptations, such as inlet polders for short-term, high-impact storage.

The study highlights the critical role of strategic stakeholder management in both port and water storage operations. Internal stakeholders such as port authorities, external stakeholders such as terminal operators, and legislative and public policy stakeholders, including government ministries, all have important roles to play. Community stakeholders ensure alignment with societal values and sustainability goals.

This study presents four innovative dual-function solutions for combining port terminal functions with water storage functions: port lock systems, floating ports, aquifer storage recovery (ASR) and decentralised water management. Port lock systems, traditionally used to control vessel traffic and manage water levels, offer the potential for natural basin filling, but present scheduling and environmental challenges. Floating ports use Very Large Floating Structures (VLFS) or Modular Floating Structures (MFS) to create adaptable infrastructure, offering flexibility and environmental benefits but requiring careful stability management. ASR provides an underground water storage solution that protects water from evaporation, but requires careful management to avoid contamination and clogging. Decentralised water management, through green roofs, tree pits and artificial buffers, treats rainwater at its source, integrating water storage into urban areas while providing environmental and recreational benefits despite potential concerns about soil contamination.

The proposed dual-function design framework is visualised in Figure 1. The framework defines requirements based on the analysis of the two separate functions and the stakeholder analysis. The framework defines conceptual designs based on the analysis of the dual-function solutions. Thirty-one constraints are identified, some of which are used to specify the conceptual designs, while others are case-specific. The objectives, mainly based on stakeholder interviews, include maximising storage capacity, storage period, recovery rate, physical and nautical space for port operations, and minimising investment costs and environmental impact. Based on the constraints, four conceptual designs are developed that incorporate technically feasible port terminal and water storage functions.

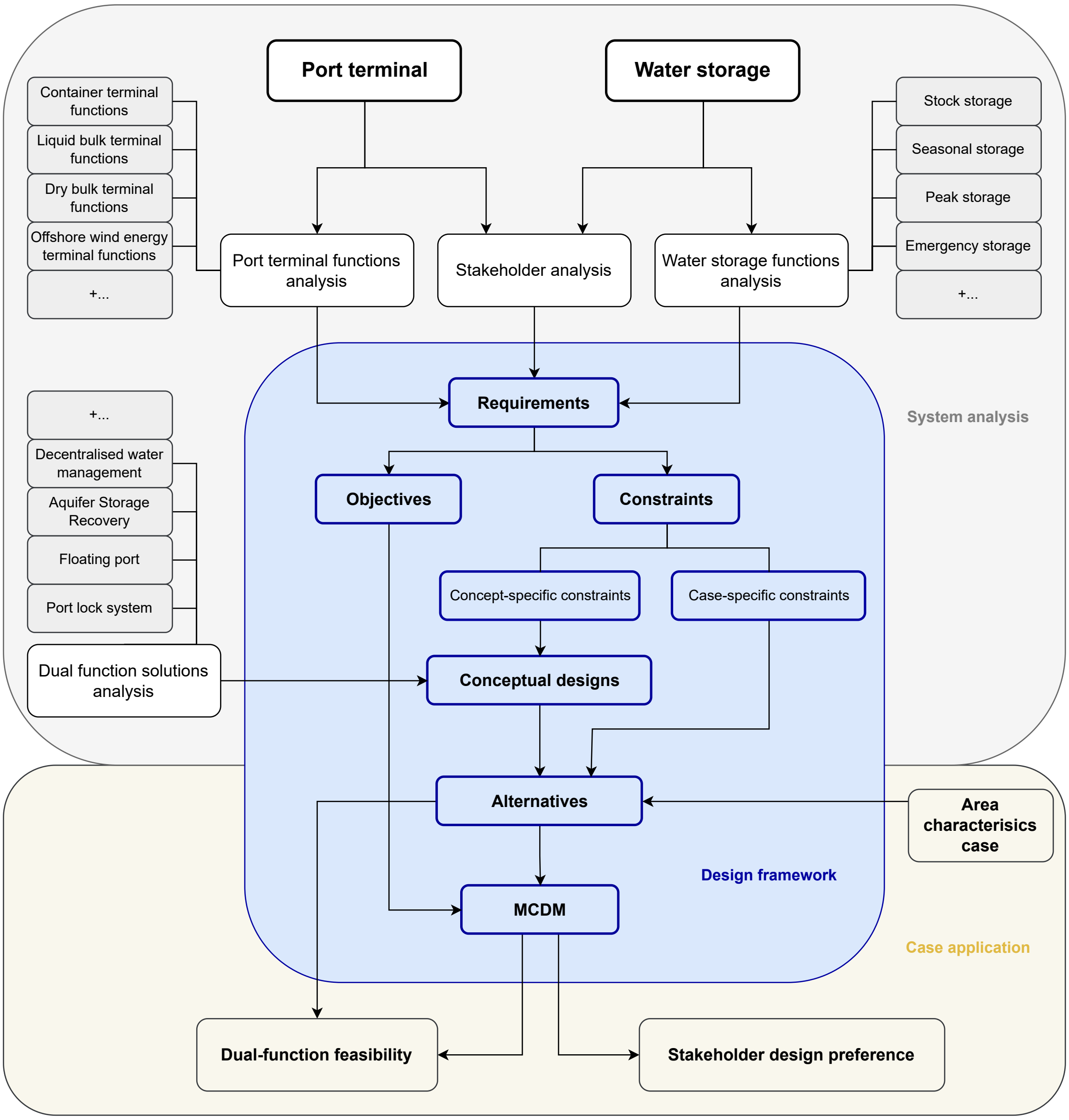

Figure 1: Dual-function design framework for port terminal and water storage functions [created by author]

The case study focuses on the Amsterdam Houtrakpolder area and applies the design framework. The northern part of the Houtrakpolder is analysed, taking into account the spatial constraints of an environmental project and a residential area. Decentralised water management is ruled out due to high groundwater level. The objectives of the framework are assessed in a questionnaire using the Direct Assignment Technique (DAT), which allows decision-makers to assign points directly to the criteria. Based on the combined power/interest grid, stakeholders considered to have the highest interest and power in both functional systems combined are consulted for the DAT. The analysis of the criteria weights, visualised in Table 1, shows that storage capacity and period are crucial for all stakeholders, with varying emphasis on recovery rate, physical and nautical space, investment costs and environmental impact.

Organisation	**Storage capacity**	**Storage period**	**Recovery rate**	**Physical space**	**Nautical space**	**Investment costs**	**Environmental impact**
Province of NH	0.26	0.13	0.03	0.03	0.03	0.26	0.26
Port of Amsterdam	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DGLM	0.12	0.12	0.16	0.18	0.12	0.16	0.12
DGWB	0.21	0.21	0.18	0.00	0.00	0.21	0.21
Mun. Amsterdam	0.27	0.27	0.45	0.00	0.00	0.00	0.00
Mun. HLM	0.23	0.23	0.23	0.02	0.02	0.02	0.23
RWS-WNN	0.26	0.21	0.18	0.13	0.13	0.02	0.08
HvR	0.26	0.26	0.13	0.00	0.00	0.21	0.13
Waternet	0.23	0.23	0.19	0.02	0.02	0.12	0.19

Table 1: Normalised criteria weights (ideal situation)

DAT is a straightforward method for assigning weights to criteria as part of Multi Criteria Decision Making (MCDM). The framework suggests a separate MCDM evaluation for each decision maker. The next step in the MCDM method is to evaluate the performance of the alternatives against the 7 criteria, resulting in the performance matrix in Table 2. The port lock system involves the construction of a port basin with a lock to manage water levels, suitable for peak and emergency storage, but with no potential for water recovery due to contamination risks. This design, with the largest storage capacity, is inspired by existing port infrastructure such as the Port of Antwerp and uses flexible water level management. The floating port alternative proposes the creation of a lake with floating infrastructure for port operations. This system, which uses flexible water level management with small fluctuations, emphasises environmental benefits such as reduced greenhouse gas emissions and the potential for new brackish water development. However, it faces significant challenges due to high investment costs and limited storage capacity. The ASR system, designed for seasonal storage, stores water in an underground aquifer and involves the separation of port operations to minimise the risk of contamination, while maintaining the existing regional water management functions of the polder. It requires the lowest investment costs and has a moderate environmental impact.

Criterion	**Unit**	**Max/min**	**Alt. 1: Port lock system**	**Alt. 2: Floating port**	**Alt. 3: ASR**
Storage capacity	m^3 (million)	max	2.85	0.42	1.18
Storage period	dagen	max	0.66	0.1	183
Recovery rate	%	max	0	0	50
Physical space	hectare	max	160	105	145
Nautical space	hectare	max	50	105	50
Investment costs	€ (million)	min	620.2	1303.2	44.6
Environmental impact	Scale 0-5	min	5	1	3

Table 2: Criteria performance matrix

The ASR system emerges as the preferred option for all stakeholders, performing consistently across the different criteria and excelling in its ability to recover water and store it for a longer period of time. This finding is based on the results of the additive value functions presented in Table 3. The port lock system is the second most preferred due to its high storage capacity, despite its high environmental impact and significant investment costs. The floating port alternative is the least preferred, mainly due to its high cost and limited storage capacity. In a sensitivity analysis, the MCDM results for a 50% increase or decrease in the importance scores of any of the 7 criteria are evaluated and show that for all stakeholders, no weight adjustment changes the dominant position of the ASR alternative. Therefore, it can be concluded that an ASR solution in the Houtrakpolder as a dual-function system is in line with stakeholder interests.

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0.44	0.29	0.66
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0.45	0.36	0.77
Ministry of IenW (DGWB)	0.31	0.19	0.75
Municipality Amsterdam	0.27	0.04	0.84
Municipality HLM	0.28	0.26	0.71
RWS-WNN	0.46	0.32	0.72
HHS Rijnland	0.37	0.14	0.76
Waternet	0.33	0.22	0.73

Table 3: Results MCDM (ideal situation)

Although the Port of Amsterdam did not complete the questionnaire, it is expected that the ASR system is also the preferred dual-function solution for this stakeholder. This does not mean that all stakeholders involved in this case have the same priorities. If the design were to be developed to a level with more operational detail, it is expected that interests related to water storage will also conflict. Furthermore, when assessing the performance values of the ASR alternative, it is found that water would have to be captured outside the Houtrakpolder area. It is also found that it is uncertain whether such an underground water storage system of this size and with the soil characteristics of the Houtrakpolder area would achieve the desired infiltration rate to be effective. Therefore, it cannot be concluded that the ASR system is technically feasible as a dual-function system in the Houtrakpolder. Combined with the results of the MCDM, it can be concluded that at this stage in the development cycle of the dual-function designs, there is no system combining the port and water storage functions that is technically feasible and in line with the interests of the stakeholders in the Houtrakpolder.

The proposed solutions show a conflict between the two spatial functions due to the limited area available. It is recommended to adopt a systems approach at the level of the main water management system and the entire port area. This approach would address the limitations of the framework by allowing the combination of different design options and levels in the morphological chart and the integration of spatial functions beyond the dual-function system. Furthermore, at a more detailed design level, sub-functions of a port terminal that are less in conflict with the water storage function should be explored. Future research should also focus on the governance and ownership structures for implementing dual-function systems. Given the novelty of such systems in the Netherlands, there is uncertainty about the identification of stakeholders and the extent of their power and interests. In addition, the integration of port authorities into broader initiatives such as the Delta Programme Central Holland could facilitate better coordination and resource management. New governance structures, policy instruments and infrastructure ownership need to be explored to support the systems approach and ensure robust and efficient interfaces between functional systems.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
ARK/NZK	Amsterdam-Rijnkanaal/Noordzeekanaal
DGLM	Directorate-General for Aviation and Maritime Affairs
DGWB	Directorate-General for Water and Soil (DGWB)
DWT	Deadweight Tonnage
GM	Metacentric Height
HRP	Houtrakpolder
HvR	Hoogheemraadschap van Rijnland
IenW	Ministry of Infrastructure and Water Management
EZK	Ministry of Economic Affairs and Climate
LOA	Length Overall
MFS	Modular Floating Structure
NOVEX	National Environmental Vision Extra
NOVI	National Environmental Vision
NZK	Noordzeekanaal
NZKG	Amsterdam Noordzeekanaalgebied
PoA	Port of Amsterdam
RWS	Rijkswaterstaat
RWS-WNN	Rijkswaterstaat West-Nederland Noord
TEU	Twenty Foot Equivalent Unit
VLFS	Very Large Floating Structure

1 Introduction

1.1. Research context

The Netherlands faces major spatial challenges, including the need for new housing, renewable energy infrastructure, climate adaptation, agricultural constraints and biodiversity conservation. These are tasks that require major social and spatial interventions, while balancing utility, aesthetics and future sustainability. Moreover, they all take up space, while territory is limited. In response, the Dutch government outlined three guiding principles in the National Environmental Vision (NOVI): prioritising multifunctionality over single-use, focusing on regional characteristics and avoiding burden shifting. It also emphasises the steering role of the water system in environmental planning. The next challenge is to apply these principles to sectoral and regional NOVI developments (Planbureau voor de Leefomgeving, 2023).

Under the National Environmental Vision Extra (NOVEX) programme, all levels of government are working together in sixteen priority areas. The provinces work with water boards and municipalities to translate national goals and objectives into spatial terms that can be incorporated into provincial plans. Amsterdam Noordzeekanaalgebied (NZKG) is one of the NOVEX areas where several functions come together, but the available space is limited. Required spatial functions include, but are not limited to, the Amsterdam port area, the energy transition, the transition to a circular economy, housing and water storage (De Nationale Omgevingsvisie, 2023).

The Houtrakpolder is a large polder on the south side of the Noordzeekanaal, used mainly for recreational purposes. In the master plans of the Municipality of Amsterdam (Gemeente Amsterdam, 2020) and the Bestuursplatform NZKG (Stuurgroep Visie Noordzeekanaalgebied, 2013), the area was strategically reserved for the expansion of the port area of Amsterdam. However, according to the new development perspective of NOVEX-NZKG, this reservation may be lifted as an option. If there are alternative possibilities for port development, the Houtrakpolder should be reserved for other spatial functions, in particular energy functions (such as a transformer station) and also (peak) water storage functions. As both functions are of high social and economic importance, the possibility of combining water storage and port functions should be explored. The research problem described in the context of the Amsterdam Houtrakpolder case is visualised in Figure 1.1.

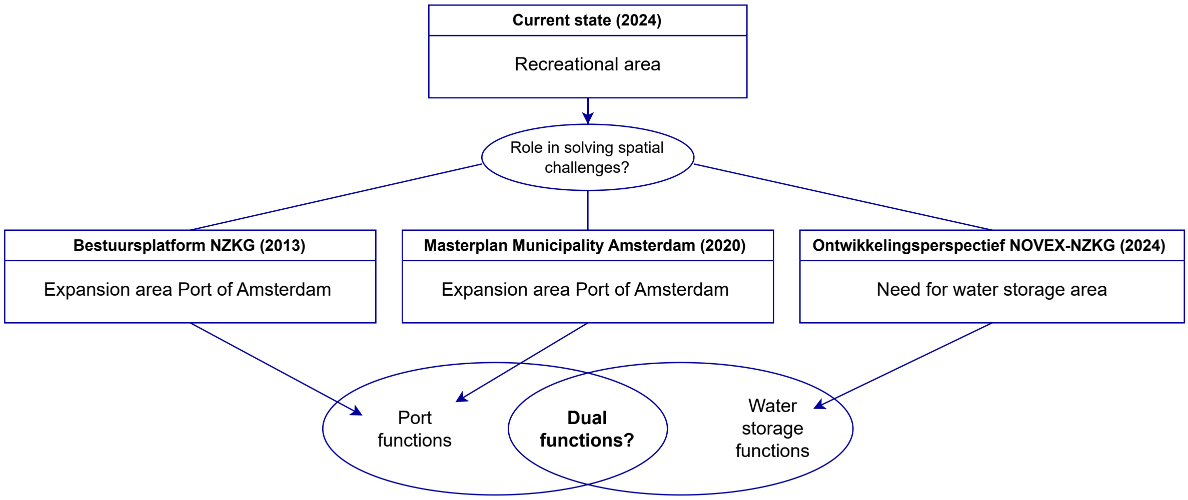

Figure 1.1: Research problem Amsterdam Houtrakpolder case [created by author]

1.2. Research gap

The dual-function of port terminal and water storage has not been explicitly addressed in the scientific literature. In reality, however, many seaports are already forced to integrate water management into their strategies. The Port of Antwerp implements a multi-faceted approach to water management, focusing on conservation, recycling and maintaining the quality of the water (Port of Antwerp Bruges, 2023). Historically, significant parts of the port area were built with dock systems behind locks. Due to the high tidal range of the river leading into the port, their design is intended to maintain a stable water depth for vessels at berth. However, in the 1990s the Port of Antwerp began to develop river-based terminals, recognising the time-sensitive nature of container ship operations and the potential risks and delays associated with lock operations, including the risk of collision (Notteboom et al., 2022).

Innovative water storage techniques have been scientifically researched, but not compared with each other or applied to a port area. For example, decentralised stormwater management solutions are being applied in an urban context, including measures such as green roofs and tree pits with a focus on water infiltration (Dickhaut & Richter, 2020). In addition, the spatial challenges in the Netherlands are leading to various initiatives in the field of floating infrastructure research. The studies present a hopeful scenario in which some of the port infrastructure and operations will be relocated to the sea. However, it is unclear whether and how these promising innovations can be applied within a port to combine its functions with water storage.

As the dual function is not explicitly studied, the initial literature review focused on studies of port terminal design and potential solutions for integrating water storage. In addition, existing literature on the design of floating architecture in other non-port applications and the design of dual-function systems was reviewed. The methodologies used in the existing studies vary widely, with literature reviews combined with case and/or design studies emerging as a prominent tool. While simulations provide valuable predictive insights, their applicability is sometimes limited by data availability and system complexity. The literature falls short in comparing potential water storage techniques in different port contexts and in considering their function in a water management system. It is evident that while the existing literature contributes individual pieces to the puzzle, a comprehensive comparative analysis that considers different solutions, different port applications and the dual functionality of solutions is still needed. The research gap analysis is summarised in Table 1.1.

Reference	Focus					Methods				
	Port functions	Lock systems	Decentralised water storage	Floating infrastructure	Dual-functions	Literature review	Case study	Design study	Systems Engineering	Simulation
Notteboom et al. (2022)	X									
Gharehgozli et al. (2019)	X					X		X		
van Vianen et al. (2011)	X					X				
Y. Chang et al. (2013)		X					X			
Schindler et al. (2020)		X					X	X	X	
Cavallaro et al. (2017)		X					X			X
Mel (2021)		X					X			X
Samant and Brears (2017)			X			X	X			
Dickhaut and Richter (2020)			X			X	X			
Rodrigues et al. (2023)			X			X				
R. Liu and Coffman (2016)			X							
Nicolet et al. (2023)	X			X		X	X			
Ang et al. (2020)	X			X			X	X		X
van der Wel et al. (2010)	X			X				X		X
Lim (2019)	X			X		X	X			
Nakajima et al. (2021)				X		X	X	X		
Ambica and Venkatraman (2015)				X			X	X		
El-Shihy and Ezquiaga (2019)				X		X	X	X		
Stankovíc et al. (2021)				X			X	X	X	
Maier (1999)					X	X				
Soudian and Berardi (2021)					X		X	X	X	
Patryniak et al. (2022)					X			X	X	
Doufene et al. (2014)					X		X	X	X	
Chetouani et al. (2023)					X		X	X	X	
This research	X	X	X	X	X	X	X	X	X	

Table 1.1: Research gap analysis summary

1.3. Research objective and scope

Based on the research context and the identified research gap, this study aims to provide a framework for integrating water storage techniques with port functions to form a dual-function system. A comprehensive framework for the integration of port and water storage systems will be developed and empirically validated through application to the Houtrakpolder case.

The framework to be developed will focus on the technical feasibility of dual-function solutions and the interests of stakeholders involved in both systems. The study aims to provide innovative solutions, but does not consider the detailed design and optimisation of the associated infrastructure elements. Furthermore, the study will focus exclusively on a port terminal and water storage facility yet to be built. The upgrading of existing infrastructure is not considered. In addition, a single case will be used to validate the framework.

When integrating water storage systems, the study will focus on water retention. Only water management solutions that prioritise water retention over discharge will be considered. A water storage technique that optimises the discharge capacity to other water management systems is contrary to the primary NOVI guideline of avoiding burden shifting (Bestuursplatform NZKG, 2023). The Netherlands also faces unique water management challenges. One third of the country is below mean sea level and without dunes, dikes and pumps, 65% of the country would be under water at high tide (Hoeksema, 2007). Because of this unique situation, the framework will focus on the application of dual-function solutions in the Netherlands.

Port terminals used to be divided into three types: general cargo, bulk cargo and passenger terminals. Passenger terminals represent only a small segment of today's port facilities. General cargo can be handled by three different types of terminals: break-bulk, neo-bulk and container terminals, the latter being the most common. Bulk cargo includes liquid bulk and dry bulk, which require different handling procedures (Notteboom et al., 2022). Therefore, this study examines the selection of port terminal operations focusing on three main categories of cargo: containers, liquid bulk and dry bulk. In addition, offshore wind energy terminals focused on the import, production or storage of sustainable fuels are included in the scope. Whilst the NOVEX programme includes a requirement for space for the energy transition (De Nationale Omgevingsvisie, 2023), ports have the potential to achieve greater energy efficiency through the implementation of innovative technologies (Iris & Lam, 2019).

1.4. Research questions

The following research question will be addressed in order to accomplish the research objective described: **How can a dual-function system framework for incorporating water storage with container, liquid bulk and dry bulk cargo, and offshore wind energy terminal operations in the Netherlands, be developed, and validated in the context of the Houtrakpolder?** To answer the main research question, several sub-questions have been formulated:

1. How are different forms of water storage, and container, liquid bulk, dry bulk and offshore wind energy terminals designed and operated?
2. What solutions exist for incorporating water storage with port operations for container, liquid bulk, dry bulk and offshore wind energy terminals?
3. How to evaluate the technical feasibility of the dual-function solutions?
4. What are the interests of stakeholders in port and water management systems in the development of dual-function solutions?
5. Considering the Houtrakpolder case, which dual-function solution is technically feasible and in line with stakeholder interests?

1.5. Research methodology

The research methodological steps in this study are based on previous work investigating dual-function transport facilities. Specifically, Chetouani et al. (2023) investigated the possibility of integrating logistics functions into mobility hubs. They conducted a requirements analysis by collecting and organising data from the literature and expert interviews. This data was used to construct frameworks that took into account relevant conditions, which were then validated with a case study. For this research, the framework is adapted and visualised in Figure 1.2, showing the different methods that will be used, their objectives, how they are interrelated and how they relate to the research questions. The methods to be used are described in the following sections.

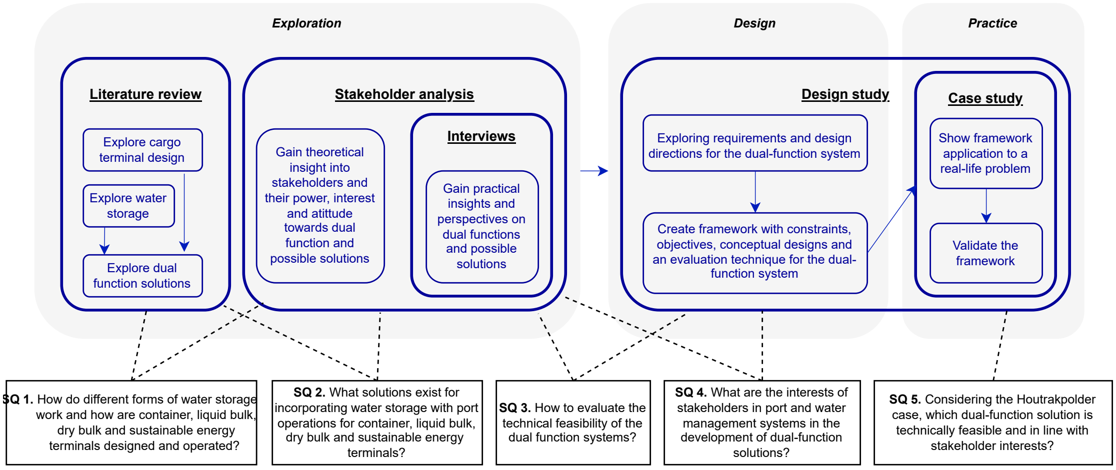

Figure 1.2: Research methodology steps [(Chetouani et al., 2023), adapted by author]

1.5.1. Literature review

Conducting a literature review is important to develop an understanding of theoretical concepts and terminology (Rowley & Slack, 2004). This understanding is essential for the development of water storage methods and the current layout of cargo terminals before a common application can be investigated and evaluated. In addition, a literature review will be carried out to summarise the current state of knowledge on the chosen research topic (Flink, 2009). A thorough evaluation of existing information on potential dual function solutions and comparable dual functions is essential before embarking on the design research phase.

1.5.2. Stakeholder analysis

Once the key issues and components of a project have been identified, a stakeholder analysis can identify the parties that may be affected, followed by an assessment of their level of interest and influence. Its particular strength lies in its prospective dimension, where it can be used to predict and provide information to influence the future. At the same time, it is important to recognise that stakeholder analysis has inherent limitations relating to the unpredictable nature of future events and the provisional nature of the information gathered (Brugha & Rvasovszky, 2000).

It is expected that the implementation of dual-function solutions will involve a wide range of public and private sector stakeholders whose interests may conflict. In order to design a comprehensive framework, it will be necessary to identify stakeholders involved in both functions, as well as potential new parties resulting from the merger, and to assess their level of interest and influence. In addition, the stakeholder analysis will provide valuable perspectives on which industry experts to interview.

1.5.3. Interviews

Because it is possible to identify individuals who occupy key positions in relation to the research question, interviews are used as a method of data collection. Interviews may be preferred to questionnaires not only because of the depth of insight they provide, but also because of the reluctance of key informants to complete questionnaires. Interviews are used to gather factual information or to gain insight into opinions, attitudes, experiences, processes, behaviours or predictions (Rowley, 2012). This in-depth understanding is considered essential to the creation of the desired framework. Due to the limited availability of information on the solutions, as suggested by Chetouani et al. (2023), this research will use semi-structured interviews. Semi-structured interviews take a variety of forms. However, for an inexperienced researcher, it is advisable to use an interview schedule of about six to twelve well-formulated questions, possibly with sub-questions, mostly in a predetermined order but with room for flexibility (Rowley, 2012).

1.5.4. Design study

A design study is used to design a visualisation system that supports the solution of a specific real-world problem, validate the design and reflect on the lessons learned in order to refine visualisation design guidelines (Sedlmair et al., 2012). This is in line with the aim of this research to develop and empirically validate a comprehensive framework for the integration of port and water storage systems.

Systems Engineering (SE) is an interdisciplinary design approach that focuses on defining customer needs and required functionality early in the development cycle (INCOSE, 2023). This corresponds to the subject of innovative dual-function solutions. Subsequently, SE enables the realisation of successful systems by documenting requirements and performing design synthesis and system validation (INCOSE, 2023). The design approach has several advantages for this research. It allows the comparison of different design alternatives, links the contexts of different disciplines to system performance, and includes both qualitative and quantitative measures (Soudian & Berardi, 2021).

1.5.5. Case study

Case studies are commonly used in exploratory design studies to analyse a phenomenon, generate hypotheses and validate a method. Compared to other empirical research methods, such as written surveys, case studies have particular advantages in this research. They allow data to be collected in context and facilitate the use of a multi-method approach. The primary aim of the case study is to implement and validate the decision framework. It is important to consider any limitations related to selection bias and generalisability of the cases (Teegavarapu & Summers, 2008).

1.6. The Amsterdam Houtrakpolder case

The research problem as discussed in Section 1.1 describes conflicting strategic plans for the Houtrakpolder in the master plans of the municipality of Amsterdam, Bestuursplatform NZKG and the development perspective of NOVEX-NZKG. In addition, a large part of the existing port area will be used to build tens of thousands of apartments in the new Port-City district. The Port-City plan, which is part of the municipality's Environmental Vision 2050, is based on the high demand for housing and the regulated city limits (van Dort & van der Kerk, 2024). The Houtrakpolder area is also part of the Spaarnwoude Park 2040 vision. The vision describes a natural park between the cities, easily accessible, versatile and with a regional reputation. The future plan has been drawn up by the Spaarnwoude Recreation Board, with input from the province, the municipality, businesses, organisations and residents (Projectgroep visie Spaarnwoude Park, 2020).

Before excluding any spatial policies or deciding on them, the Ministry of Infrastructure & Water Management, as commissioner of this research, wants to have thoroughly explored the dual-function solutions. The findings of this research may contribute to this. The Maritime department recognizes the Port of Amsterdam as a port of national importance. A clear message is conveyed that when the national government wants to sustain this position, substantial investments need to be made in main infrastructure. This places the Houtrakpolder case in a greater picture of a large number of nautical renovation tasks and major (replacement) projects in NZKG, with a leading role for the Ministry of IenW (Arcadis, 2023).

1.7. Structure

Finally, based on the methodological steps discussed in Section 1.5, the research will be structured according to the chapters presented in Figure 1.3.

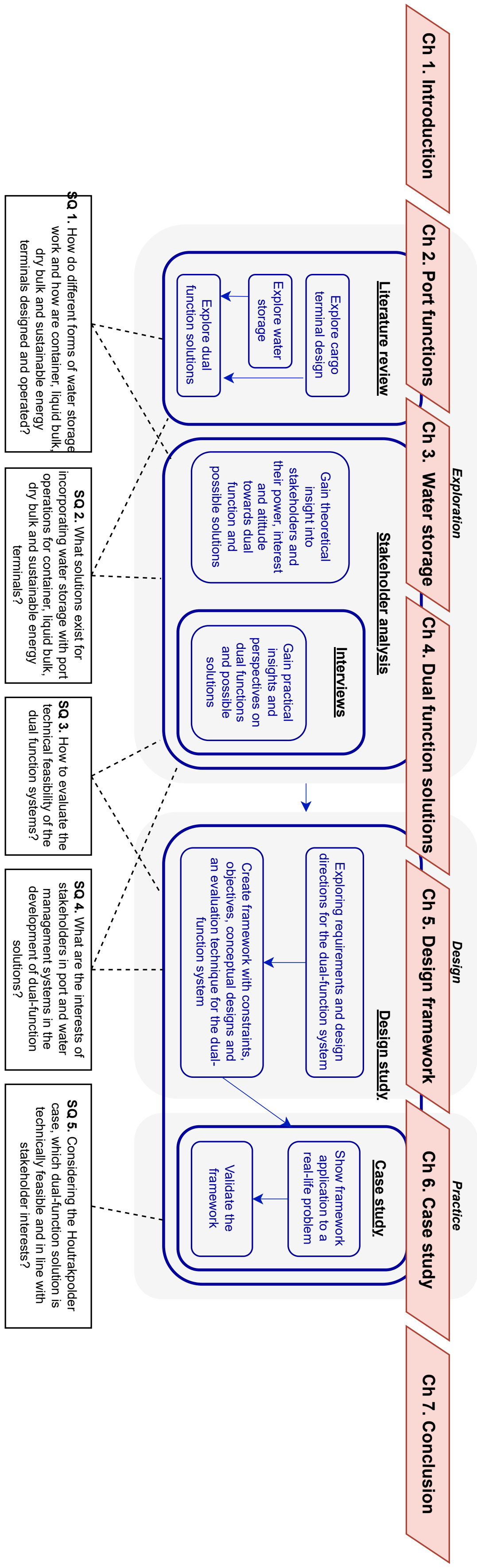

Figure 1.3: Research chapters [(Chetouani et al., 2023) adapted by author]

2
Port terminal functions

A seaport consists of various terminals that serve as critical links between sea and land transport, with the capacity of the port determining the volume of cargo it can handle in a given period of time. Port terminals are the physical interfaces between these sea and land transport modes, capable of handling different types of cargo, including containers, bulk and roll-on/roll-off (Ro-Ro) cargo, within a given timeframe (Bassan, 2007). As mentioned in Section 1.3, this study will focus on three main types of cargo: containers, liquid bulk and dry bulk, and will also include offshore wind energy terminals, reflecting the increasing demand for space due to the transition to renewable energy. In general, the functions of a port terminal can be divided into three sub-functions (Dohmen, 2016):

- Storage
- Transport, transhipment and transfer
- Value added logistics

Storage and transport are considered the primary functions of a terminal, while value-added logistics such as blending, tank-to-tank transfers or the addition of additives are considered secondary. In addition to these primary and secondary sub-functions, ensuring security through supporting activities is essential. Alternatively, terminal operations can be divided into three functional systems: seaside operations, yard operations and landside operations (Dohmen, 2016). This functional distinction is advantageous as it allows a detailed analysis and comparison of the specific sub-functions inherent in different types of terminals. In addition, the physical location of a port terminal function (seaside, yard or landside) is crucial when evaluating potential dual-function solutions. The delineation of port functions is visualised in Figure 2.1. The stakeholders for each type of terminal are also defined.

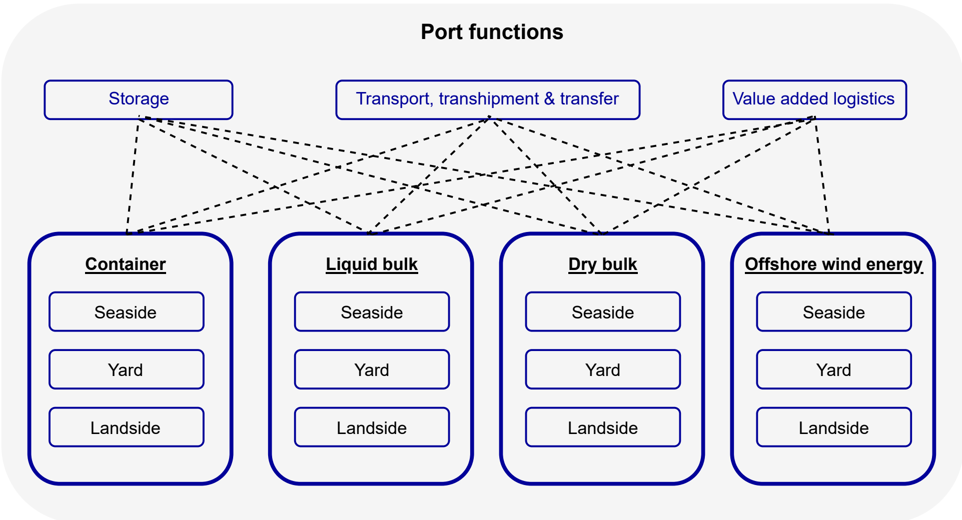

Figure 2.1: Port terminal functional systems [created by author]

2.1. Container terminals

A container terminal is a specialised facility for the transshipment, handling and temporary storage of containers between at least two modes of transport. It consists of various areas, including quays, yards and equipment such as cranes, together with supporting facilities such as administration and maintenance buildings, and warehouses (Notteboom et al., 2022). Figure 2.2 shows a typical layout of a container terminal.

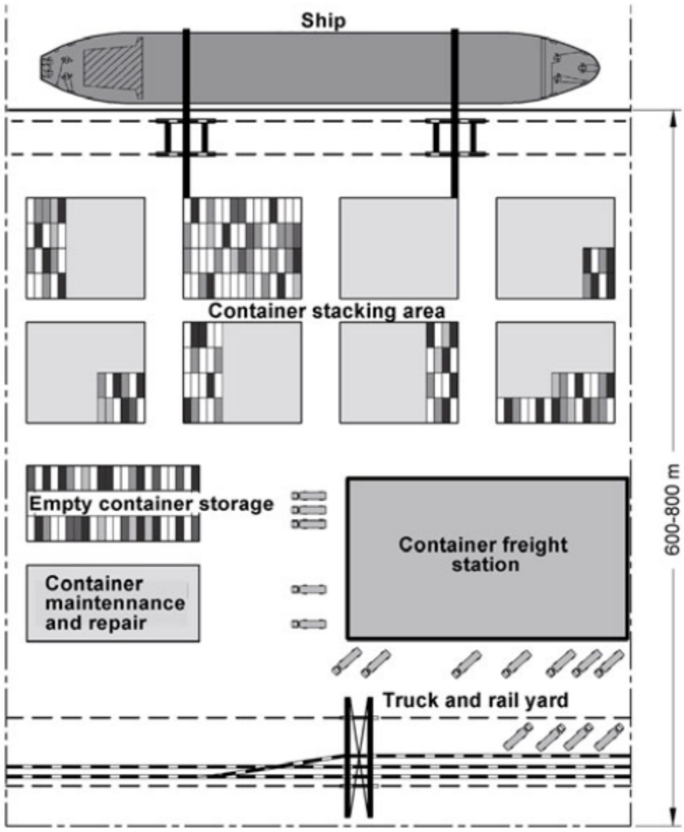

Figure 2.2: Container terminal general layout (Brinkmann, 2005)

2.1.1. Seaside operations

A terminal's seaside operations begin or end at the approach channel, which is designed according to the guidelines of the World Association for Waterborne Transport Infrastructure (PIANC). These guidelines take into account both vertical dimensions, such as depth and draught, and horizontal dimensions, including width. Other critical factors include clearance under the keel and the use of ship manoeuvring simulation tools. In cases where terminals are accessed through locks or tide gates, these structures often set the size standards for ships and influence the design of the terminal. With the increase in global port activity, there has been a move towards standardisation of terminal designs, particularly in the container sector. This standardisation includes construction techniques and guidelines, promoting efficient and scalable designs (Notteboom et al., 2022).

The berth is where a container ship docks, and technical specifications such as length and draught are critical. These specifications have become increasingly challenging in recent decades as the size of container ships has increased. Table 2.1 outlines the different classes of container vessels and their specifications, showing the trend of increasing dimensions over time. The New Panamax class, designed to fit precisely into the locks of the expanded Panama Canal, is expected to set the standard for port infrastructure design for the foreseeable future (Rodrigue, 2020). New Panamax vessels can carry up to 12,500 twenty-foot equivalent units (TEUs), have a length overall (LOA) of 370 metres and a draught of 15.2 metres, requiring a pier length of at least 400 metres. The largest container ships, with an LOA of 415 metres, require a berth length of 450 metres (Notteboom et al., 2022).

The vessel arrival process typically begins with the submission of a nomination form containing specific details about the vessel and the assignment, such as the vessel's name, Estimated Time of Arrival (ETA), call sign, size, the product it is carrying and the quantity of the product. Once a nomination is accepted by the terminal, the vessel is assigned a time slot and berth for loading and/or unloading. The next step in vessel handling is the arrival or pilotage stage, during which the vessel approaches the terminal and is guided to its designated berth. This stage also includes the occupation of the target berth and the surrounding waters. (Brouns, 2015).

Class	TEU	LOA (m)	Beam (m)	Draft (m)
Early Containerships (1956-)	500-800	137	17	9
Fully Cellular (1970-)	1,000-2,500	215	20	10
Panamax (1980-)	3,000-3,400	250	32	12.5
Panamax Max (1985-)	3,400-4,500	290	32	12.5
Post Panamax I (1988-)	4,000-6,000	300	40	13
Post-Panamax II (2000-)	6,000-8,500	340	43	14.5
VLCS (2006-)	11,000-15,000	397	56	15.5
New-Panamax (2014-)	12,500	366	49	15.2
ULCS (2013-)	18,000-21,000	400	59	16
MGX-24 (2019-)	21,000-25,000	400	59	16

Table 2.1: Container vessel specifications [created by author, based on Rodrigue (2020)]

In addition to their dimensions, the design of quay walls is critical as they act as a soil retaining structure and provide mooring, load bearing and sometimes water retaining functions. Key considerations include minimising environmental impact, ensuring construction and operational safety, and adapting to local seabed conditions and materials (Notteboom et al., 2022).

The quayside apron facilitates the movement of containers between ships and storage areas, primarily using straddle carriers or holsters. Straddle carriers are preferred because they can move containers directly between the quayside and storage stacks. Container cranes are usually located on the quayside and the apron serves as the area directly below these cranes for loading and unloading operations. The efficiency of a container crane is determined by factors such as lifting capacity, weight handling and lateral coverage. Modern container cranes can cover 18 to 24 containers wide, which indicates their ability to serve ships of corresponding width. A gantry crane can perform approximately one movement (loading or unloading) every two minutes (Notteboom et al., 2022). In addition, the dimensions of quay cranes and horizontal transport equipment between the quay wall and the yard are crucial for efficient operations. Strategic planning is required to specify the equipment needed to meet operational requirements and to determine the quantity required for effective container throughput (Böse, 2011).

2.1.2. Yard operations

Container storage within the yard acts as a temporary holding area for containers awaiting loading onto ships or distribution inland (Notteboom et al., 2022). Yard infrastructure planning begins with the calculation of yard slots, taking into account factors such as annual quay wall throughput, container dwell times and maximum allowable yard utilisation. This calculation is essential for optimising yard space and operational efficiency (Böse, 2011). The size of the yard also depends on the size of container vessels served by the port and can be divided into export and import stacks, with stacking density varying according to equipment and yard configuration (Notteboom et al., 2022).

Yard layouts in container terminals can be either linear or block configurations. Linear layouts, often found in rail terminals, involve containers stored on chassis or in linear stacks, allowing straddle carriers to circulate. These configurations typically store containers one or two high, which is common for average density yards that can store around 700 TEUs per hectare. Alternatively, some terminals opt for a vertical block layout where road trucks and transporters interact with yard cranes at each end of the block. This layout simplifies traffic control and is favoured by automated container terminals for its efficiency (Lee & Kim, 2012). Block layouts served by gantry cranes allow higher stacking densities but require effective yard management systems to minimise container re-handling (Notteboom et al., 2022).

Refrigerated (reefer) and empty container storage areas are essential components of yard operations in container terminals. These areas are specifically designed for reefer and empty containers, with customised stacking configurations to meet their specific needs (Notteboom et al., 2022). In addition, on-site facilities include administrative buildings for logistics operations, maintenance areas for heavy equipment, and container loading stations for consolidation and deconsolidation operations (Notteboom et al., 2022).

In container terminal yard operations, there is an increasing focus on adopting innovative layouts to improve efficiency, expand capacity and minimise environmental impact. Recent proposals have highlighted strategies such as vertical expansion and layout optimisation methodologies that integrate simulation and queuing networks to achieve these objectives (Gharehgozli et al., 2019).

2.1.3. Landside operations

In container terminal landside operations systems, creating effective connections to hinterland transport systems is critical to maintaining a seamless flow of cargo. Key planning components include the truck gate, railway station or barge terminal, which act as links between the terminal and various inland transport modes. Terminals without connections to inland container transport operate mainly as transhipment facilities (Böse, 2011).

For truck-based terminals, the gate serves as the main entry and exit point for terminal operations and can accommodate up to 25 trucks at a time in large terminal facilities. Modern gate operations integrate remote inspection systems to streamline processes and reduce paperwork through electronic documentation. Appointment systems prioritise the verification of truck driver, truck, container and chassis identities. Trucks are then allocated specific slots in the truck drop/pick up area for container delivery or collection. Containers are then transferred to or from the chassis using holsters, straddle carriers or gantry cranes, depending on the design of the terminal. Efficient management, often supported by scheduling systems, ensures prompt availability of containers for truck collection (Notteboom et al., 2022).

Many container terminals have adjacent rail terminals that are directly linked to allow efficient rail transport. On-dock or near-dock rail terminals facilitate the assembly of large container unit trains for long-distance inland markets. On-dock rail facilities offer the advantage of bypassing marine terminal gates for container clearance (Notteboom et al., 2022).

In addition to connecting to hinterland transport systems, landside functions include tasks such as empty container storage and internal container transport. The correct sizing of equipment for these tasks, both in terms of quality and quantity, is essential to maintaining efficient terminal operations (Böse, 2011).

2.2. Liquid bulk terminals

Liquid bulk terminals play a vital role in global supply chains, facilitating the movement of a wide range of commodities including oil, gas, chemicals, renewable energy and food products. With the increasing shift towards renewable and sustainable energy sources, these terminals are becoming even more critical for transporting the fuels of the future (Royal Haskoning DHV, 2024). Figure 2.3 shows a typical layout of a liquid bulk terminal.

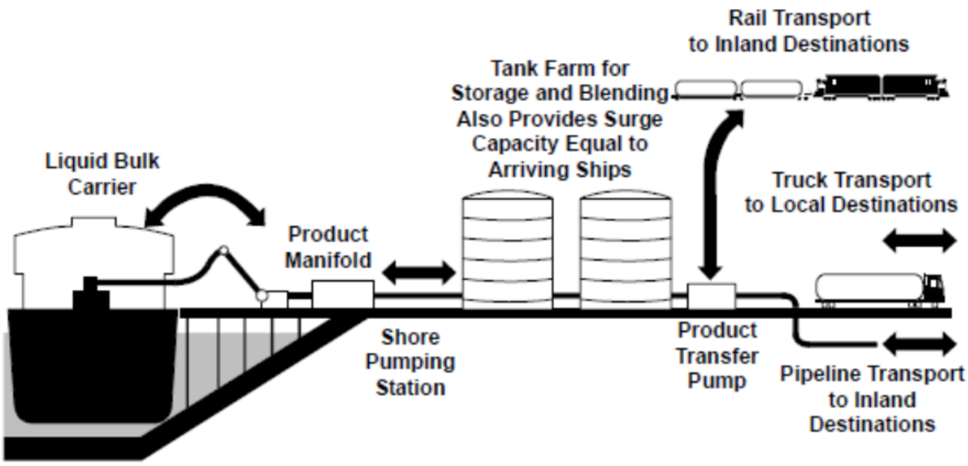

Figure 2.3: Liquid bulk terminal general layout (Madueke, 2013)

2.2.1. Seaside operations

Seaside operations at liquid bulk terminals involve various activities essential for the efficient handling of liquid and gaseous cargoes carried by various types of vessels, including oil tankers, chemical tankers, bulk carriers and gas carriers (Dohmen, 2016). Table 2.2 describes the different classes of liquid bulk carriers and their specifications. Unlike container terminals, the arrival rates of vessels at liquid bulk terminals are often unpredictable due to the nature of the oil trade and the close link between production scheduling of (chemical) processes in supply and demand. Furthermore, oil products are interchangeable. Seaside operations include the berthing of vessels and the provision of connections for cargo transfer. Gangway facilities facilitate the safe embarkation and disembarkation of personnel, while pump lines connected to vessels via jib cranes facilitate the transfer of cargo (Bogers, 2017).

Class	DWT	LOA (m)	Beam (m)	Draft (m)
Coastal tanker	< 50,000	205	29	16
Aframax	80,000	245	34	20
Suezmax	125,000-180,000	285	45	23
Very Large Crude Carrier (VLCC)	180,000-320,000	330	55	28
Ultra Large Crude Carrier (ULCC)	320,000-550,000	415	63	35

Table 2.2: Liquid bulk vessel specifications [created by author, based on Notteboom et al. (2022)]

Loading arms, hoses and pumps are essential equipment for liquid bulk terminals. Terminal pumps are typically used for loading operations, while ship pumps are used for unloading operations and booster pumps are used for long-distance cargo transfer operations (Dohmen, 2016). Loading hoses or arms are essential for transferring liquid bulk cargoes between ships and terminal facilities. Loading arms, consisting of movable tubes, are commonly installed on jetties or quay walls to facilitate transfer operations (Notteboom et al., 2022). Buoy moorings, including conventional buoys and single point moorings, provide offshore facilities for larger vessels when port depths are insufficient for jetty operations (Dohmen, 2016).

Operational parameters such as berth waiting and idle times are critical to ensuring fast loading and unloading operations. Contractual agreements between terminals and customers ensure compliance with minimum flow rates, pressure limits and viscosity requirements to maintain efficient pumping speeds during cargo transfer operations. These flow rates range from 500 m^3/hour for small bunker barges to 15,000 m^3/hour for large vessels such as VLCC or ULCC supertankers. If the predetermined flow rate cannot be achieved within the pressure limits, the product may need to be heated to reduce its viscosity. Modern liquid bulk terminals prioritise environmental sustainability by capturing and recovering hydrocarbon vapours or volatile organic compounds (VOCs) to reduce emissions. Vapour recovery systems are tailored to the product being handled, with sulphur components removed before entering the recovery system (Notteboom et al., 2022).

2.2.2. Yard operations

The yard operations of a liquid bulk terminal include several functions essential for the storage, handling and maintenance of liquid and gaseous products prior to import or export. Typically, the yard includes tank storage and technical facilities such as pumping stations. Many terminals are directly connected by pipelines to chemical or petrochemical production sites, which helps to ensure smooth transport (Notteboom et al., 2022).

Product storage in the yard involves dividing tanks into different groups based on specifications and dimensions to determine which products can be stored in each tank. These groups of tanks may be interconnected via coupling rooms, allowing connections to be made with sea-side, landside or other yard tanks. In addition, terminal operators may carry out service activities such as heating or blending on behalf of customers, particularly relevant in scenarios where biofuels are blended with petrodiesel (Bogers, 2017). Alternatively, storage restrictions may be imposed to prevent mixing or ensure safety, with each product typically stored in dedicated tanks to maintain quality and integrity. Unlike container terminals, where multiple cargoes can share the same space, liquid bulk terminals follow strict rules to comply with dangerous goods regulations. These safety and spill prevention measures have a significant impact on terminal operations and require thorough preparation (Dohmen, 2016).

Yard functions in a liquid bulk terminal also include volume measurement, sampling, pressure testing, tank cleaning and pipeline maintenance to ensure the integrity of the products (Bogers, 2017). Safety measures, including fire prevention, odour control, vapour treatment and equipment maintenance, are critical to minimising the risks associated with handling liquid bulk (Dohmen, 2016).

2.2.3. Landside operations

The landside operations of a liquid bulk terminal involve a variety of tasks focused on receiving and delivering products for distribution inland by truck and train (Bogers, 2017). Loading stations, whether for trains or lorries, require specific infrastructure tailored to the efficient handling of liquid bulk cargoes. Similar to container terminals, straddle carriers or Automated Guided Vehicles (AGVs) are commonly used to transport containers both on land and at the quayside, enabling continuous loading and unloading operations. However, unlike container terminals, the loading and unloading of liquid bulk cargo is a continuous operation, often requiring specialised equipment such as pipelines. In addition, the availability of equipment, including pipelines, may need to be flexible to accommodate multiple products (Dohmen, 2016).

The pipeline system plays a critical role in the transport of chemicals, where dedicated pipelines are essential for safe and efficient transport. While different oil products can often use the same pipelines, cleaning is required when switching between different products, highlighting the importance of cleaning activities in planning operations. Chemicals typically require dedicated pipework and tanks to prevent potentially dangerous reactions. Similarly, biofuels and vegetable oils require careful handling to prevent contamination, while LPG and LNG require insulated pipeline systems to maintain specific pressure and temperature conditions (Dohmen, 2016). In addition, landside functions include lorry filling and weighing stations, which are essential for both inbound and outbound transport operations (Bogers, 2017).

2.3. Dry bulk terminals

Dry bulk terminals play a crucial role in port operations, facilitating the movement of loose dry materials between suppliers and users in the global transport chain (Schott & Lodewijks, 2007). These terminals typically handle two main categories of dry bulk commodities: major bulk commodities, which include coal, iron ore, grain, bauxite/alumina and phosphate rock, and minor bulk commodities, such as fertilisers, agricultural products, cement, sand, petroleum coke and scrap metal. Major bulk commodities often have different grades and applications, leading to different trade patterns and terminal designs for export and import terminals. Dry bulk terminals typically handle products that benefit from economies of scale (Notteboom et al., 2022). Figure 2.4 illustrates a typical layout for both export and import dry bulk terminals.

Figure 2.4: Dry bulk export terminal (left) and import terminal (right) general layout (PIANC, 2019)

2.3.1. Seaside operations

Dry bulk terminals can accommodate a variety of vessel types, from large bulk carriers such as Cape-size and Panamax vessels for large bulks to smaller and more versatile vessels such as Handymax vessels for small bulks (Notteboom et al., 2022). Table 2.3 describes the different classes of dry bulk carriers and their specifications. Each class is designed to accommodate different cargo volumes and trade routes (Kleinheerenbrink, 2012).

Class	DWT	LOA (m)	Beam (m)	Draft (m)
Small Handy-sized	15,000-25,000	160	24	9
Handy-sized	25,000-50,000	186	28	11
Handymax	35,000-50,000	194	29	11
Supramax	50,000-60,000	214	32	12
Panamax	70,000	224	32	12
Post-Panamax	98,000	236	38	15
Aframax	80,000-125,000	258	39	15
Cape-Sized	100,000-180,000	284	43	17
Suezmax	125,000-200,000	295	45	18
Very Large Bulk Carrier	180,000	305	47	18
New Panamax	186,000	300	48	15
Wozmax	250,000	335	53	21
Chinamax	380,000-400,000	372	62	24

Table 2.3: Dry bulk vessel specifications [created by author, based on PIANC (2019)]

Export terminals focusing on coal and iron ore typically use stacker reclaimers alongside ship loaders to move cargo between the yard and bulk carriers (Notteboom et al., 2022). For import terminals, bulk carriers are unloaded using grabs or continuous ship unloaders and the material is then moved to a stockyard using belt conveyors and stackers (Schott & Lodewijks, 2007). The choice of crane type and grab depends on operational requirements, such as the size of the vessels and how efficiently the cargo can be handled. Loading and unloading operations for smaller materials often involve a variety of equipment, such as gantry cranes, jib cranes, mobile cranes, floating cranes and loader/unloader systems, together with conveyor and elevator systems where necessary (Notteboom et al., 2022).

The capacity of a dry bulk terminal depends on factors such as the length of the quay and the amount of cargo it can handle. The quay length factor indicates the amount of cargo that can pass through in kilotons per metre of quay per year and helps to determine how long the quay should be when planning the terminal. Another factor in seaside operations is the (un)loading capacity, which is measured in kilotons per hour. However, research shows differences between the guidelines found in the literature and the actual characteristics of terminals, highlighting the importance of using data-driven approaches to design and control terminal operations (van Vianen et al., 2011).

2.3.2. Yard operations

The yard operations of a dry bulk terminal include several functions and facilities to effectively oversee the storage, handling and distribution of bulk commodities. A critical component of this system is the storage yard, which acts as a buffer between fluctuating demand and supply, ensuring smooth operations by separating the inbound and outbound sides of the terminal (Schott & Lodewijks, 2007). Storage capacity and throughput are influenced by factors such as differences in bulk density between commodities. In general, import terminals have greater storage capacity and throughput than export terminals, mainly due to their location and operational requirements (van Vianen et al., 2011).

Export terminals typically handle a limited range of material types, often located close to mining sites or owned by trading or mining companies, and occasionally require significant unsold stocks to regulate commodity trading prices. In contrast, import terminals handle various types and grades of major bulk materials, requiring sufficient terminal space to handle dispersed stockpiles and meet certification standards. These terminals may provide additional services such as washing, screening, blending and compacting to improve product quality and meet customer requirements. They also invest in technology to reduce environmental impacts such as energy consumption, noise and dust emissions (Notteboom et al., 2022).

Minor bulk storage facilities, whether open or covered, are often divided into separate bays to store different products or grades (Notteboom et al., 2022). The choice between open and closed storage systems depends on product requirements and environmental considerations, with increasing influence on terminal layout and material handling principles (Schott & Lodewijks, 2007).

Stockpiles at dry bulk terminals are handled using forklifts for loading and reclaimers for retrieval. Import terminals typically have twice the stacking and reclaiming capacity of export terminals, allowing them to handle the same throughput efficiently (van Vianen et al., 2011). Dust control is an important consideration at dry bulk terminals, requiring the implementation of measures such as dust covers, misting systems, sprinklers and optimised stockpile designs to reduce emissions and minimise environmental impact (Notteboom et al., 2022).

2.3.3. Landside operations

The landside operations of a dry bulk terminal include several processes and infrastructure designed to facilitate the smooth movement of bulk commodities to and from the terminal. Export terminals are typically closely linked to the hinterland transport system, with rail transport often being used to connect the extraction areas to the terminal. The location of export terminals is often determined by a balance between hinterland and sea access, with the aim of optimising transport efficiency and accessibility (Notteboom et al., 2022).

Import terminals rely heavily on rail and inland waterway transport to connect to the hinterland where possible. Coordination of services is essential to effectively accommodate both water and land modes and to ensure the smooth transfer of goods from ocean-going vessels to inland distribution networks (Notteboom et al., 2022).

To facilitate the movement of bulk products within the terminal, forklifts and reclaimers are used to move materials from the yard to loading stations for various modes of transport (Notteboom et al., 2022). In export terminals, wagons are unloaded using tippers or self-unloading wagons and the material is then transferred to bunkers before being moved to the storage yard using vibratory or apron feeders (Schott & Lodewijks, 2007). The (un)loading capacities, measured in kilotons per hour, are essential for optimising terminal operations and throughput in dry bulk terminals (van Vianen et al., 2011).

2.4. Offshore wind energy terminals

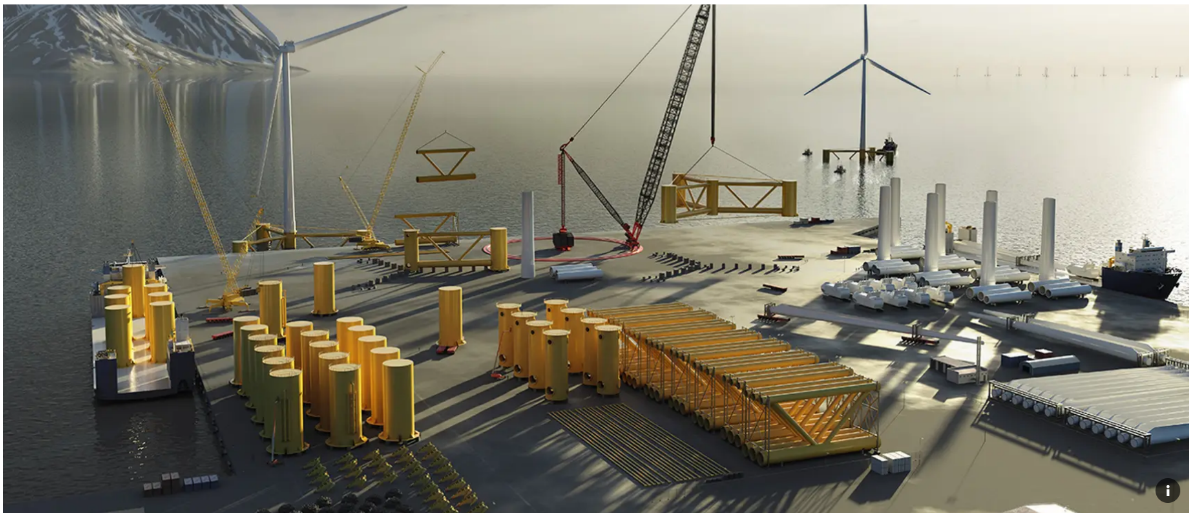

Figure 2.5: Offshore wind energy terminal layout (Business Norway, 2024)

As key energy hubs, ports not only facilitate the import and export of traditional energy products such as LNG, coal and oil, but also play a key role in the transport networks for sustainable energy sources such as hydrogen. Hydrogen is essential for decarbonising maritime transport and linking continental energy networks with offshore energy production facilities (Saborit et al., 2023). Ports are therefore essential components in the global energy transition, particularly with the expansion of offshore wind energy initiatives.

Ports perform various functions related to offshore wind energy, including construction, operation, maintenance and energy integration (Lammers et al., 2023). In the dynamic landscape of offshore wind projects, ports are key to reducing costs and increasing efficiency. By accommodating larger components, vessels and increased activity, they provide comprehensive support throughout the lifecycle of offshore wind assets (WindEurope, 2017). Figure 2.6 summarises how seaports can contribute to the offshore wind energy production process by defining seven port types with associated activities (Junqueira et al., 2020).

Port Type	Activity
Port of imports/exports	Reception of components from manufacturers on the ground, which are handled and stored for later loading on ships, which will transport them to ports intended for manufacture and assembly.
Port of manufacture	Manufacture of equipment such as turbines, foundations, and offshore wind cables.
Mounting port	Pre-assembly of the components (turbines and foundation units) received from the factories.
Port of mobilization	Loading of turbines components and foundation units already pre-assembled, in vessels, to the offshore wind farm where they will later be installed.
Offshore port	Multipurpose offshore terminals that enable a reduction in installation and transportation costs, as well as a decrease in response time for the maintenance of wind farms.
Operation and maintenance port	Provide the offshore wind farm with support services for operation and maintenance. These ports must be located at a relatively short distance from the park to reduce travel time for employees, minimize the use of parts, and optimize working times on site.
Research ports	Areas for offshore prototypes, test turbines, training, and instruction facilities.

Figure 2.6: Offshore wind energy port types (Junqueira et al., 2020)

2.4.1. Seaside operations

The seaside operations system of an offshore wind energy terminal includes various activities and infrastructure critical to the efficient handling and transportation of wind turbine components. Different types of vessels are used for construction, maintenance and operations, including floating crane and jack-up vessels, as shown in Figure 2.7. Factors such as port depth, quay length, deadweight and seabed suitability are essential to accommodate large vessels with deep drafts and to ensure the stability and functionality of jack-up vessels during loading and unloading (Akbari et al., 2017). In addition, outbound logistics require consideration of overhead and horizontal clearances to ensure the safe passage of vessels carrying turbine components from port to open sea (Guillen et al., 2011).

VESSEL	VESSEL SIZE	GROSS TONNAGE	LIFT CAPACITY/ HEIGHT
Floating Crane Vessels			
Smit Land LM Balder	110m 30m 7.6m	7772t	500t / 60m
Smit Tak Taklift 4	83m 35m 7.0m	4854t	2400t / 75m
Smit Tak Taklift 7	73m 30m 5.5m	3513t	1200t / 65m
Bugsier Thor	76m 24m 4.7m	2667t	350t / 80m
Uglarid Uglen	78m 26m 4.3m	1589t	600t / 75m
Jackup Vessels with integral crane			
Ballast Nedam Buzzard	43m 3Dm 4.2m	1750t	198t / 62m
Interbeton 1B909	43m 3Dm 4.4rn	1796t	272t / 57m
Amec Wyslift	38m 32m 4.4m	1410t	280t / 50m
Seacore Deep Diver	3Dm 2Dm 4.5m	1675t	50t / 51m

Figure 2.7: Offshore wind energy vessel specifications (Guillen et al., 2011)

Staging areas are often strategically located in front of berths to streamline the loading and unloading of components, allowing for uninterrupted assembly and shipping operations. In particular, components such as rotor hubs, blades, foundations, tower sections and substations are assembled close to the dock area due to their size and weight. In such cases, seaport operations have to meet additional requirements in terms of berths, crane lifting capacities and transport lanes to accommodate various logistics (Guillen et al., 2011).

2.4.2. Yard operations

The yard operations system of an offshore wind energy terminal includes several functions that are critical for the efficient management of components, in addition to the functions of a heavy lift terminal. A key aspect is to ensure sufficient storage space. This should be strategically located close to the pier front to reduce transport distances and allow for smooth pre-assembly or loading operations. Criteria for the availability of storage space include open and covered storage areas, as well as the load capacity of the storage facilities (Akbari et al., 2017).

In addition, the presence of a component manufacturing facility is critical, particularly for installation ports. Locating turbine manufacturing facilities at these ports can reduce transportation costs and streamline logistics by allowing components to be shipped directly from the manufacturing facility to the port (Akbari et al., 2017).

A dedicated workshop area is also essential for O&M (operations and maintenance) ports. It facilitates the efficient repair of broken or faulty components, ensuring the uninterrupted operation of the wind farm (Akbari et al., 2017). The yard operations system can also provide storage for support infrastructure, including storage trucks, cranes and welding equipment. Particularly for O&M ports, office space is required for project developers, contractors and manufacturers to effectively coordinate and monitor port activities (Guillen et al., 2011).

2.4.3. Landside operations

The landside operations system of an offshore wind energy terminal includes several critical functions to facilitate the efficient transport and handling of large wind turbine components and equipment. A key consideration is the distance to key component suppliers. Large offshore wind components, such as turbine blades and towers, must be transported from their manufacturing facilities to the installation ports. However, certain types of offshore wind foundations are preferentially manufactured in the ports themselves. The proximity of the terminal to these manufacturers and suppliers is crucial in determining transport costs and logistical efficiency (Akbari et al., 2017).

In addition, road access to the terminal is critical for transporting turbine components from the manufacturing sites to the port facilities. trucks, self-propelled modular transporters (SPMTs) and flatbed trailers are commonly used to transport components such as blades. To meet certain specifications, the lane width on straight roads must typically be around 5.5 metres. Adequate horizontal clearance around access and site roads is also essential, particularly when using heavy equipment such as crawler cranes, which can require a clearance of up to 11 metres (Akbari et al., 2017).

2.5. Stakeholders

The success of a port (terminal) depends not only on its physical layout and performance indicators, but also on its ability to integrate the objectives of various stakeholders into the port's objectives. The concept of stakeholders is crucial in port management and refers to individuals or groups that have an interest in or are affected by the port's operations. Ports act as economic and technological hubs where stakeholders with different interests work together to create wealth. Therefore, effective stakeholder engagement is essential for value creation in ports (Henesey, 2006). Based on a broad perspective and a Landlord Port model, Notteboom and Winkelmans (2002) have defined four main stakeholder groups in a port community, which will be discussed in this section: internal stakeholders, external stakeholders, regulatory and public policy stakeholders, and community stakeholders. Globally, the Landlord Port model is the dominant governance model for larger and medium-sized ports. The notable advantage of the model is that it clearly distinguishes between the port authority and the service providers, thereby promoting a competitive environment between the different service providers within the port (van Reeven, 2010). Figure 2.8 illustrates the power and interests of the different stakeholders (groups) to be discussed.

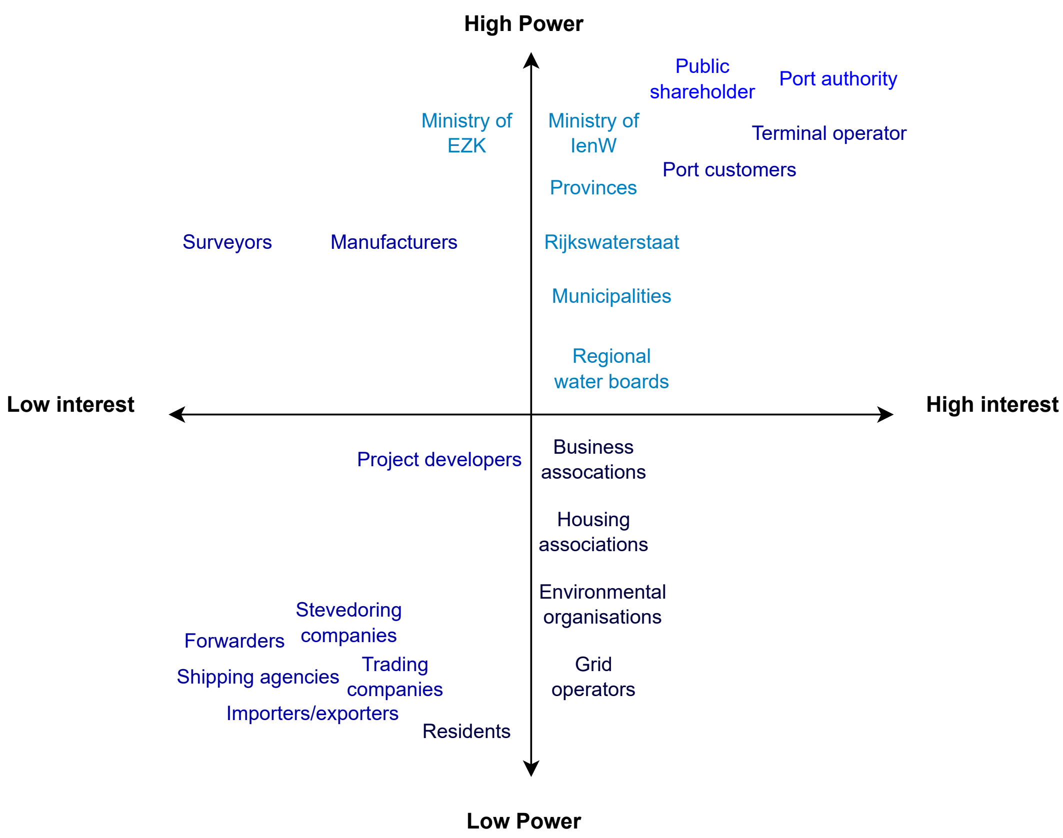

Figure 2.8: Power/interest grid port functions [created by author]

2.5.1. Internal stakeholders

Internal stakeholders include parties within the organisational boundaries of the port authority, such as managers, employees, board members, shareholders and trade unions (Notteboom & Winkelmans, 2002). Dutch seaports have historically been governed by regional or municipal public organisations, with relatively limited national involvement (de Langen & van der Lugt, 2006). The larger port authorities in the Netherlands operate as independent government-owned companies, such as Groningen Seaports. The public company consists of a general meeting of shareholders, a supervisory board and a management board. In this case, the shareholders include both regional (Province of Groningen) and local (Municipality of Eemsdelta and Municipality of Het Hogeland) levels of government (Groningen Seaports, 2024). The Port of Rotterdam is the only port authority that is partly owned by the Dutch national government (Port of Rotterdam, 2024).

The port authority enforces the operation of port systems within the port area (Ha et al., 2019). In addition to its role as landlord, the port authority typically acts as regulator and operator of the port. In the landlord role, the port authority oversees the management of the port facilities under its control, typically including the maintenance of structures such as jetties and the dredging of navigation channels. As a regulator, it sets charges, supervises subcontracted services and implements safety measures. It also enforces both national laws and port-specific regulations. As an operator, the port authority provides essential day-to-day services to ships, such as navigational assistance and tugboat services (Notteboom et al., 2022).

2.5.2. External stakeholders

The external stakeholder group included parties that invest directly and indirectly in the port area. Directly investing parties are terminal operators, stevedoring companies, freight forwarders, shipping agencies. In addition, industrial companies in the area and supporting industries such as ship repairers and port labour pools usually invest directly. Parties investing indirectly in the port area include port customers, trading companies and importers/exporters (Notteboom & Winkelmans, 2002).

Of the identified stakeholders, terminal operators and port customers are considered to have the greatest influence on the functions of port terminals. Terminal operators are granted the authority to operate and provide services to port users within the port area under either a concession or lease agreement (Ha et al., 2019). Port customers are not only purchasers of port services but also influence the provision of these services in the supply chain involved (Ha et al., 2019). For liquid bulk terminals, a surveyor is typically involved as an external stakeholder, hired independently by the customer or terminal to verify on their behalf that the product quality is as expected (Brouns, 2015). In addition, the offshore wind energy sector includes several external stakeholders, including project developers, original equipment manufacturers and service providers serving the offshore wind sector (Elkinton et al., 2014).

2.5.3. Legislation and public policy stakeholders

The legislation and public policy stakeholder group includes government departments responsible for transport and economic affairs, environmental departments and spatial planning authorities (Notteboom & Winkelmans, 2002). While the Dutch government plays a relatively minor role in the management of seaports, it funds significant infrastructure and expansion efforts. The national investment policy requires that the benefits of any investment outweigh its costs, which requires a socio-economic impact study approved by the national authorities. This assessment prioritises the benefits to Dutch consumers and businesses (de Langen & van der Lugt, 2006). However, this only applies to the five ports of national importance prioritised by the Ministry of Economic Affairs: Rotterdam, Moerdijk, Amsterdam/NZKG, Groningen and North Sea Port. Their position is based on the storage and transhipment of goods in the ports and their contribution to the national economy and employment. By recognising their importance, the ministry also wants to consider these ports as an integrated system in order to increase their economic value for the Netherlands in the future (Ministerie van Infrstructuur en Waterstaat, 2020).

As discussed in Section 1.1, the NOVEX programme involves all levels of government working together on spatial planning in the Netherlands. The twelve provinces work together with Rijkswaterstaat

(RWS), the regional water boards and municipalities to spatially translate, combine and integrate the national tasks and objectives into the provincial plans (De Nationale Omgevingsvisie, 2023). In their role within NOVEX, these parties are clearly part of the legislative and public policy stakeholder group. Finally, the Ministry of Economic Affairs and Climate (EZK) is involved in all functions of a port terminal through its main objective of partnering towards a climate-neutral society and a strong, open economy (Rijksoverheid, 2024b). EZK is the initiator of several NOVEX areas (De Nationale Omgevingsvisie, 2023) and is the public director of a mega-project to store CO2 in the North Sea via pipelines under the port of Rotterdam (Ministerie van Infrstructuur en Waterstaat, 2020).

2.5.4. Community stakeholders

Finally, the community stakeholder group includes civil society organisations, the general public and other non-market actors (Notteboom & Winkelmans, 2002). As port (terminal) activities are associated with congestion and environmental externalities, public relations initiatives are needed. By mitigating its negative externalities and promoting the specific interests of community members, the port can expand its social capital (Notteboom et al., 2022). Social capital highlights the importance of the state of social relationships and factors such as cooperation, trust, commitment and leadership (Richmond & Casali, 2022). Based on the NOVEX programme, the following main community stakeholders for port functions in the Netherlands are identified: business associations, housing associations, grid operators, environmental organisations and residents.

2.6. Conclusion

This chapter provides an in-depth examination of the different types of terminals within ports, including container terminals, liquid bulk terminals, dry bulk terminals and offshore wind energy terminals. Each type of terminal is analysed in detail across three operational domains: seaside operations, yard operations and landside operations. The analysis shows that while the core functions of storage, transport, handling and value-added logistics are common to all terminals, the specific operations and equipment used are highly specialised and tailored to the type of cargo handled. Container terminals, characterised by specialised facilities for transhipment, handling and storage, rely heavily on quays, yards, cranes and (automated) equipment for efficient operation. Liquid bulk terminals, essential for handling liquid and gaseous cargoes, emphasise the importance of berthing facilities, loading arms, hoses and pumps, as well as strict safety measures for hazardous materials. Dry bulk terminals focus on the handling of bulk materials, requiring specific infrastructure such as stackers and reclaimers for loading and unloading, and the implementation of dust control measures to minimise environmental impact. Offshore wind energy terminals are key hubs for the import, production or storage of sustainable fuels. These terminals require facilities for the assembly and shipment of large components, with a focus on storage space, a high-capacity quay, component manufacturing facilities and repair workshops.

The chapter also highlights the critical role of strategic stakeholder management in port operations. Stakeholders are categorised as internal, external, legislation and public policy, and community groups, each with different interests and impacts on port operations. The port authority emerges as a key internal stakeholder, assuming multiple roles including landlord, regulator and operator to ensure the smooth functioning of port activities. External stakeholders such as terminal operators, port customers and service providers have a direct impact on the operational efficiency of terminals. Legislative and public policy stakeholders, including government ministries and local authorities, set the overall framework within which ports operate, with a focus on safety, environmental protection and economic competitiveness. Community stakeholders, including local residents and environmental organisations, play a key role in ensuring that port operations are in line with societal values and sustainability goals.

3
Water storage functions

Water storage, is defined as the temporary collection of (rain)water in natural and artificial landscapes such as soil, ditches, streams, rivers, lakes, ponds and designated water storage areas (Rijksoverheid, 2024a). As stated in the research scope (see Section 1.3), this study will focus on water storage functions, prioritising water retention over drainage, with a specific focus on the unique water management environment of the Netherlands. For this purpose, four main functions of water storage can be defined: stock storage, seasonal storage, peak storage and emergency storage. These functional categories and their implications are presented in Table 3.1. This chapter examines the strategies associated with these main functions and discusses their relevance to water management systems and storage design models. It will also explore the potential for implementing water storage functions in different landscape types in the Netherlands.

water storage function	**solution for...**	**strategy**	**occurrence**	
			frequency (number/year)	**duration**
Stock storage	water shortage	the local retention of precipitation, in particular summer showers, in order to postpone the inflow of (area-foreign) water for as long as possible	many times a year	several days to weeks
Seasonal storage	water shortage	storing water surpluses in the winter aimed at reducing water shortages for agriculture and nature reserves in the summer	annual cycle	many months
Peak storage	flooding	the temporary storage of water aimed at preventing flooding elsewhere	annually - 1:100	a few days
Emergency storage	flooding	the temporary storage of water aimed at preventing calamities/disasters	1:100 - 1:10,000	several days to weeks

Table 3.1: Water storage main functions [(Habiforum, 2002) adapted by author]

3.1. Stock storage

Stock storage involves the retention of water for strategic use (Massop et al., 2015) and serves as a proactive measure against water shortages by locally capturing precipitation, especially from summer showers. The aim is to postpone dependence on external water sources by extending local water availability by several days to weeks, as required several times a year (Habiforum, 2002).

3.1.1. Water management systems

Stock storage is primarily about storing water within the local water management system, focusing on capturing and storing rainwater where it falls. This strategy is essential to meet the challenges of spatial pressure and increasing urbanisation. In urban areas, intensified land use and increased impervious surfaces lead to rapid runoff, preventing rainwater from naturally infiltrating into the ground. Various measures can be taken to counteract these effects and increase water storage capacity. These include increasing the absorption capacity of the soil by reducing surface cover, using rain barrels or local water basins, installing green roofs, creating additional space in the system's capillaries such as ditches and constructing tree pits (Werkgroep Water NOVEX NZKG, 2023). Water storage in the local system also includes initiatives to encourage residents to green their gardens. Some Dutch municipalities are considering introducing a 'garden tile tax' to make paved gardens less financially attractive (Rijksoverheid, 2024a).

3.1.2. Storage design models

Widened watercourses

The 'widened watercourses' design model plays a crucial role in both the stock storage and peak storage functions. The latter is discussed in Section 3.3. By widening watercourses and providing terraced or gradually sloping banks, a significant increase in water storage capacity is achieved. Water level fluctuations are typically between 0.5 and 1 metre (Habiforum, 2002).

Furthermore, this model positively impacts various soil-related issues such as drought and waterlogging, affecting the soil's bearing capacity and thereby its usability for other activities. Additionally, the model supports biodiversity by more closely mimicking natural conditions and contributes to the development of nature-friendly shores (RIVM, 2011). This storage design model can be applied to various landscape types, including both peatland and clay polders. Especially in clay polders, widened watercourses contribute significantly to stock storage and peak storage functions (Habiforum, 2002).

Flexible water level management

Allowing groundwater levels to fluctuate can increase the storage capacity of the soil during heavy rainfall. This makes 'Flexible water level management' a cost-effective model for addressing unnatural groundwater system configurations in both rural and urban areas. Flexible groundwater levels are often linked to flexible surface water levels (RIVM, 2011). Most water systems operate with fixed water levels for the summer and winter periods. This system can be moved to a flexible water level management system where water levels can vary within a range. Flexible surface water level management is an important strategy for dealing with water shortages and surpluses throughout the year (Gemeente Haarlemmermeer & Hoogheemraadschap van Rijnland, 2015) and is therefore also applicable to seasonal storage and peak storage.

An innovative approach to flexible water level management is the enhanced reclamation system strategy, known in Dutch as 'verbeterd droogmakerijsysteem'. This strategy sets the upper limit of the flexible water levels uniformly for all controlled sections at the current summer level of the polder water system. By aligning the maximum water levels in all sections, the polder operates as a single system. Sections with limited water storage capacity can benefit from the storage capacity of other sections. This integration maximises the use of water storage capacity throughout the polder, resulting in a more resilient system. The enhanced reclamation system can be implemented in reclamation areas, new urban developments, and where feasible in existing urban areas (Gemeente Haarlemmermeer & Hoogheemraadschap van Rijnland, 2015).

New marshes

The 'New marshes' design model focuses on the creation of new marshes as an effective method of retaining local water, thereby directly supporting stock storage. Clean, local water is essential to this model as it promotes more natural groundwater fluctuations, increasing the overall water storage capacity of the area while maintaining the ecological integrity of the marshes. These marshes also provide additional capacity for peak water storage by capturing excess rainwater from the polder. In clay polders, where marsh vegetation thrives in nutrient-rich conditions, marshes can also manage peak flows from the (Habiforum, 2002) storage basin system. The storage basin system, known as 'boezem' in Dutch, regulates the water level in a polder. During wet periods, the storage basin system drains water from the polders, while during dry periods it supplies water to the polders if necessary (Waterschap Amstel Gooi en Vecht, 2024).

New marshes can provide a range of secondary spatial functions related to nature and nature-based recreation. In clay polders, they also offer potential for biomass harvesting, such as reeds and willows, for energy production, providing an innovative approach to combining ecological benefits with renewable energy sources. However, new marshes can also be created in areas where groundwater naturally comes to the surface. Deep reclaimed areas, dependent on their soil, can act as magnets for groundwater, making the creation of new marshes unviable (Habiforum, 2002). A reclamation area, known in Dutch as a 'droogmakerij', is a clay polder that was originally a lake, other large open water or wetland. A polder, in general, is an area surrounded by flood defences whose water level can be artificially regulated (Geographixs, 2024). New marshlands can also be created in peatland polders by strategically raising the water level to stop further subsidence and stimulate new peat growth (Habiforum, 2002).

Storage polder in urban edges

The design model of 'Storage polders in urban edges' focuses on the storage of urban water and emphasises the importance of maintaining water quality through the integration of a recirculating water system. By circulating the water through the storage polder, the water quality is further improved before it is released back into the urban waterways. This model includes various types of storage, including stock, seasonal and peak storage, with water level fluctuations of 0.5 to 0.8 metres, and is primarily used to manage urban water. It is particularly effective in storing peak water at the edge of the city, where the built environment does not have sufficient capacity to manage extreme rainfall internally (Habiforum, 2002).

In urban edge areas, there is significant potential to combine water storage with other spatial functions. For example, the development of floating homes. Energy production through biomass cultivation and cold and heat storage is also feasible with the presence of water bodies and proximity to potential consumers, including businesses and residential complexes. In addition, the circulation of water in wet peripheral zones can restore cultural-historical values and limit the urbanisation of rural areas by creating a natural barrier (Habiforum, 2002).

The implementation of storage polders in beach ridge landscapes is feasible, but presents challenges due to the permeability of the sandy soil (Habiforum, 2002). However, in low lying areas prone to rapid flooding, construction is generally less advisable due to the high risk of damage and casualties. Therefore, from a risk zoning perspective, reserving the lowest lying areas primarily for water storage appears to be a preferable future strategy (Pieterse et al., 2009).

Storage basin

The design of a storage basin, called a 'bergingsboezem' in Dutch, is a main model for seasonal water storage. However, it can also be used for stock and peak storage. This model primarily uses the grasslands along the dams and is designed to retain water specific to the area, operating independently of the main water storage basin system or 'boezem'. Its importance lies in its central role in seasonal storage, capturing rainwater and seepage to maintain optimum water levels in nearby polders during periods of drought. The design typically accommodates water level fluctuations of up to 1 metre (Habiforum, 2002). In addition, the capacity of a reservoir can be increased by incorporating a floodplain, known in Dutch as the 'uiterwaard', which is the area between a river, or in this context the storage basin system, and a dike that facilitates drainage when water levels are high (Rijkswaterstaat, 2024a).

The Storage design model also offers opportunities for multifunctional use. It paves the way for innovative living and business models in and around water, such as floating homes and greenhouses. Beyond practical applications, a storage basin can play a key role in the revival of water-related cultural and historical elements. In reclamation areas (clay polders) with a groundwater suction effect, the storage design model can mitigate this effect. Furthermore, this model can be adapted to the peatland polder landscape (Habiforum, 2002).

3.2. Seasonal storage

Seasonal storage stands out as a key strategy for managing water scarcity by bridging the gap between abundant water supplies in winter and the shortages experienced by agriculture, nature reserves and industry in summer. This method involves storing water for several months each year, making the most of natural variations in water availability (Habiforum, 2002)(Werkgroep Water NOVEX NZKG, 2023). It also plays a crucial role during dry periods in stabilising water levels to prevent damage to infrastructure and in cleaning the water system to reduce salinisation caused by brackish infiltration (Bremer et al., 2004). Seepage in this context refers to the process by which groundwater is forced to the surface under pressure (Waterschap Rivierenland, 2024). In order to distinguish water with different salinity, the categories fresh water (less than 150 mg chloride/l), brackish water (between 150 and 1000 mg chloride/l) and salt water (more than 1000 mg chloride/l) are traditionally used (TNO, 2024).

3.2.1. Water management systems

In water management practice, seasonal storage is mainly associated with the regional water system, which involves the dedication of large areas specifically for the temporary containment of regionally specific water. This strategy integrates the concept of water storage with different spatial functions, where the inundation depth is generally kept at a minimum level, except in cases of very deep polders (Werkgroep Water NOVEX NZKG, 2023). The term 'inundation depth' refers to the depth of water after deliberate flooding of a region (STOWA, 2017). The regional water system is managed by the regional water boards, a stakeholder that will be further elaborated in Section 3.5. Compared to peak storage, a topic to be addressed in Section 3.3, the implementation of seasonal storage within the regional system requires significantly larger areas of (Werkgroep Water NOVEX NZKG, 2023).

In addition, the interface between the regional and main water systems provides additional opportunities for seasonal storage. This intermediate zone can act as a water conservation reservoir. The aim of these storage areas is to alleviate the demands on the regional system without putting excessive pressure on the main system. The main system is managed by Rijkswaterstaat, a stakeholder that will also be discussed in more detail in Section 3.5. The water retained in these intermediate areas is predominantly fresh, in contrast to the more saline water of the primary system. These zones have potential for multifunctional spatial use, facilitating ecological conservation and recreational activities, and possibly even accommodating extensive agricultural operations (Werkgroep Water NOVEX NZKG, 2023).

3.2.2. Storage design models

New ponds

The 'New ponds' design with variable water levels provides another innovative method of seasonal water storage. The presence of a permanent body of water positions seasonal storage as a primary function, although peak storage remains a viable option. These ponds, which can accommodate water level fluctuations of 1 to 1.5 metres, are able to utilise water from both local sources and the wider (Habiforum, 2002) storage basin system.

The dual-use potential of these new ponds is significant, although influenced by factors such as water quality, allowable water level fluctuations and depth. Residential and recreational activities near water require clean water. Meanwhile, ponds created for sand extraction, with depths of 10 metres or more, are particularly suitable for thermal energy storage, benefiting local homes and businesses with heating or cooling needs. In addition, the extensive banks surrounding these ponds provide fertile ground for growing energy crops such as willow and reed, offering business potential for energy companies at the appropriate scale. However, the fluctuating water levels of these deep ponds require careful management to ensure compatibility with local geo-hydrological conditions, given their interaction with groundwater (Habiforum, 2002).

In clay polders where the clay layer is thin and the underlying sand is not too fine, the process of sand extraction can facilitate the formation of these ponds. In the context of beach ridge landscapes, the creation of new ponds can mitigate desiccation within dune valleys. In general, the high quality and increased volume of inflowing dune water makes this type of landscape particularly suitable for water storage (Habiforum, 2002).

Flexible water level management

The flexible water level management model, as discussed in Subsection 3.1.2 can also be applied for the seasonal storage function.

Storage polder in urban edges

The storage polder in urban edges design model, as discussed in Subsection 3.1.2, can also be applied for the seasonal storage function.

Storage basin

Finally, the storage basin model, as discussed in Subsection 3.1.2, can also be applied for the seasonal storage function.

3.3. Peak storage

Peak storage serves as a critical solution for flood control (Habiforum, 2002), involving the temporary storage of water to prevent flooding in other areas (Massop et al., 2015). This function of water management is aimed at accommodating excess water during periods of heavy rainfall or runoff, with the frequency of such peak storage events varying from once every one to one hundred years. The water is stored for a short period of time, typically a few days (Habiforum, 2002).

Peak storage is becoming increasingly important in the context of climate change, sea level rise, land subsidence and urbanisation, all of which contribute to the increased risk of high water levels in water bodies and the potential for flood-related disasters. Peak storage is often directly related to the pumping capacity of water bodies. When increasing pumping capacity through engineered solutions is no longer a viable option to address the above challenges, the creation of water storage sites for peak storage during extreme rainfall events becomes imperative (van Kruiningen et al., 2004).

3.3.1. Water management systems

Similar to the seasonal storage function, the peak storage function includes storage in the regional water management system and in the areas between the regional and main water management systems. The effects of water storage in these systems on water quality, quantity and spatial functions can be found in Subsection 3.2.1.

3.3.2. Storage design models

Inlet polder

The 'Inlet polder' design, also known as an overflow polder, plays an important role in the Dutch water management system. This design consists of a part of a larger agricultural polder, surrounded by dikes and adjacent to the storage basin system (boezem), which is specially designed for the temporary storage of excess water. It is mainly used for peak and emergency water storage and shows great promise for supporting dual use, especially in agriculture. Farmers are usually compensated for the temporary use of their land for water storage. This compensation helps to offset any potential loss in land value and repair any damage caused by the water after a peak storage event (Habiforum, 2002).

The amount of water these inlet polders can hold varies, with water levels potentially fluctuating between 1 and 2.5 metres. The frequency with which an inlet polder is used can range from once a year to once a century, or even less frequently in cases where it is intended for emergency storage. The water held in these polders is usually sourced from the storage basin system, which helps to ensure that the water quality is suitable throughout the storage period. The inflow polder model is particularly compatible with peatland polders and areas of deep reclamation (Habiforum, 2002).

Inner polder

Another strategic method of peak storage management is the 'Inner polder' design. In this approach, a section of a polder, surrounded by dikes and located at a lower elevation, is used specifically for the temporary storage of excess water from neighbouring polders. Acting as a buffer, the inner polder captures peak flows until conditions allow the water to be released back into the storage basin system (boezem) (Habiforum, 2002).

Fluctuations in water levels of 1 to 1.5 metres are expected, with the frequency of use varying from annually to once a century. The primary use of the inner polder is closely linked to agricultural practices, possibly including arable farming in the less frequent use scenario. This model of water storage is compatible with landscapes characterised by deep reclamation (clay polders) (Habiforum, 2002).

Widened watercourses

Widened watercourses as water storage design model can also be applied for the peak storage function, as discussed in Subsection 3.1.2.

Flexible water level management

The flexible water level management model, as discussed in Subsection 3.1.2 can also be applied for the peak storage function.

New marshes

The new marshes model, as discussed in Subsection 3.1.2 can also be applied for the peak storage function.

Storage polder in urban edges

The storage polder in urban edges design model, as discussed in Subsection 3.1.2, can also be applied for the peak storage function.

Storage basin

The storage basin model, as discussed in Subsection 3.1.2, can also be applied for the peak storage function.

New ponds

Finally, the new ponds design model, as discussed in Subsection 3.2.2, can also be applied for the peak storage function.

3.4. Emergency storage

Finally, emergency storage is identified as a critical water storage function to prevent flooding and avert catastrophes or disasters. This function involves the temporary storage of water to mitigate extreme and infrequent hydrological events that may occur once every 100 to 10,000 years. Emergency storage may also be required in urgent situations due to system failures or pumping problems. The duration for which water is held in emergency storage can vary from several days to weeks (Habiforum, 2002).

3.4.1. Water systems

Emergency storage in water management primarily involves the storage of water in and from the main system. Storage in the main system involves the adjustment of water levels in the main system to temporarily store water above normative levels. These adjustments have a significant impact on the surrounding environment, including potential obstructions to navigation, the need to close locks more frequently, and an increased risk of sewer overflows. As a result, drainage from these systems may need to be diverted, requiring increased discharge capacity from smaller canals and pumping stations. In addition, a higher water level in the main system requires adjustments to quays and building heights along the canal (Werkgroep Water NOVEX NZKG, 2023).

In addition to storage in the main system, neighbouring polders can be used as reservoirs to manage high water levels in the main system during extreme weather conditions with limited discharge options. However, the use of these polders, especially for emergency storage, often leads to disruption of inland use due to the brackish and polluted nature of the stored water, making regular agriculture impossible and posing a risk of further salinisation of adjacent areas (Werkgroep Water NOVEX NZKG, 2023).

3.4.2. Storage design models

Flexible water level management

The flexible water level management model, as discussed in Subsection 3.1.2 can also be applied for the emergency storage function.

Inlet polder

The inlet polder as water storage design model can also be applied for the emergency storage function, as discussed in Subsection 3.3.2.

3.5. Stakeholders

As with port functions, the success of a water storage model depends on its ability to integrate the objectives of different stakeholders. Similar to the stakeholder analysis for port terminal functions, this section defines and discusses the following four main stakeholder groups in relation to water storage: internal stakeholders, external stakeholders, regulatory and public policy stakeholders, and community stakeholders. Figure 3.1 illustrates the power and interests of the different stakeholders (groups) that will be discussed.

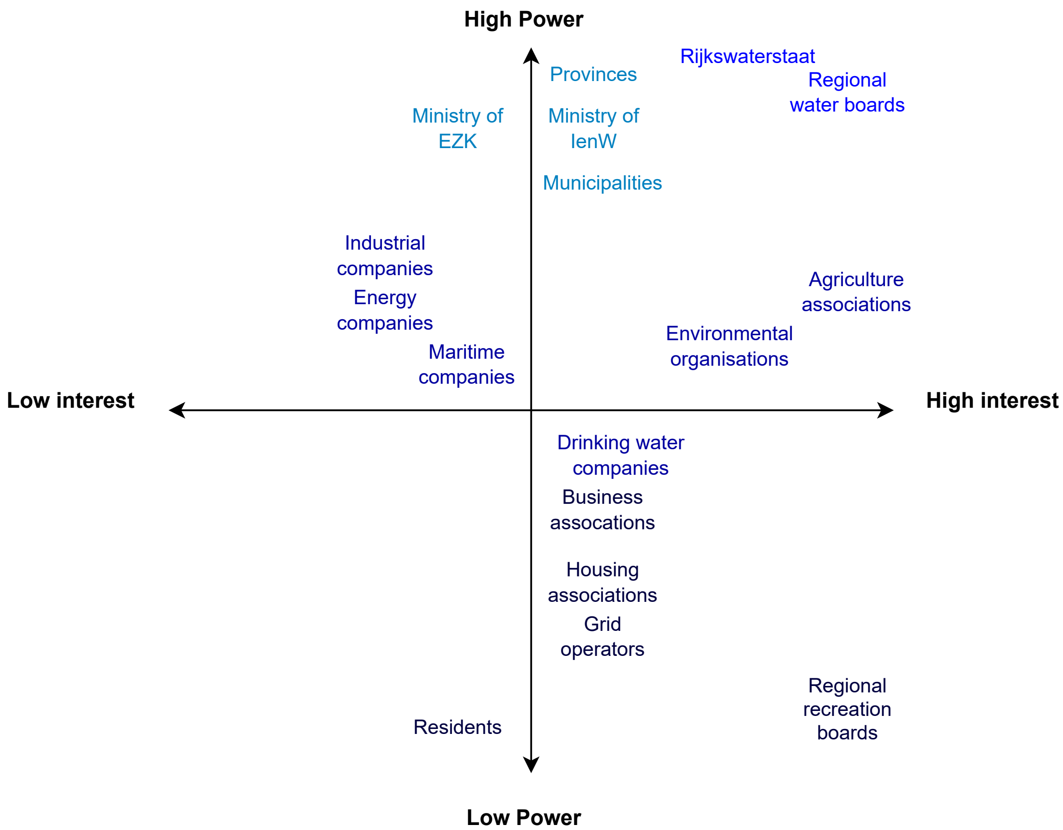

Figure 3.1: Power/interest grid water storage functions [created by author]

3.5.1. Internal stakeholders

In this case, internal stakeholders include parties within the organisational boundaries of the regional water boards. Together, Rijkswaterstaat (RWS) and the regional water boards are responsible for the day-to-day management of the water system in the Netherlands.

Rijkswaterstaat is the operational arm of the Dutch Ministry of IenW and plays a central role in the country's water management. As the custodian of all major rivers, lakes, the North Sea and the Wadden Sea, it manages the distribution of water from rainfall and rivers throughout the Netherlands to protect against flooding and ensure an adequate supply for nature, agriculture and shipping. RWS uses a variety of measures to deal with the constant threat of flooding, including continuous monitoring, issuing water level forecasts and maintaining defences such as dikes, dams and storm surge barriers. It also addresses the challenges of increasingly warmer and drier summers by optimising the distribution of scarce fresh water. A key task is also to maintain water quality, in cooperation with other Dutch and European water managers, to ensure that it meets the needs of agriculture, fisheries, industry and drinking water companies, while supporting natural habitats and recreational activities (Rijkswaterstaat, 2024c).

In the Netherlands, regional water boards, known in Dutch as 'Waterschappen' or 'Hoogheemraadschappen', are key actors in water management and are responsible for water control within specific regions (Rijksoverheid, 2024b). These authorities have three core tasks in the regional water system. Firstly, to ensure water safety by protecting the land from flooding by reinforcing dikes and creating space for rivers. Secondly, to maintain clean water in ditches, rivers, lakes and streams by cleaning wastewater and preventing pollution. Thirdly, to manage water levels to prevent both surpluses and shortages, which includes storing water during droughts and facilitating drainage during heavy rainfall (Unie van Waterschappen, 2024). The Netherlands is divided into 21 regional water management systems, whose water boards are shown in Figure 3.2.

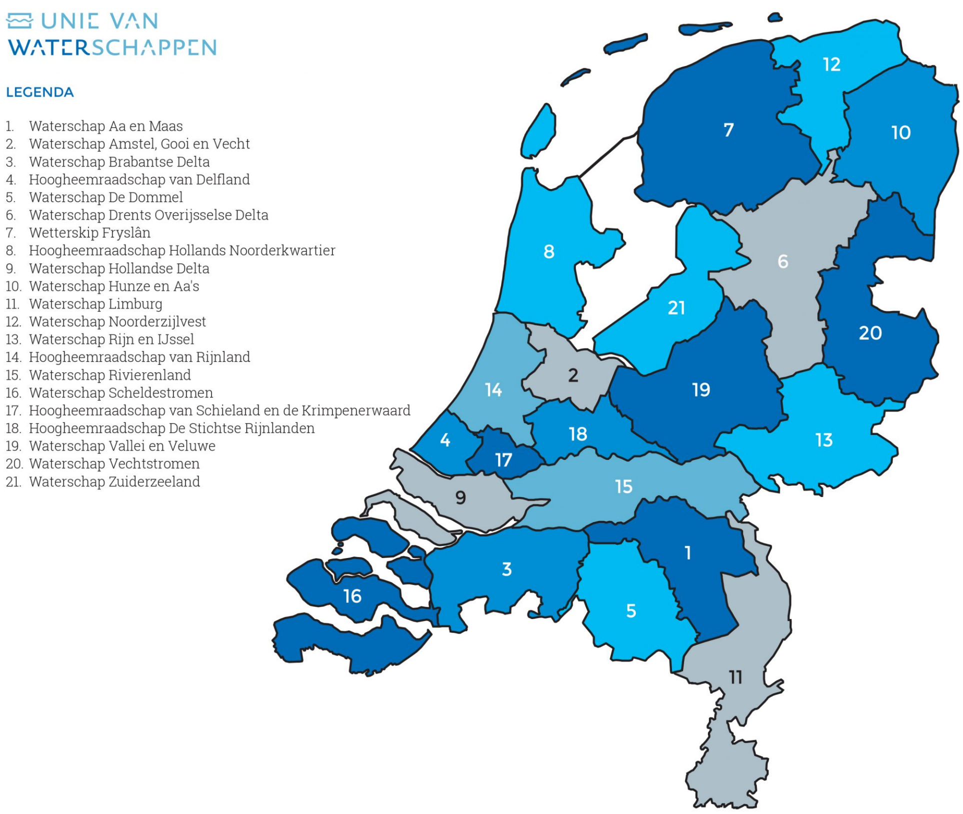

Figure 3.2: Regional water boards in the Netherlands (Unie van Waterschappen, 2024)

3.5.2. External stakeholders

In this case, the external stakeholder group includes parties that depend on the water management system for their daily operations. The stakeholders' interest in water management is related to flooding, salinisation or both. The western and northern regions of the Netherlands are particularly affected by salinisation, a process driven by the intrusion of seawater (external salinisation) and the emergence of saline groundwater (internal salinisation), which leads to the salinisation of surface water in predominantly low-lying areas. During dry periods, salinisation is exacerbated by the lack of freshwater supply, allowing saltwater to advance further inland, affecting various stakeholders (Rijkswaterstaat, 2024b).

Agriculture, as the world's largest consumer of water, is critically dependent on effective water management for optimal food production. Key factors in agricultural water management include water availability, sustainability, irrigation, drainage, nutrient runoff and soil properties. While water is essential for agricultural productivity, agricultural practices also have a significant impact on water balance and quality (Wageningen University & Research, 2024b). Depending on the sensitivity of the crop, certain chloride concentrations in groundwater can lead to crop damage. The adaptability to salinisation varies between agricultural sectors, with greenhouse horticulture showing high sensitivity but resilience through fresh water circulation. However, crops such as potatoes and maize, most open-air horticulture and tree and fruit crops find it difficult to adapt (H. de Boer and S. Radersma, 2011).

From a nature conservation perspective, salinisation presents both threats and opportunities. About 68% of the natural areas in the Dutch lowlands are potentially sensitive to salinisation, with 19% being highly sensitive. Salinity peaks can damage freshwater-dependent natural habitats, leading to the death of plant species in polders due to brackish inflow water. Salinisation affects both aquatic and terrestrial nature, with brackish water containing not only high chloride concentrations but also significant amounts of sulphate. On the other hand, managing salinisation by allowing sea level rise, restoring freshwater-saline transitions and allowing for natural water level fluctuations can create opportunities for the emergence of new brackish nature with species that have become rare due to the closure of sea arms. In addition, high chloride concentrations can slow down peat decomposition in low peat bogs, reducing the release of undesirable nutrients (M. Paulissen, 2008).

Drinking water companies are committed to developing investment plans to maintain and improve water infrastructure, including pipelines and treatment plants. These plans are essential to adapt to changes such as climate change and population growth, and to ensure the continued supply of drinking water, even in emergency situations such as floods (Rijksoverheid, 2024b). Elevated chloride levels not only affect the taste of drinking water, but also serve as an indicator of other salts that can adversely affect water quality. An increased salt content in tap water can lead to increased corrosion and wear of technical installations in homes and businesses. Similar effects occur in the technical installations of the industrial and energy sectors, which rely heavily on water for their operational processes and cooling systems (Informatiepunt Leefomgeving, 2024).

The relationship between water management and the shipping industry covers several key areas: water level management, discharges and the challenges of salinisation [Appendix B.1]. High water levels can damage infrastructure such as tunnels and bridges. Locks, which act as primary water barriers, have to be closed when external water levels are too high, potentially preventing ships from passing under bridges. The shipping industry is also affected by the dynamics of water discharge through pumping or draining ('spuien'), with draining in particular creating strong currents that are problematic for navigation. Restrictions on dewatering requested by the industry may be refused if pumping cannot compensate [Appendix B.7]. The introduction of saltwater into the main water system through locks (during ship passage) poses further challenges, especially during extreme droughts when insufficient freshwater inflow leads to increased salinity. This situation requires the restriction of lock operations [Appendix B.1].

3.5.3. Legislation and public policy stakeholders

As with port functions, the legislation and public policy stakeholder group includes government departments responsible for transport and economic affairs, environmental departments and spatial planning authorities (Notteboom & Winkelmans, 2002).

Provincial governments play a key role as spatial managers, evaluating and prioritising spatial interests within their jurisdiction. They face the challenge of managing land scarcity, which requires combining functions or making selective choices. Water storage is of paramount importance in this context, not only because of the significant space requirements, but also because of the limited choice of sites suitable for water storage [Appendix B.8]. When considering water storage in local water management systems, it is the responsibility of the municipality to safeguard general societal interests and oversee various spatial interests (Habiforum, 2002).

The designation of emergency storage areas goes beyond the sole responsibility of the regional water boards and extends to public order and safety concerns. Therefore, the task of designating emergency polders lies primarily with the municipalities within the regional water system, reflecting the broader governance and oversight required beyond the capacity of the water authorities alone (Habiforum, 2002).

At the national level, the Ministry of IenW, through its Directorate-General for Water and Soil (DGWB), formulates policies covering water security, climate adaptation, specific area water projects and soil management. In addition, the Ministry of EZK is involved in all aspects of water storage, in line with its overall objective of promoting a climate-neutral society (Rijksoverheid, 2024b), and its involvement in several NOVEX areas (De Nationale Omgevingsvisie, 2023).

3.5.4. Community stakeholders

Finally, as with port functions, the community stakeholder group includes civil society organisations, the general public and other non-market actors (Notteboom & Winkelmans, 2002). Based on the NOVEX programme, similar key community stakeholders are identified for water storage functions in the Netherlands: business associations, housing associations, grid operators and residents. In the Netherlands, there is a trend of increasing demand for fresh water due to increasing housing construction, the energy transition and the transition to a circular economy. Increasing amounts of water are also needed for humidification of peatlands to prevent subsidence and CO2 emissions. Finally, regional recreation boards should be highlighted as community stakeholders, as the spatial function of recreation can easily be combined with the water storage function [Appendix B.5][Appendix B.8][Appendix B.9].

3.6. Conclusion

In conclusion, it is important to recognise the multifaceted nature of water storage functions and their importance within the Dutch water management system, which is characterised by stock, seasonal, peak and emergency storage. These functions serve different needs, ranging from mitigating of water shortages to flood prevention, while their implementation is related to a variety of water management systems and storage design models, limited by the landscape type of the area.

Stock storage focusses primarily on the local retention of rainfall, using storage within local water management systems and design models such as widened watercourses and flexible water level management. Seasonal storage, aimed at bridging seasonal variations in water availability, uses the regional water system and design models such as storage basins and new ponds. Peak storage, essential for flood control, involves temporary storage solutions within regional and main water systems, including intake and inner polders. Emergency storage, designed to prevent disasters, uses main system adaptations and design models such as inlet polders for short-term, high-impact water storage. All models are strategically designed to maximise efficiency and effectiveness, taking into account regional characteristics, potential impacts on local ecosystems and the needs of surrounding communities. Some of the models have clear potential for multifunctional spatial use.

The stakeholder analysis reveals a complex network of internal and external parties, legislative and public policy stakeholders and community groups, each with a strong interest in water storage. The key roles of high power and high interest groups are highlighted, including RWS, regional water boards, provinces, IenW, municipalities, agricultural associations and environmental organisations. Their roles range from direct management and operational responsibilities to advisory, regulatory and community engagement functions. The involvement of these diverse groups underscores the need for collaborative approaches to water storage to ensure that solutions not only address technical and environmental challenges, but also align with broader societal goals and regulatory frameworks.

4
Dual-function solutions

The final step before developing the dual-function framework is to understand the practices of designing dual-function systems and explore potential solutions. This section integrates findings from different scientific studies to explore the application of dual-function research in the context of innovative water storage solutions combined with a port basin. Some dual-function studies (Patryniak et al., 2022)(Doufene et al., 2014)(Chetouani et al., 2023) have already been discussed in Section 1.5 and used to motivate the methods applied in this research.

A key concept in the design of dual-function systems is the notion of a system-of-systems, which refers to a composition of systems that maintain both operational and managerial independence. Operational independence ensures that each component, whether related to water storage or port operations, can fulfil its purpose independently. Managerial independence suggests that these systems can be managed independently, which is critical to the flexibility and adaptability of the overall framework (Maier, 1999). Although not every solution for integrating water storage with port functions, can be categorised as a system of systems, design principles derived from systems of systems studies are highly relevant to the dual-function. For example, the need for voluntary cooperation between different system components requires carefully designed mechanisms and incentives (Maier, 1999). This principle is essential to ensure that the various elements of the port basin and water storage systems work together harmoniously to support both port operations and water management. Interface design is another critical area of systems-of-systems architecture. The greatest challenges and opportunities lie at the interfaces between different systems (Maier, 1999). In the context of this research, this highlights the importance of designing interfaces between water storage areas and port terminals to ensure seamless integration and operation. The interfaces must be robust and efficient, facilitating the transfer and management of resources, information and operations between the two systems.

A perfect example of the development of a pre-design framework for a dual-function system is provided by a study on Climate Responsive Facades. Although focused on facades, the framework's performance-based approach can be adapted for another dual-function system. The steps outlined in the framework, from defining objectives and context to technology screening and conceptual design, provide a structured approach to designing systems that respond effectively to environmental, operational and management challenges. The study shows that the impact of these early stages on the ultimate performance and effectiveness of systems cannot be overstated (Soudian & Berardi, 2021). Understanding key design parameters and their impact on project objectives such as efficient water management, safe and effective port operations and cost savings is essential. In the context of spatial planning, Nationaal Onderzoekprogramma Kennis voor Klimaat (2011) has defined four dimensions of multifunctionality to guide the exploration of solutions:

1. Intensification of space use: elevation or more intensive use.
2. Interweaving of space use: combining functions that are not mutually exclusive.
3. Stacking/deepening: such as the concept of Water storage under sports fields.
4. Relations in time: different uses in seasons or over time.

4.1. Port lock system

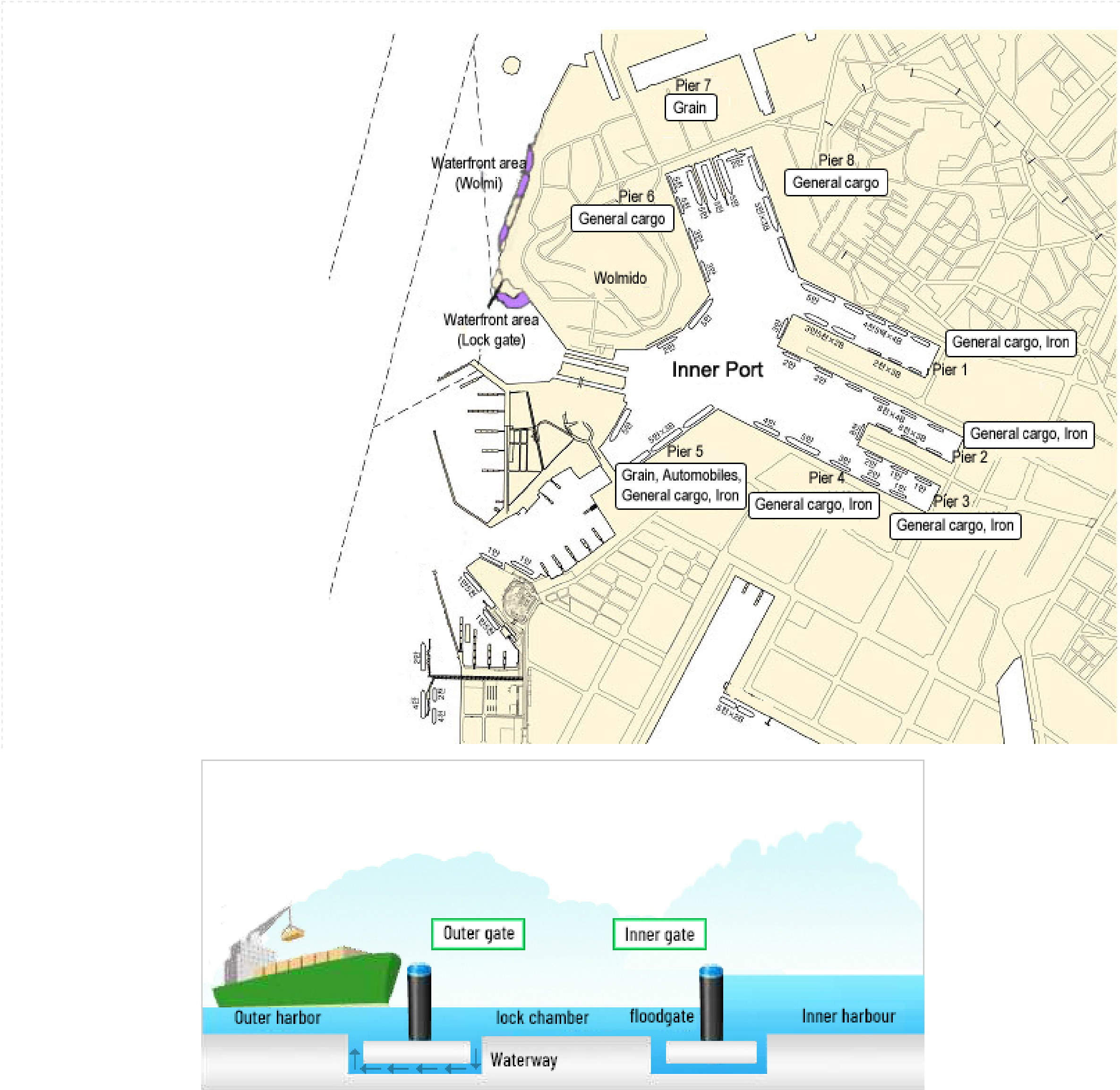

Figure 4.1: Port lock system Port of Incheon (Ministry of Oceans and Fisheries, 2024)

In the search for a comprehensive framework for the implementation of dual-function port terminal and water storage systems, the literature suggests that port lock systems could be a promising solution. Traditionally used to manage vessel traffic and water levels, these systems offer opportunities for innovative water storage. Figure 4.1 shows the port lock system in the South Korean port of Incheon, which, like Antwerp, has to cope with high tidal fluctuations.

High tides in ports present operational challenges, and locks are used to maintain water levels. However, the operation of these locks often leads to water loss in the port basin. To overcome this, the port basin can be filled naturally at high tide outside of the port. However, it is argued that this process leads to complex scheduling challenges. Optimising lock operations involves a number of stakeholders, including vessels, port authorities and environmental agencies. Each of these stakeholders brings different priorities and decision-making processes that affect the overall scheduling and operation of lock systems (Schindler et al., 2020). Therefore, creating a framework for the dual-function would require a holistic approach that integrates these different interests and ensures efficient and harmonious operation of the lock systems. An intelligent control framework for energy efficient water level management has been proposed, integrating data acquisition, machine learning for predictive modelling, and software agents for model and stakeholder integration (Schindler et al., 2020). Such a system could improve the efficiency of water storage and port operations, minimising energy consumption. However, the environmental impact of lock systems should not be neglected, particularly in terms of greenhouse gas emissions. Studies, such as those focussing on the Port of Incheon, show that lock-related activities, such as vessel transit and post-lock manoeuvring, are major contributors to CO2 emissions in ports (Y. Chang et al., 2013).

The MoSE system in Venice provides a practical example of how lock systems can be integrated into wider environmental and operational strategies (Cavallaro et al., 2017)(Mel, 2021). This system, consisting of mobile gates at several lagoon inlets, demonstrates how lock operations can be aligned with environmental management and port activities. In the context of the dual-function, similar strategies could be used to balance water storage needs with port operations, minimising impacts on maritime traffic and local ecosystems. In addition, hydrodynamic simulations and modelling, as used in the MoSE system, are valuable in understanding the effects of lock system operations (Mel, 2021).

4.2. Floating port

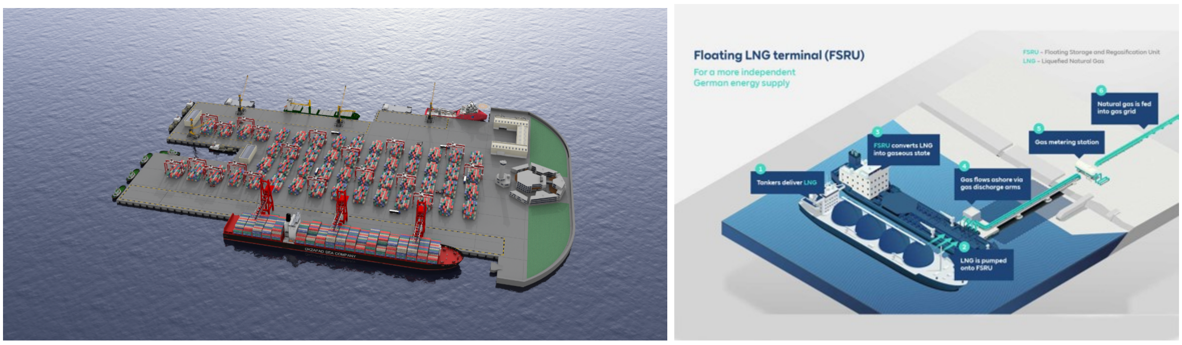

Figure 4.2: Floating container terminal (Kyllmann, 2022) and floating liquid bulk terminal (MATCH, 2024)

In developing a framework for the dual-function, floating infrastructures emerge as another innovative solution. Literature highlights various aspects of floating port infrastructure research, including its economic potential, environmental sustainability and innovative applications in port operations. Extensive studies are carried out on the stability of Very Large Floating Structures (VLFS) and, more recently, Modular Floating Structures (MFS), where smaller modules are connected to form large platforms. Figure 4.2 shows examples of two VLFS as a floating port solution: a floating container terminal and a floating liquid bulk (LNG) terminal.

Additionally, in the context of VLFS, a study of floating hydrocarbon storage facilities provides insights into the structural and operational implications of these solutions. The hydrocarbon facilities, in this case tailored to the specific coastal conditions in Singapore, demonstrate the feasibility of constructing large floating structures in benign sea states. Other potential applications have been highlighted, including floating LNG regasification facilities, desalination plants and even urban developments (Ang et al., 2020). Studies on MFS have demonstrated their economic viability as floating spaces for consolidation and transshipment of container ships. An assessment methodology that integrates logistical and economic factors has been proposed, providing insights into the optimal number of floating platforms, relevant cargo flows and other critical elements for project success. The methodology combines time optimisation and cost estimation models and is applied to the ports of Rotterdam and Antwerp. It provides a basis for further research and business case development (Nicolet et al., 2023).

In particular, the floating quay concept is presented as a novel approach to expanding quay capacity in space-constrained ports. Their flexibility and adaptability to changing vessel draughts and environmental conditions, such as rising sea levels and seismic activity, make floating quays a practical solution. The design of floating quays varies from port to port, taking into account end users, stacking allowances and crane operations. Studies of their dynamic stability, using models such as TU Delft's DELFRAC, suggest that while static stability can often be ensured, dynamic stability in wave conditions requires careful assessment (van der Wel et al., 2010). However, in sheltered inland waters, these challenges may be less significant. The Sea-Scape project in Singapore further illustrates the potential of MFS, whose hydrodynamic response to waves and wind is computationally manageable. The solution offers not only environmental benefits, such as being unaffected by rising sea levels and reducing greenhouse gas emissions, but also economic benefits, such as lower life-cycle costs compared to land-based structures. Industries such as hydrocarbon refineries, tank farms and shipyards are identified as suitable for floating out, even with the potential to manage bulk cargoes efficiently and contain spills more effectively in water than on land (Lim, 2019).

In contrast to modular floating structures for port functions, for example floating houses have been widely realised (Ambica & Venkatraman, 2015). Therefore, the development of floating architecture can contribute to innovative water storage solutions in a port basin. The challenge of designing floating platforms for civil use, as opposed to offshore floating platforms in the oil industry, requires a unique process. According to Nakajima et al. (2021), it involves minimising large slopes and ensuring adequate static stability under different multi-load conditions. In addition, the study emphasises the importance of a systematic approach in the preliminary design phase of floating structures (Nakajima et al., 2021). This approach is particularly relevant to the design of port basins where stability and safety are paramount due to the diverse and dynamic nature of port operations. Moreover, the choice of structural materials, the floating mechanism and the ability to withstand lateral forces are critical factors in the manual design of a floating house (Ambica & Venkatraman, 2015). The concept of metacentric height (GM) as a measure of stability is often applied, with a positive GM indicating increased stability. It should be noted, however, that specialised software is required to solve these comprehensive stability analyses (Ambica & Venkatraman, 2015).

An evaluation design matrix for mitigating the effects of rising sea levels provides additional context. This matrix evaluates different solutions for rising sea levels based on cost, durability, construction time, lifespan and environmental impact. The advantages of floating structures identified in the literature are significant and are consistent with the advantages of floating ports. The structures are cost effective in deep water, environmentally friendly, quick to assemble and offer flexibility in terms of expansion or dismantling. In addition, floating structures are resistant to seismic shocks and do not suffer from subsidence problems, making them stable and adaptable (El-Shihy & Ezquiaga, 2019).

4.3. Aquifer Storage Recovery

Aquifer Storage Recovery (ASR) is an innovative water management technique in which excess water is infiltrated into aquifers in the ground and extracted when water is needed. Infiltration of excess freshwater is done through wells or infiltration ponds, while extraction is mainly done through wells. This method allows dual use of land, with the surface being used for residential, commercial and natural areas, while the subsurface is used for water storage. ASR has been successfully applied in various sectors, including the drinking water industry and agriculture, particularly for storing rainwater for irrigation in greenhouses. A schematic representation of ASR for greenhouse water supply is shown in Figure 4.3. More recently, its use has been extended to urban water management and climate adaptation measures to reduce flood risks and maintain freshwater availability during dry periods (Bremer et al., 2004)(STOWA, 2019).

ASR differs significantly from open infiltration systems and deep infiltration systems (Aquifer Storage, Transfer and Recovery) in that ASR allows water to be stored and recovered at a single site using a single well. This is in contrast to the other underground water storage methods, which require separate sites for infiltration and recovery and are therefore not considered for a potential dual-function solution (STOWA, 2016).

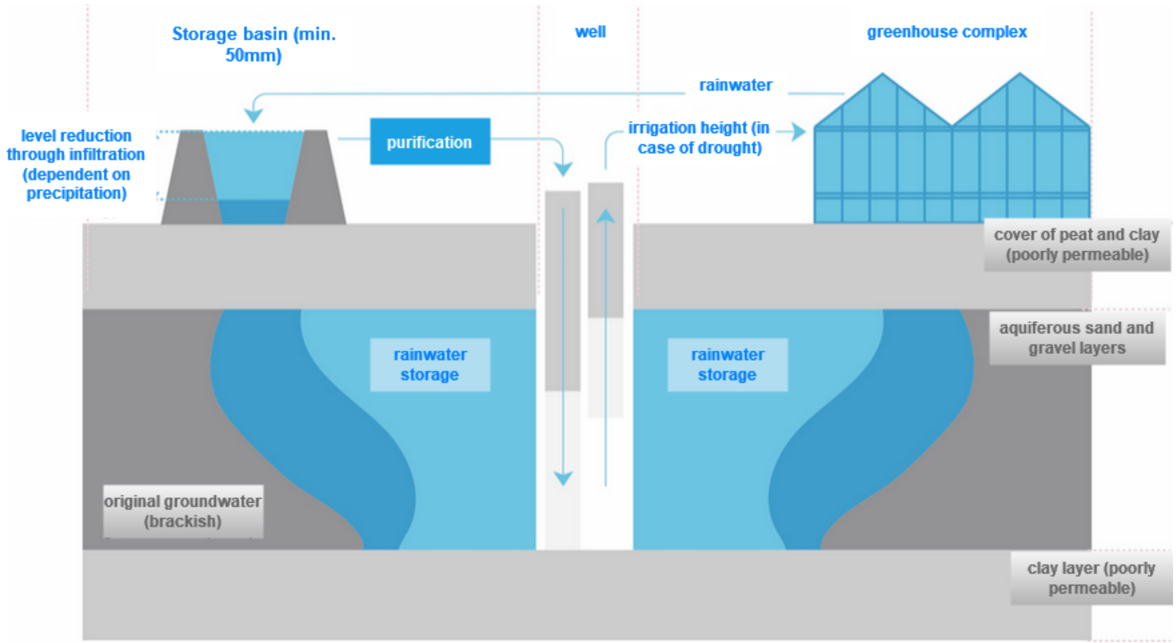

Figure 4.3: ASR schematic visualisation [(STOWA, 2019) adapted by author]

The primary advantage of ASR is its minimal surface footprint, which offers significant space savings compared to traditional surface water storage methods. In addition, ASR systems protect water from evaporation and external contamination, ensuring that a higher quantity and quality of water is available for use. On the downside, ASR poses technical and operational challenges, including the potential for aquifer contamination and clogging of pipes. There is also a risk of reduced public engagement due to the invisibility of water storage, and remaining uncertainty about the long-term reliability and maintenance of the systems (Bremer et al., 2004)(van Doorn et al., 2013).

An ASR system is only effective if the flow rate at which water can be stored in the aquifer is greater than the flow rate which is required to achieve the recovery rate. The recovery rate measures the efficiency of ASR systems, by indicating the proportion of stored water that can be recovered with acceptable quality. While recovery efficiency estimates can be conservatively set at around 50%, this value can vary depending on aquifer characteristics and the quality of injected water. The complexity of the recovery process requires advanced modelling to accurately predict results, taking into account the interaction between injected water and native groundwater. In saline environments, scaling up and improving well configurations could be used to improve recovery rates. Injected freshwater that cannot be recovered still contributes to the desalination of water in the aquifer. (Bremer et al., 2004)(Lowry & Anderson, 2006)(STOWA, 2019)(van Doorn et al., 2013).

The success of ASR projects depends largely on local geological and hydrological conditions, such as groundwater chloride levels and flow rates, and the geological structure of the subsurface. If the groundwater is saline, the injected fresh water moves to the surface due to the density difference with the saltier groundwater. Rapid groundwater flow causes runoff from the fresh bubble. As a result, the stored water mixes with saltier water and perhaps also with unwanted metals or other polluting elements. Finally, a minimal aquifer thickness of 7 metres has been mentioned for underground water storage to be effective (van Doorn et al., 2013).

Economic considerations are critical in assessing the feasibility of ASR projects. The costs associated with ASR vary depending on land prices, water treatment requirements, environmental compliance, and construction and operating costs. Despite these variables, ASR is often a cost-effective alternative to surface water storage, not only because it requires less land, but also because it significantly reduces water losses due to evaporation. Studies and implementations, including those in the Netherlands and Australia, have shown that ASR can offer significant economic benefits, particularly in dry environments, by providing an efficient and reliable water supply (Bremer et al., 2004)(Khan et al., 2008).

4.4. Decentralised water management

Decentralised water management is another potential solution for water storage in port areas. This approach offers innovative strategies for sustainable water management and environmental sustainability in waterfront developments, as evidenced by various case studies and research. The principle of decentralised water management is to treat stormwater as close to its source as possible, reducing runoff through collection, storage, infiltration and evaporation technologies (Dickhaut & Richter, 2020).

Key components of this approach include green roofs and tree pits designed for infiltration. These components have shown promise in dense urban areas, although their effectiveness in retaining runoff can vary depending on technical and climatic factors (Dickhaut & Richter, 2020). Research into the combination of rainwater harvesting and greywater reuse represents a viable strategy for improving urban water security. These systems, typically implemented in residential and commercial settings, contribute to potable water savings and can significantly reduce urban flooding risks. However, it is argued that further empirical studies are needed to optimise the design configurations of these systems, taking into account their environmental, technological and functional objectives (Rodrigues et al., 2023).

The HafenCity Hamburg and Waterfront Toronto projects are exemplary in demonstrating the effectiveness of decentralised water storage systems in urban contexts. In HafenCity, instead of conventional dike construction, buildings were constructed on artificial bases elevated above sea level, addressing the risk of flooding while preserving the aesthetic and functional aspects of the waterfront. Waterfront Toronto's approach to sustainable community building includes the implementation of minimum green building requirements. A key aspect of these initiatives is the integration of innovative water management features. For example, Waterfront Toronto uses rainwater harvesting systems in its parks, where rainwater is collected locally, treated and stored for a variety of uses, including irrigation and marshland flushing. In addition, green roofs are proposed as a solution for reducing stormwater runoff, improving air quality and mitigating the urban heat island effect(Samant & Brears, 2017). The proposed requirement to install green roofs on 60% of developed available roof space should be considered when evaluating the effectiveness of decentralised measures in the context of a single port basin.

An innovative application of dredged material in green roof systems is demonstrated by R. Liu and Coffman (2016). Through experiments, the study shows that lightweight aggregate (LWA) made from heated dredged material can be used in green roofs to provide enhanced water retention and environmental benefits (R. Liu & Coffman, 2016). This approach not only addresses the problem of sedimentation in water bodies, but also opens up new possibilities for green infrastructure and stormwater control measures.

In Dutch spatial planning, the integration of water buffers, both natural and artificial, plays a crucial role in the local management of peak flows of rain or river water. These water buffers are more in line with this study's focus on water retention, as opposed to solutions such as green roofs, which focus on drainage. Natural water buffers make use of existing water bodies, such as ponds or streams, by channeling water through ditches or underground drainage systems. Artificial water buffers, on the other hand, involve the construction of basins specifically designed for the temporary storage of peak flows. A major advantage of artificial buffers, such as wadis, is the ease with which underground drainage and infiltration systems can be integrated beneath the buffer. This facilitates the controlled release and infiltration of stored water and shows its potential for integrating a water storage function into a harbour basin (RIVM, 2011).

Wadis, a special type of artificial water buffer, are green ditches in urban areas designed for water disposal, drainage and infiltration. They collect rainwater, purify it and allow it to infiltrate into the ground, thus combating floods and droughts. For its storage function, a wadi can use infiltration crates or water-retaining granules (Kennisportaal Klimaatadaptatie, 2020). A schematic representation of a wadi with an underground drainage and infiltration system is shown in Figure 4.4.

Figure 4.4: Wadi schematic visualisation [(Kennisportaal Klimaatadaptatie, 2020) adapted by author]

The implementation of wadis and other water buffers is not without its challenges. Concerns such as potential soil contamination by heavy metals from run-off and compatibility with (underground) land use policies need to be addressed. However, the benefits, including enhanced biodiversity through the selection of specific vegetation and the provision of recreational spaces, contribute positively to urban green-blue infrastructure. As wadis are often located in residential areas, they can also help to raise public awareness of water storage issues in cities (RIVM, 2011).

Underground drainage and infiltration systems can also be considered as a decentralised water management solution for water storage in other contexts. Infiltration crates, installed under surfaces such as sports fields, provide a temporary storage solution for excess rainwater, which can infiltrate into the ground as saturation decreases. Boreholes filled with highly permeable materials facilitate rapid infiltration and can be topped with a well to collect dirt and sediment and increase buffer capacity. Both systems are only effective above the groundwater level, ensuring maximum storage and infiltration capacity (RIVM, 2011).

4.5. Conclusion

This chapter introduces four innovative dual-function solutions for combining port terminal functions with water storage functions: port lock systems, floating ports, aquifer storage recovery (ASR) and decentralised water management. Each solution has its benefits, potential risks and limitations which will affect its ability to fulfil the sub-functions defined in Chapter 2 and Table 3.1.

Port lock systems, traditionally used to control vessel traffic while managing water levels, highlight the potential for natural basin filling at high tide. However, this method presents complex scheduling challenges for port operations and raises concerns about environmental impacts, particularly in terms of greenhouse gas emissions. Lock operations should be coordinated with environmental management and port activities to minimise impacts on shipping and local ecosystems.

Another innovative solution is floating ports, which use Very Large Floating Structures (VLFS) or Modular Floating Structures (MFS) to create adaptable maritime infrastructure. These structures not only demonstrate economic viability for the consolidation and transshipment of container ships, but also offer flexibility in response to changing environmental conditions such as sea level rise and seismic activity. Their environmental friendliness, cost effectiveness and ease of installation make them a promising solution for integrating water storage into port terminals. Despite their advantages, the dynamic stability of these structures in wave conditions requires careful consideration.

Aquifer Storage Recovery (ASR) introduces an underground approach to water storage, where excess water is infiltrated into aquifers for later extraction. The technique offers a space-efficient alternative to traditional surface water storage methods, while protecting water from evaporation. However, technical and operational challenges, such as the potential for aquifer contamination and the risk of clogging, highlight the need for careful planning and management to ensure the long-term viability of ASR systems. In addition, the success of ASR projects depends on local geological and hydrological conditions, emphasising the importance of site-specific assessments.

Decentralised water management approaches, including the use of green roofs, tree pits and artificial buffers such as wadis, prioritise the treatment of stormwater at source. This strategy not only reduces runoff, but could also facilitate the integration of water storage functions into the urban fabric of port areas. There are concerns about soil contamination and compatibility with land use policies, but the environmental and recreational benefits of these green infrastructures, underline the potential of decentralised water management as a dual-function solution.

5 Design framework

Based on the input from the previous chapters and the interviews conducted, a framework can be proposed for the design of a dual-function system consisting of both port terminal and water storage functions. The framework defines requirements, consisting of objectives and constraints, based on the analysis of the two separate functions and the stakeholder analysis. The framework introduces conceptual designs based on the analysis of the dual-function solutions. The conceptual designs can be seen as solution directions based on the system analysis of Chapter 2, Chapter 3 and Chapter 4, limited in design by the concept-specific constraints. The conceptual designs are used to generate design alternatives based on case input on area characteristics and case-specific constraints. The final step of the framework is an evaluation of the design alternatives through Multi-Criteria Decision Making (MCDM), using the objectives as the main input. Both during the generation and evaluation of the design alternatives dual-function feasibility is assessed. The design framework is visualised in Figure 5.1. It should be noted that the framework is subject to two design assumptions:

1. The dual-function system will be implemented in an inland area adjacent to the main shipping route of an existing port.
2. Vessel movements associated with the port functions will also be to or from this main route.

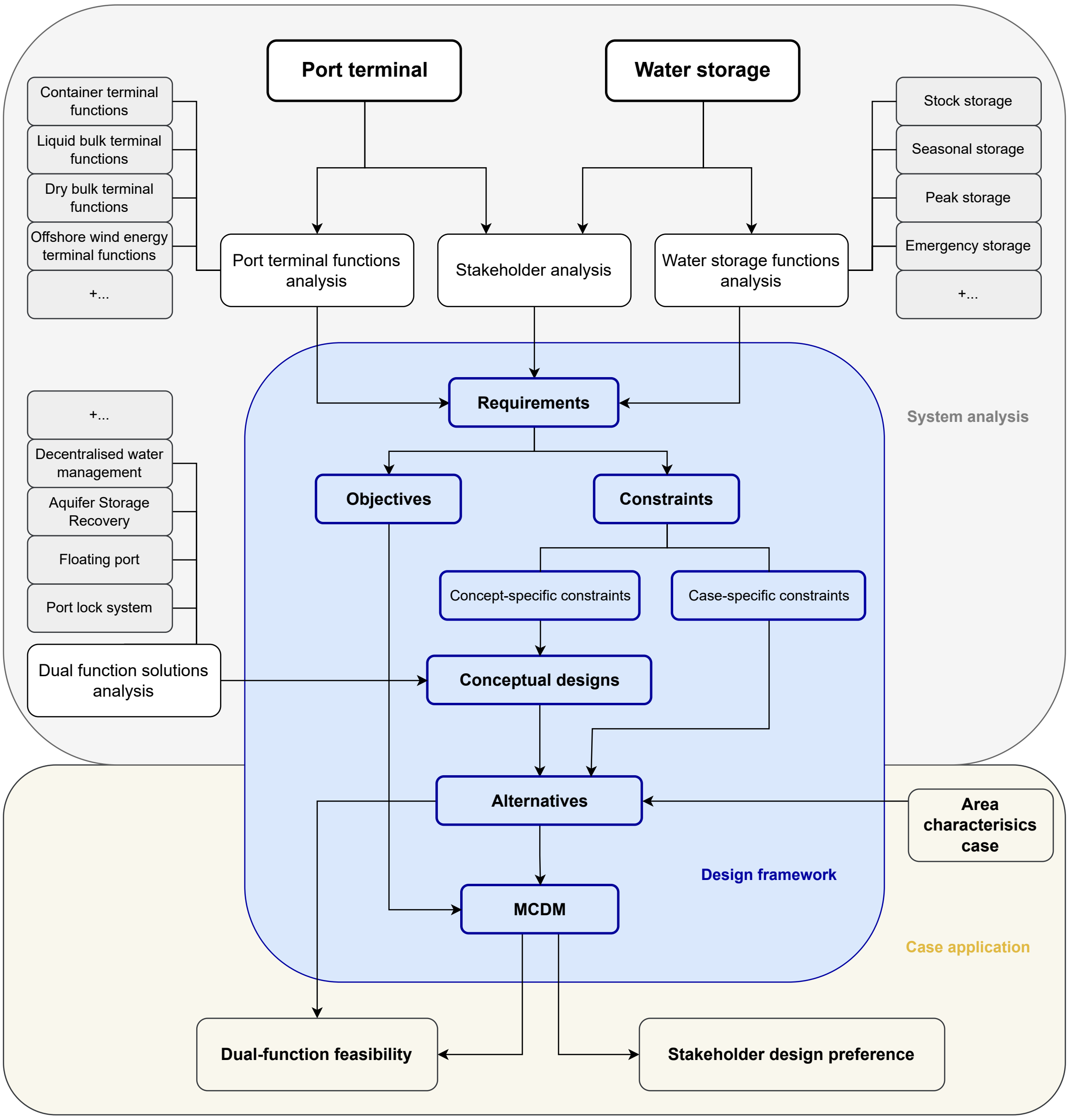

Figure 5.1: Dual-function design framework for port terminal and water storage functions [created by author]

5.1. Requirements

Based on the analysis of both the port terminal and water storage functions, and the stakeholder interviews, the requirements for a dual-function system are identified and divided into objectives and constraints.

5.1.1. Objectives

The requirements that are defined as objectives in the development of the dual-function are mainly based on the stakeholder interviews. The repeatedly highlighted objectives are presented in Table 5.1, which also describes which interview in the appendix or (sub)section of the system analysis is used as input. As illustrated in Figure 5.1, all objectives are used to evaluate design alternatives. The objectives are translated into criteria and quantified in Section 6.3 based on input from the case. The objectives and their dependencies are discussed in more detail in the remainder of this section.

#	Input section	Objective
O1	Appendix B.1, Appendix B.5, Appendix B.8	The total water storage capacity of the area should be maximised.
O2	Appendix B.1, Appendix B.5	The time period that water can be stored in the area should be maximised.
O3	3.5, 4.3, Appendix B.2, Appendix B.5, Appendix B.7	The amount of stored water that can be recovered and used to combat water shortages should be maximised
O4	Appendix B.4, Appendix B.6, Appendix B.8	The available physical space for port terminal operations in the area should be maximised.
O5	Appendix B.6	The available nautical space for port terminal operations in the area should be maximised.
O6	4.2, 4.3.	The total investment costs for the dual-function solution should be minimised.
O7	3.1.2, 3.4, 3.5, 4.1, 4.4, Appendix B.1, Appendix B.8, Appendix B.9	CO2 emissions, and impact on agriculture, nature, biodiversity and a green living environment in the area should be minimised.

Table 5.1: Objectives

O1: Storage capacity

The first objective is to maximise the total water storage capacity of the area. Water storage usually replaces or supplements a certain amount of pumping capacity. The required pumping capacity depends on the water management systems involved and the desired level of flood protection. The amount of storage capacity, for example in cubic metres, indicates how much of this pumping capacity can be filled by the water storage capacity. For surface storage, the storage capacity can be estimated by multiplying the dimensions of the water storage area by the maximum water level fluctuations of the storage design model used. For underground storage, the dimensions of the aquifer or infiltration box and its physical properties should be considered.

O2: Storage period

The second objective states that the storage time for water in the area should be maximised. If the storage area is only used for peak storage, its capacity can be reached in a few hours, and it loses its function until it is emptied again. However, depending on the storage area, water could be stored for a longer period and fulfil a stock storage or seasonal storage function. Therefore, the storage period should be estimated based on the solution's storage function and its infiltration flow rate.

O3: Recovery rate

The third objective is to maximise the amount of water that can be recovered and used to combat water shortages. More evaporation and less rainfall in the summer months are expected to reduce the supply of fresh water in the Netherlands. At the same time, the demand for clean fresh water is expected to increase due to population growth, economic growth and more intensive land use. This includes expected water shortages for the energy transition, shipping, and peatland irrigation to prevent subsidence and CO2 emissions. For surface water storage, the recovery rate is heavily influenced by evaporation and contamination. For underground water storage, the recovery rate depends on the thickness and permeability of the aquifer, the salinity of the groundwater, the rate of any background flow and the sealing of the aquifer.

O4: Physical space

The next objective states that the available physical space for port terminal operations in the area should be maximised. Physical port space refers to space on land, on or alongside a quay, for the performance of one of the defined port (sub)functions. The demand for physical port space in the Netherlands is subject to new factors such as the transition from fossil fuel terminals, the increasing containerisation of logistics or the development of offshore wind energy terminals. In addition, the demand for housing, other business premises and the expansion of the electricity grid are putting strong pressure on the physical space in the ports. The amount of physical space available in the area is directly dependent on the structural design of the dual-function solution.

O5: Nautical space

The next objective is to maximise the available nautical space for port terminal operations in the area. Nautical port space refers to the waterways that can be used to perform the defined port (sub)functions. The amount of nautical port space has an impact on the efficiency and safety of nautical port operations and is directly dependent on the structural design of the dual-function solution.

O6: Investment costs

The next objective is to minimise the total investment cost of the dual-function solution. In this case, the investment costs include the public construction costs of all major infrastructure required for the port function(s) and water storage function(s) of the dual-function solution, as well as the costs of fitting the solution into the area. The latter category of costs relates to land prices, water treatment requirements and environmental compliance costs. The design framework does not take into account the operational or life cycle costs of the dual-function solution.

O7: Environmental impact

The final objective is to minimise the environmental impact of the dual-function solution, consisting of CO_2 emissions and the impact on agriculture, nature, biodiversity and a green living environment. These potential negative impacts of implementing a dual-function system are based on the interests of the community stakeholders as discussed in Subsection 2.5.4 and Subsection 3.5.4. These interests are only included as an objective in the design framework, while the other stakeholders with more decision-making influence are directly consulted in the evaluation phase of the design framework in Section 5.3.

5.1.2. Constraints

Constraints are modelled as the initial and boundary conditions of concept ideation in a design study (A. Liu et al., 2019). For a system consisting of both port and water storage functions, 32 constraints are defined and presented in Table 5.2. The table also describes which (sub)section of the system analysis is used as input and the application of the constraint in the framework. As visualised in Figure 5.1, some constraints are used to generate the conceptual designs in Section 5.2, while others are case-specific and are used to generate design alternatives in Section 6.1.

#	Constraint	Input section	Application
C1	Based on the terminal type, its standard vessel dimensions have to fit in the approach channel of the port basin.	Subsection 2.1.1	Conceptual designs
C2	A liquid bulk terminal has to be flexible for unpredictable arrival rates.	Subsection 2.1.1	Conceptual designs
C3	A liquid bulk terminal has to comply with contractual agreements with its customers for ensuring quick loading and unloading operations.	Subsection 2.1.1	Conceptual designs
C4	In a liquid bulk terminal vapor recovery systems must be installed to limit external contamination.	Subsection 2.1.1	Conceptual designs
C5	A liquid bulk terminal should be connected to the hinterland either via road or rail.	Subsection 2.2.3	Design alternatives
C6	In a dry bulk terminal dust control systems must be installed to limit external contamination.	Subsection 2.3.2	Conceptual designs
C7	A dry bulk terminal should be connected to the hinterland either via rail or waterways.	Subsection 2.3.3	Design alternatives
C8	An offshore wind energy terminal has to ensure overhead and horizontal clearances to ensure safe passage of vessels carrying turbine components.	Subsection 2.4.1	Conceptual designs
C9	An offshore wind energy terminal has to ensure substantial load-bearing capacity for its quay wall, staging area and storage area.	Subsection 2.4.1	Conceptual designs
C10	An offshore wind energy terminal should be connected to the hinterland via road.	Subsection 2.4.3	Design alternatives
C11	Stock storage should be implemented by storing water in the local water management system.	Subsection 3.1.1	Conceptual designs
C12	Stock storage should be implemented by creating a storage basin, widened watercourses, flexible water management, new marshes or a storage polder in urban edges.	Subsection 3.1.2	Conceptual designs
C13	The storage basin model should be realised in reclamation areas or peatland polder landscapes.	Subsection 3.1.2	Design alternatives
C14	The widened watercourses model should be realised in peatland polder or clay polder landscapes.	Subsection 3.1.2	Design alternatives
C15	The flexible water level management model should be realised in reclamation areas, new urban developments or urban areas.	Subsection 3.1.2	Design alternatives
C16	The new marshes model cannot be realised in deep reclamation areas.	Subsection 3.1.2	Design alternatives
C17	The storage polder in urban edges model cannot be realised in beach ridge landscapes with high soil permeability.	Subsection 3.1.2	Design alternatives
C18	Seasonal storage should be implemented by storing water in the regional water management system or in the interface between the regional and main system.	Subsection 3.2.1	Conceptual designs
C19	Seasonal storage should be implemented by creating a storage basin, new ponds, flexible water management or a storage polder in urban edges.	Subsection 3.2.2	Conceptual designs
C20	The new ponds model should be realised in clay polders where the clay layer is thin and the underlying sand is not overly fine, or in beach ridge landscapes.	Subsection 3.2.2	Design alternatives
C21	Peak storage should be implemented by storing water in the regional water management system or in the interface between the regional and main system.	Subsection 3.3.1	Conceptual designs
C22	The inlet polder model should be realised in deep reclamation areas or peatland polder areas.	Subsection 3.3.2	Design alternatives
C23	The inner polder model should be realised at a lower elevation next to another polder.	Subsection 3.3.2	Design alternatives
C24	The inner polder model should be realised in deep reclamation areas.	Subsection 3.3.2	Design alternatives
C25	Emergency storage should be implemented by storing water in or from the main water management system.	Section 3.4	Conceptual designs
C26	Emergency storage should be implemented by creating flexible water management or an inlet polder.	Subsection 3.4.1	Conceptual designs
C27	Floating port as a dual-function solution has to be implemented by incorporating a terminal sub-function with limited dynamic operations to ensure dynamic stability.	Section 4.2	Conceptual designs
C28	Aquifer Storage Recovery as a dual-function solution, by definition, has to recover stored water, fulfilling a stock storage or seasonal storage function.	Section 4.3	Conceptual designs
C29	ASR has to be implemented in an area with an aquifer of at least 7 metres in thickness.	Section 4.3	Design alternatives
C30	For ASR, the flow rate at which water can be stored in the aquifer has to be greater than the flow rate which is required to achieve a recovery rate of 50%.	Section 4.3	Design alternatives
C31	Decentralised water management as a dual-function solution, can only be implemented by using artificial water buffers, fulfilling a stock storage function.	Section 4.3, Section 4.4	Conceptual designs
C32	Decentralised water management has to be implemented by positioning the storing elements above the groundwater level.	Section 4.4	Design alternatives

Table 5.2: Constraints

5.2. Conceptual designs

Based on the dual-function solution presented in Chapter 4 and the constraints in Subsection 5.1.2, four conceptual designs for a dual-function system are created in this section. In addition to the dual-function solution, each conceptual design consists of at least one feasible port terminal function, a terminal sub-function, a water storage function, a water management system and a storage design model. The next sections discuss the constraints that have shaped each conceptual design and use morphological charts to visualise them.

5.2.1. D1: Port lock system

The first conceptual design, visualised in Figure 5.2, is based on the port lock system solution as defined in Section 4.1. As it is assumed that no inner port lock will be large enough to accommodate the standard container terminal type vessel, a combination with a container terminal function is excluded (C1). The operation of a lock system is also expected to limit flexibility to unpredictable arrival rates (C2). While this constraint has been highlighted for liquid bulk terminals, 'transport, transhipment & transfer' is excluded as a sub-function for all main functions in this conceptual design. This sub-function is also excluded because it is considered that a lock system cannot ensure rapid loading and unloading operations (C3). Furthermore, the dimensions of a port lock do not allow sufficient horizontal clearance to include functions for an offshore wind energy terminal (C8). In this concept, water from the main water management system is transferred to the harbour basin behind the lock when the ships lock and the water reservoir is filled. Since water from the main system is stored, it can only be used for the emergency storage function (C25). As the harbour basin will be permanently filled, the design uses the flexible water level management storage design model (C26).

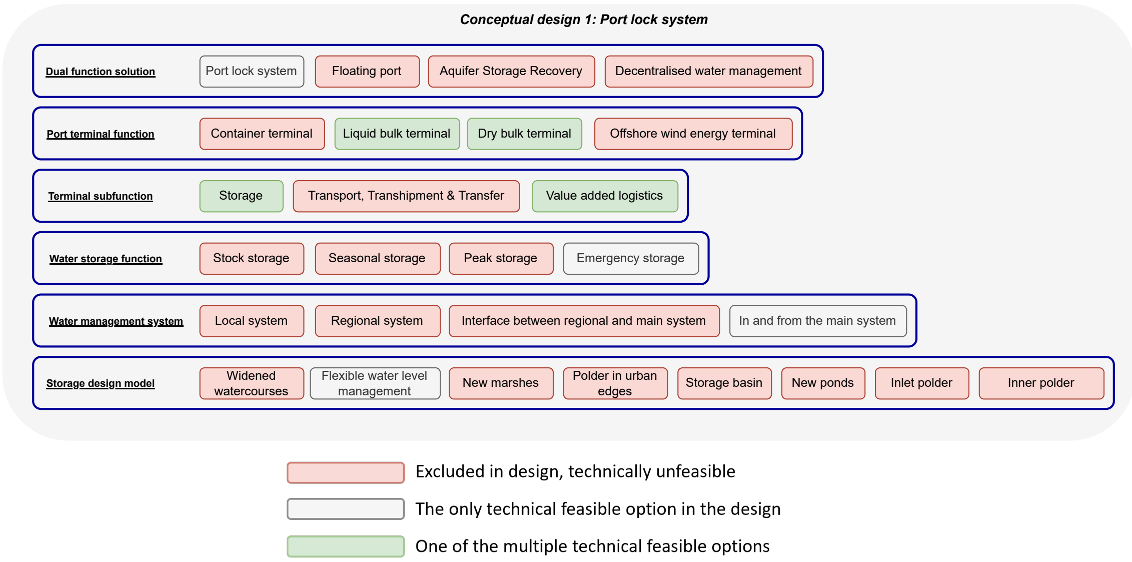

Figure 5.2: Morphological chart of conceptual design 1 [created by author]

5.2.2. D2: Floating port

The second conceptual design, visualised in Figure 5.3, is based on the floating port solution as defined in Section 4.2. Floating structures, whether VLFS or MFS, are not expected to have sufficient load bearing capacity to accommodate the operations associated with the port function of the offshore wind energy terminals (C9). In addition, the transport, transhipment & transfer sub-function is expected to result in extensive dynamic operations, limiting the ability to ensure the dynamic stability of the floating infrastructure (C27). If a body of water, such as a lake, is created in the target area to support the floating infrastructure, this body becomes part of the main water system. Therefore, if the water below the floating port is used for storage, the water is stored in the main system and the area can only be used for emergency storage (C25). As the lake will be permanently filled, this design also uses the flexible water level management storage design model (C26).

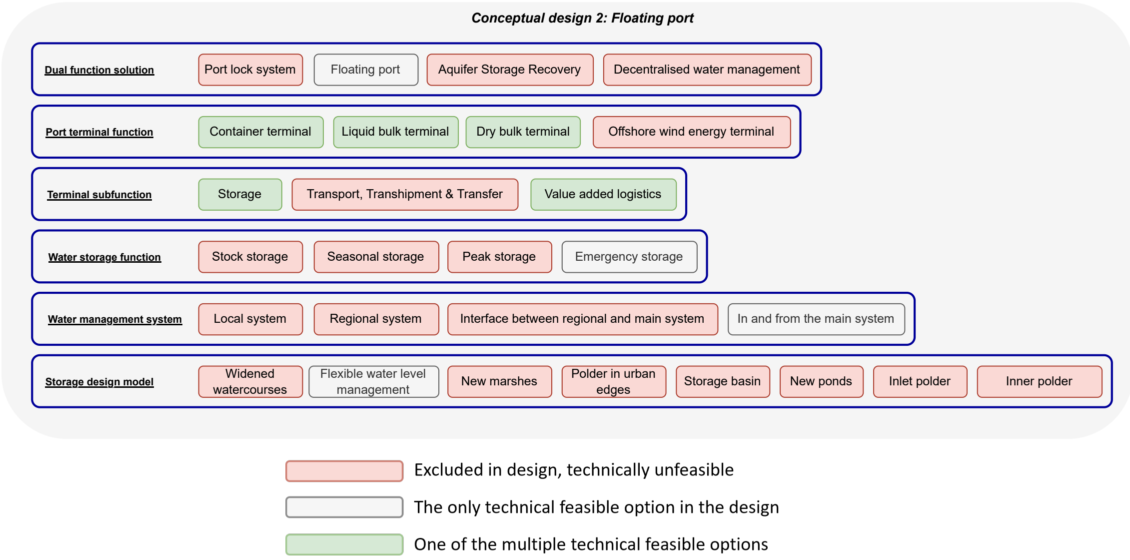

Figure 5.3: Morphological chart of conceptual design 2 [created by author]

5.2.3. D3: Aquifer Storage Recovery

The third conceptual design, visualised in Figure 5.4, is based on the Aquifer Storage Recovery solution as defined in Section 4.3. In this dual-function design, an ASR system is installed anywhere in the port area adjacent to a new port basin. As described, an ASR system is subject to potential aquifer contamination and clogging of pipes. As vapour recovery systems must be installed to limit external contamination in liquid bulk terminals (C4) and dust control systems in dry bulk terminals (C6), these port functions present too high a risk to combine with underground water storage. The same applies to value added logistics as a sub-function of all port terminal functions, where operations could pollute the air and surface or groundwater. By definition, an ASR system recovers stored water, fulfilling a storage or seasonal storage function (C28). Finally, this conceptual design uses the storage basin design model (C12, C19). Although underground, the aquifer functions independently of the 'boezem' and captures rainwater to maintain optimum water levels during periods of drought. However, unlike an above-ground storage basin model, the storage capacity depends on the size of the aquifer and is not limited to water level fluctuations of up to 1 metre.

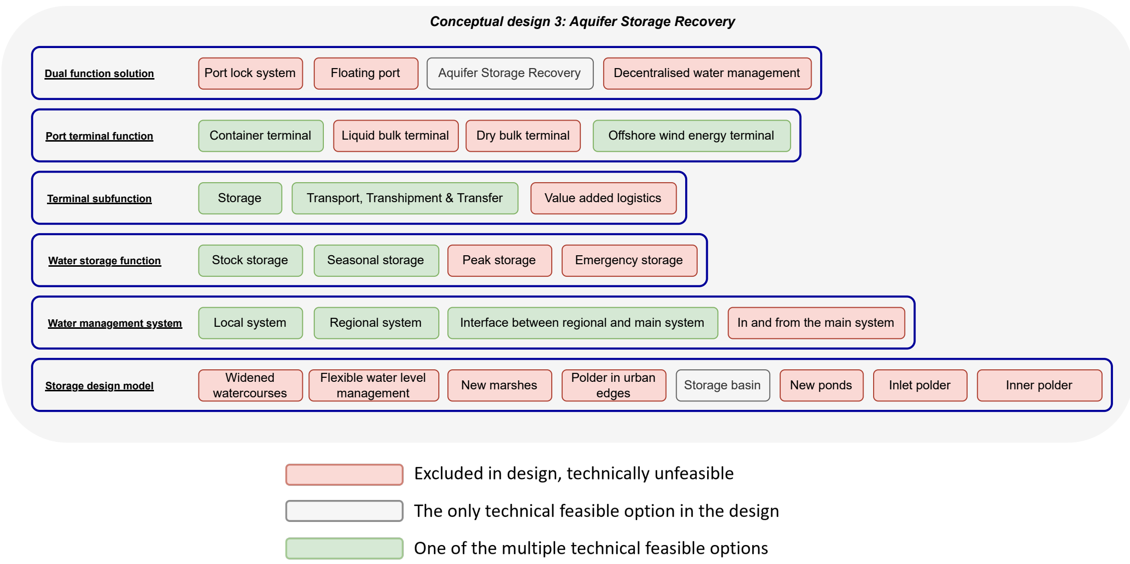

Figure 5.4: Morphological chart of conceptual design 3 [created by author]

5.2.4. D4: Decentralised water management

The fourth conceptual design, visualised in Figure 5.5, is based on the decentralised water management solution defined in Section 4.4. In this dual-function design, a decentralised water management system is installed anywhere in the port area adjacent to a new port basin. Similar to ASR, this design aims to capture water at the surface and recover it at an acceptable quality. Therefore, operations related to the liquid or dry bulk port functions or the value-added logistics sub-function are excluded from the dual-function design (C4, C6). In addition, decentralised water management in a port environment can only be implemented through the use of artificial water buffers, which fulfil a stock storage function (C31). By definition, stock storage can only be implemented by storing water in the local water management system (C11). Finally, similar to the third concept, this concept uses the storage basin design model (C12, C19), with the side note that the storage capacity depends on the size of the artificial water buffer.

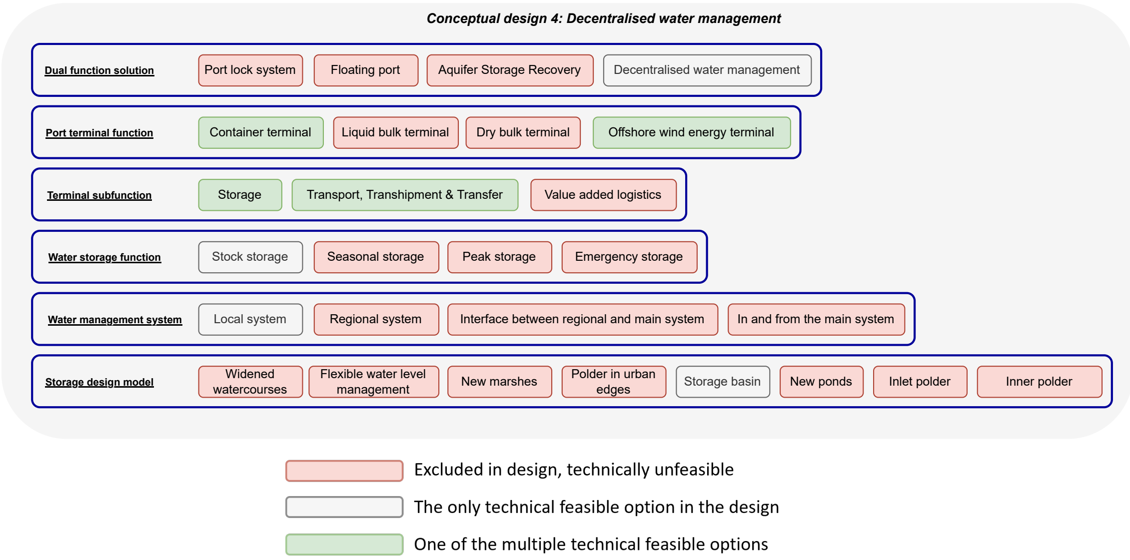

Figure 5.5: Morphological chart of conceptual design 4 [created by author]

5.3. Design evaluation

Finally, the dual-function design framework consists of a method to evaluate the conceptual designs defined in Section 5.2 based on the objectives defined in Subsection 5.1.1. In this section, the proposed Multi-Criteria Decision Making (MCDM) method is discussed together with the identified stakeholders of both functions.

5.3.1. Multi-Criteria Decision Making (MCDM)

Decision making can be defined as the identification and selection of an alternative from a set of alternatives based on the preferences of the decision maker(s). Different decision makers value the criteria involved differently (Rezaei, 2016). While there are more complex methods for group decision making, this framework proposes a separate evaluation based on MCDM for each decision maker. It is assumed that at this stage in the development of the dual-function solution, the main objective of the evaluation should be to identify the differences in the preferences of each stakeholder, rather than to decide on an overall optimal design alternative.

The goal of MCDM is to select the alternative with the best overall value. Assuming that the corresponding trade-off condition is satisfied, the preference structure for the design alternatives of the dual-function is additive (Rezaei, 2015). Consequently, the value of an alternative can be determined using a straightforward additive weighted value function, which serves as the foundational model for the majority of MCDM methods (Keeney & Raiffa, 1993). It is assumed that the seven objectives for the four conceptual designs can be quantified by reasoned estimation and used as criteria and alternatives, respectively, in the additive weighted value function shown in Equation 5.1.

$$
\begin{aligned}
&V_i = \sum_{j=1}^{n} w_j p_{ij} \\
&\text{s.t.} \\
&V_i := \text{Value of alternative } i \\
&n := \text{Number of criteria} \\
&w_j := \text{Weight of criteria } j \\
&p_{ij} := \text{Normalised score of alternative } i \text{ on criteria } j
\end{aligned}
\tag{5.1}
$$

The crucial aspect here, and what sets apart various MCDM methods, is the method by which the criteria weights are determined (Rezaei, 2015). The Direct Assignment Technique (DAT) asks users to assign points directly to the criteria. The MCDM method then asks to normalise the points so that they sum to one and can be used as weights. One approach to scoring is to provide a finite range of possible scores and ask decision makers to assign a score to each criteria according to its importance. In this case, criteria of higher importance receive a higher score than those of lower importance (Ezell et al., 2021). The framework suggests a range from 0 to 10, with a score of 0 indicating that the criterion does not play a role in the evaluation of the conceptual designs.

DAT is a straightforward method of assigning weights to criteria that does not require the decision maker to rank the importance of the entire set of criteria. The number of questions required to assign weights using the Direct Assignment Technique is limited to the number of criteria (Ezell et al., 2021). At this early stage in the development of the dual-function design, the simplicity of this method is essential to ensure stakeholder participation and to avoid misinterpretation. By using absolute scores, rather than letting decision makers divide a fixed pot of points, new criteria could be added or old ones removed (Ezell et al., 2021). This makes the framework evaluation step flexible enough to adapt to further development stages of the dual-function designs.

5.3.2. Decision makers

As discussed in the previous section, the MCDM is performed using the Direct Assignment Technique, separately for each decision maker. The decision makers are defined in the framework by combining the stakeholder analysis for the port terminal functions in Section 2.5 and the stakeholder analysis for the water storage functions in Section 3.5. The stakeholders considered to have the highest interest and power in both functional systems combined should be consulted for the DAT and are marked with a blue colour in the combined power/interest grid in Figure 5.6. It should be noted that the precise position of these blue stakeholders in the diagram does not indicate that there are any significant differences in power or interest between them. The power/interest grid is only a tool for the identification of decision makers to be consulted for the design evaluation. Stakeholders marked with a black colour in the grid are considered to have less power in the development of a dual-function design, but their interest is represented in the Environmental Impact Objective (O7) as discussed in Subsection 5.1.1.

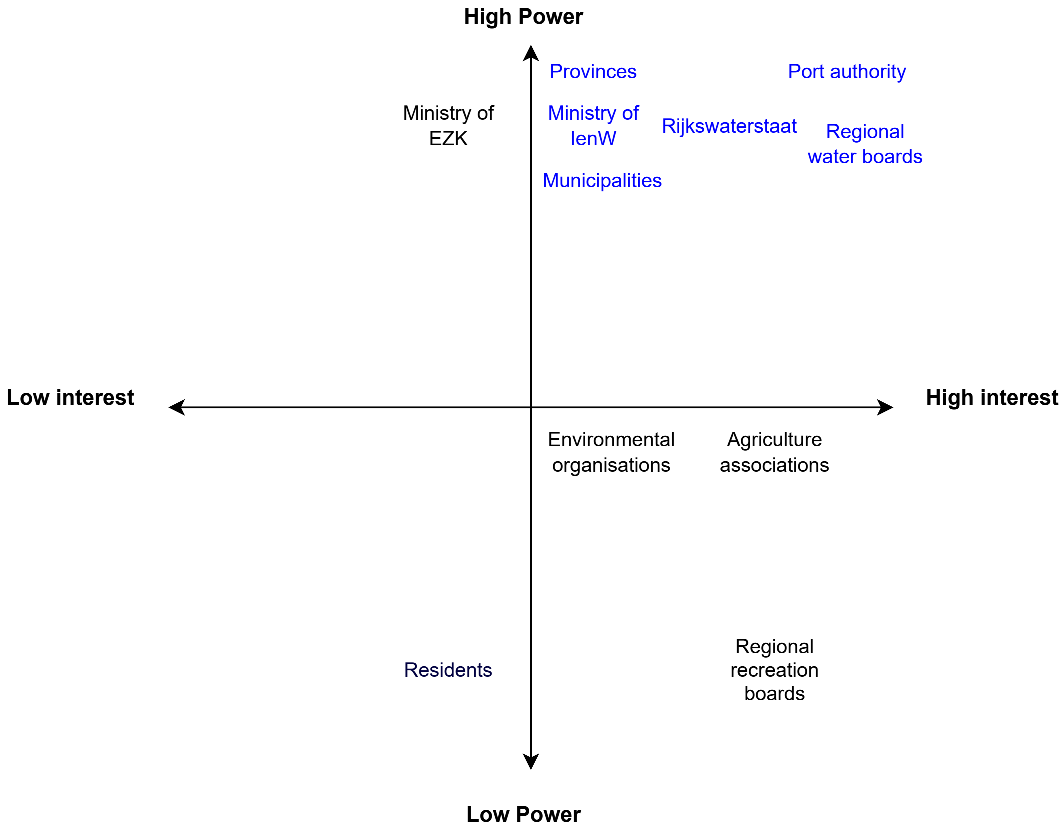

Figure 5.6: Power/interest grid dual-function design [created by author]

5.4. Framework summary

In this chapter, a design framework for a dual-function system integrating both port terminal and water storage functions is developed based on the system analysis and stakeholder interviews. The framework is structured to first identify requirements, including objectives and constraints, followed by the generation of conceptual designs. These designs are formulated taking into account system constraints and evaluated through a multi-criteria decision making (MCDM) process.

Seven primary objectives are defined: maximising water storage capacity, storage period, recovery rate, physical and nautical port space, and minimising both investment costs and environmental impact. These objectives, derived from stakeholder input, serve as evaluation criteria for the conceptual designs. In addition, 32 constraints define the operational and physical limits within which the designs must be developed. Some constraints are used to generate the conceptual designs, while others are case-specific and are used to generate design alternatives in the application of the framework.

Four conceptual designs have been proposed. The first uses a lock system for both port and emergency water storage functions. This design is limited by vessel size and flexibility constraints. The second design, a floating port, uses floating structures for port functions and the water below for emergency storage. It is limited by structural and dynamic stability constraints. The third design, Aquifer Storage Recovery (ASR), integrates an ASR system to store water underground, avoiding the risk of contamination. This design excludes high-risk port functions such as liquid and dry bulk terminals. The fourth design, based on decentralised water management, uses artificial water buffers for local water management compatible with low-risk port functions. This design emphasises the stock storage function.

The evaluation of the conceptual designs uses the Direct Assignment Technique (DAT), which allows individual stakeholders to assign weights to each objective based on their preferences. This method ensures a flexible and straightforward evaluation process that takes into account the different priorities of different stakeholders. Stakeholders with high interest and power in both port and water storage functions are identified as primary decision makers. The broader interests of the community and regulators are taken into account through the environmental impact criterion. Finally, both during the generation and evaluation of the design alternatives dual-function feasibility is assessed.

6

Case study

In this chapter, the Amsterdam Houtrakpolder case introduced in Section 1.6 will serve as a first application of the framework for the design of a dual-function system consisting of port terminal and water storage functions. The case specific area available for the dual-function serves as input for the design framework and will be discussed before following the steps defined in Chapter 5.

The northern part of the Houtrakpolder, visualised in Figure 6.1 has been identified as a potential area for the dual-function by the Ministry of IenW. The area is located south of the North Sea Canal and is used for recreation and nature with mainly grass and forest. In the western part of the polder is the village of Spaarndam, while in the eastern part are the industrial areas of the port of Amsterdam (Hoogheemraadschap van Rijnland, 2024).

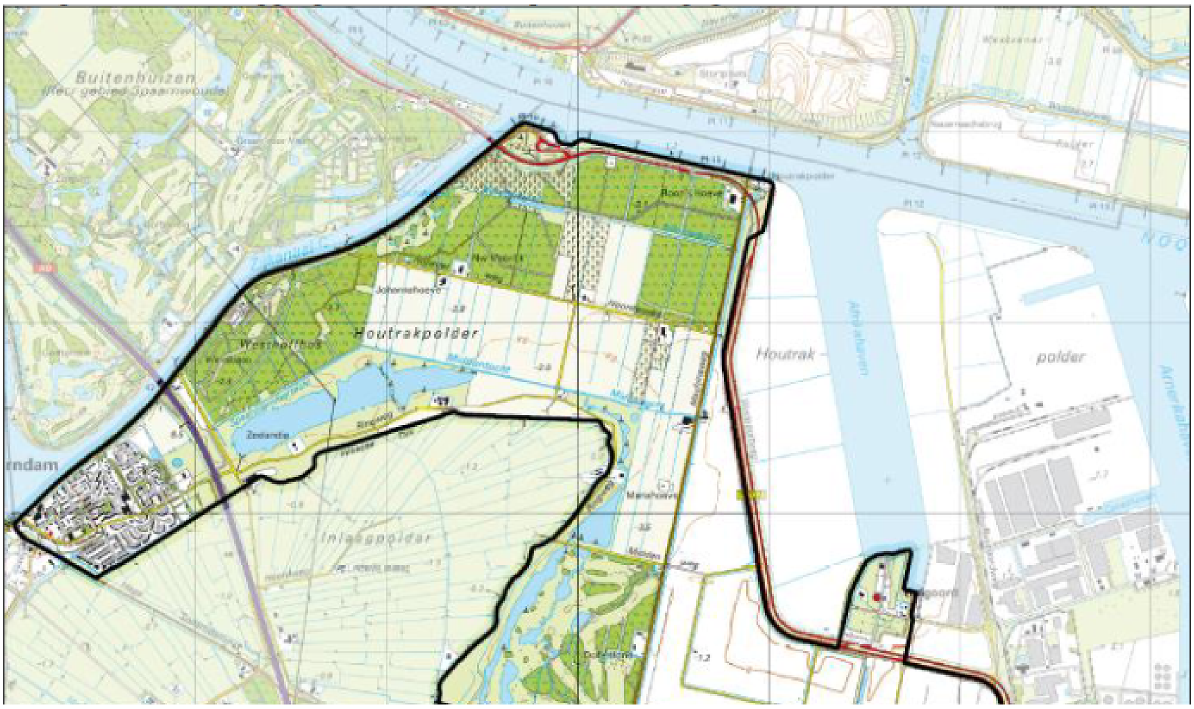

Figure 6.1: Houtrakpolder North side (van der Dussen & Buijs-Heine, 2019)

However, not the entire northern part of the Houtrakpolder is available for the design of a dual-function system. As a natural boundary between the port operations and the Spaarnwoude green buffer zone, 'Het Groene Schip' was initiated in this area in 2012. This project involved the incorporation of approximately 3 million square metres of secondary building materials (Afvalzorg, 2024). Secondary building materials are not extracted from nature. These materials are (residual) products resulting from production processes or the demolition of old buildings (Gemeente Veere, 2024). An example of this is the bottom ash that was used in the construction of the northern part of Het Groene Schip (Afvalzorg, 2024).

Bottom ash is the material left over after waste has been burned in an incinerator and contains hazardous substances that can cause environmental or health damage. Environmental authorities regularly report problems with the import, production, processing, storage and use of bottom ash. (Inspectie Leefomgeving en Transport, 2024). It is therefore considered that the risk of environmental damage is too great to allow this area to be rezoned as part of a dual-function system. In addition, the residential area that forms part of the village of Spaarnwoude is excluded, and it is assumed that a contiguous area is required for both port operations and water storage. Therefore, Figure 6.2 shows the available area in the Houtrakpolder for the dual-function system, which will be the input for the further application of the framework.

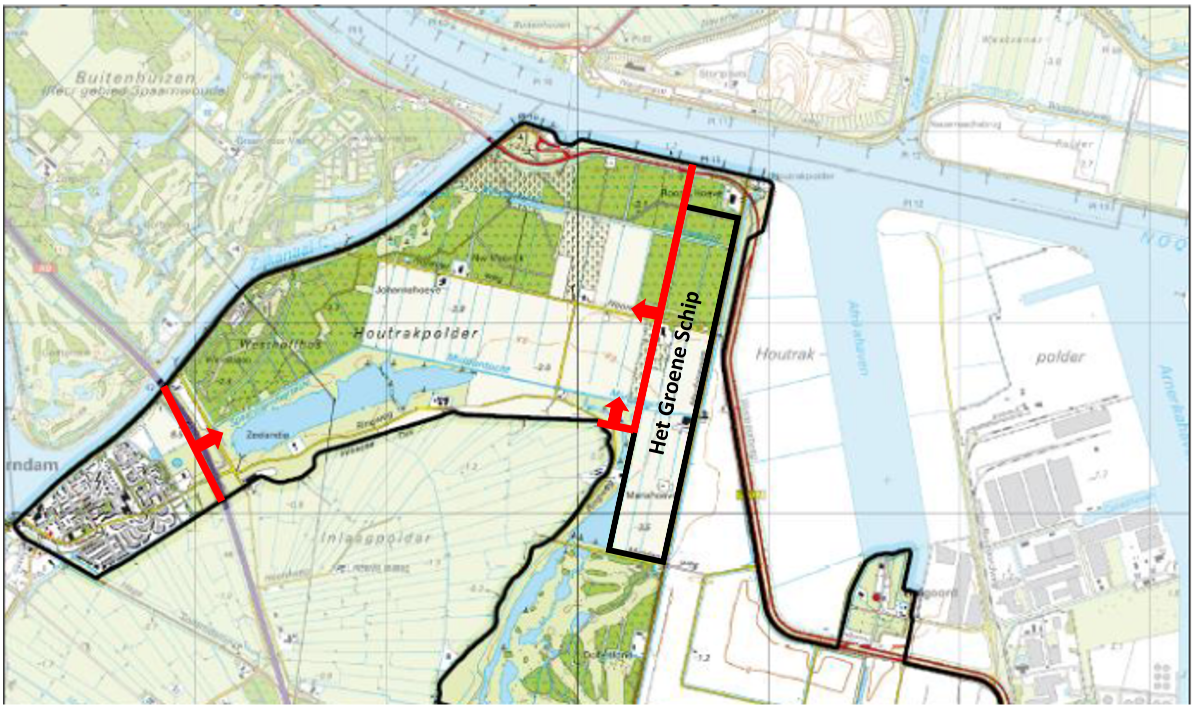

Figure 6.2: Houtrakpolder available area [created by author based on van der Dussen and Buijs-Heine (2019)]

6.1. Design alternatives

To start with the application of the dual-function framework, the 4 conceptual designs introduced in Section 5.2 are evaluated based on the properties of the case. As discussed in Subsection 5.1.2, some defined constraints are case specific and are used to generate design alternatives. The three design alternatives for a dual-function in the Houtrakpolder are visualised in Section 6.1 and will be discussed in the remainder of this section.

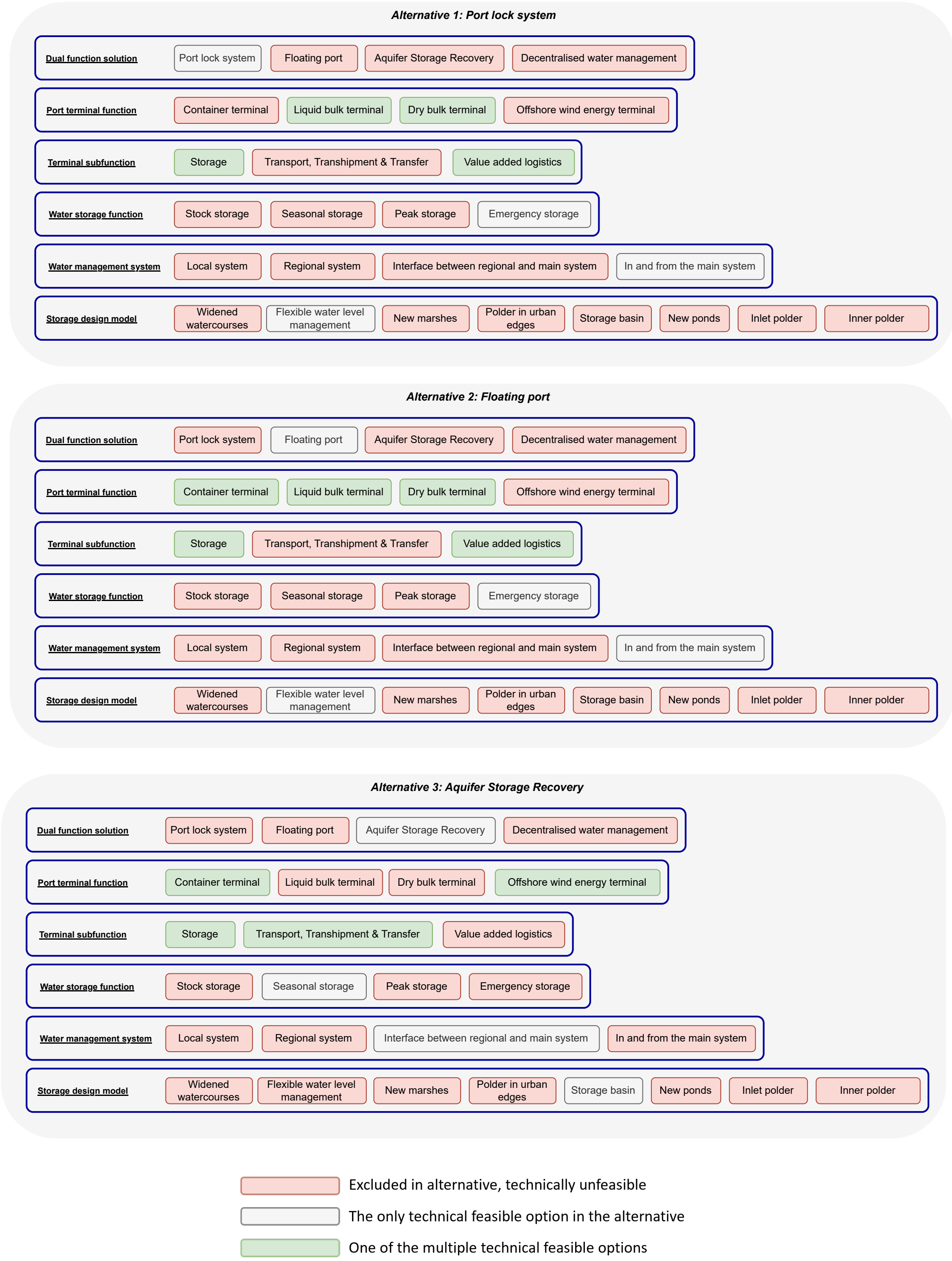

Figure 6.3: Morphological chart of design alternatives Houtrakpolder [created by author]

6.1.1. Water management systems

In order to understand the design alternatives for the Houtrakpolder case, the water management systems involved are first identified. For the Houtrakpolder case, the Noordzeekanaal (NZK) is identified as the main water management system, as discussed in Chapter 3. This means that for Alternative 1, the storage from the main water management system, which was inherent in the first conceptual design, takes into account water storage from the NZK. Similarly, based on Conceptual design 2, for Alternative 2, the storage in the main water management system takes into account the storage in the NZK.

Conceptual design 3, using Aquifer Storage Recovery, could, according to the framework, involve different water management systems. Only the storage of water in and from the main system is excluded by conceptual design. However, it should be noted that the available area shown in Figure 6.2, as a large polder area, is assumed to act on a regional scale in water management. The entire Houtrakpolder, with its 20 groundwater table areas and 3 flood protection structures, is part of the system under the control of the regional water board Rijnland (HvR) (van der Dussen & Buijs-Heine, 2019). Although an ASR of the scale of the area will most likely store water from the regional system, the aquifer will function as a separate underground system. The area would lose its current polder function in the regional system if port functions were realised on the surface. Alternative 3 is therefore categorised as storage at the interface between the regional system and the main system. As water is stored from the regional system and not the local system, Alternative 3 must by definition fulfil the function of seasonal storage (C11).

6.1.2. Hinterland connection

Considering the connection of the potential new port area to the hinterland, 3 constraints are described in Subsection 5.1.2 which are evaluated for the case. Firstly, a liquid bulk terminal should be connected to the hinterland either via road or rail (C5). Secondly, a dry bulk terminal should be connected to the hinterland either via rail or waterways (C7). Thirdly, an offshore wind energy terminal should be connected to the hinterland via road (C10).

As visualised in Figure 6.4, 15 terminals in the port of Amsterdam are connected to the rail network. These include terminals for intermodal (container) transport, dry bulk and wet bulk. The rail network in the port of Amsterdam consists of two main railway stations: Westhaven and Aziëhaven, which are both equipped with overhead lines for electric locomotives and can accommodate trains up to 750 metres long. The port's rail network will be further expanded in the coming years (Port of Amsterdam, 2024a). It is therefore expected that a new port terminal on the available land in the Houtrakpolder could be connected to this existing rail network.

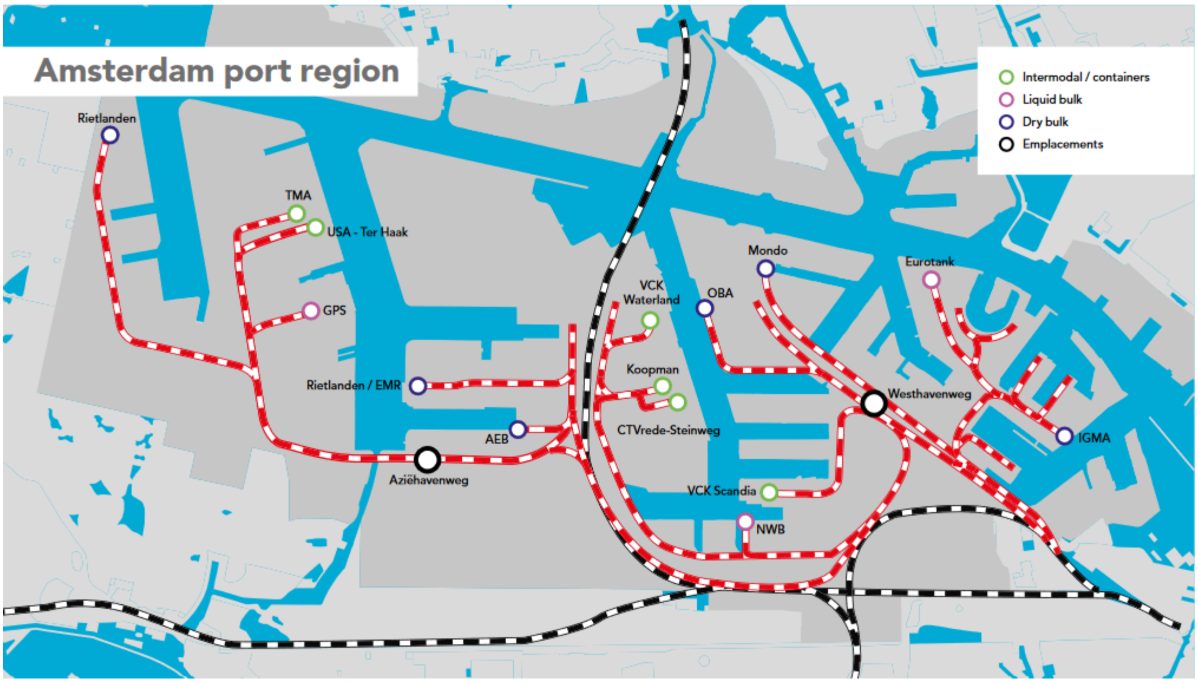

Figure 6.4: Rail transport connections Port of Amsterdam (Brenninkmeijer & Smit, 2020)

The port of Amsterdam also has excellent road connections due to its strong hub function. Schiphol Airport and the city of Amsterdam can be reached within 15 minutes (Port of Amsterdam, 2024a). Figure 6.5 shows how the new port terminal on the available land in the Houtrakpolder can be easily connected to this network via the N202 and S102 motorways. As the new terminal is expected to be connected through the hinterland by rail and road as part of the dual-function system, no port terminal functions need to be excluded for the Houtrakpolder case on the basis of the constraints discussed.

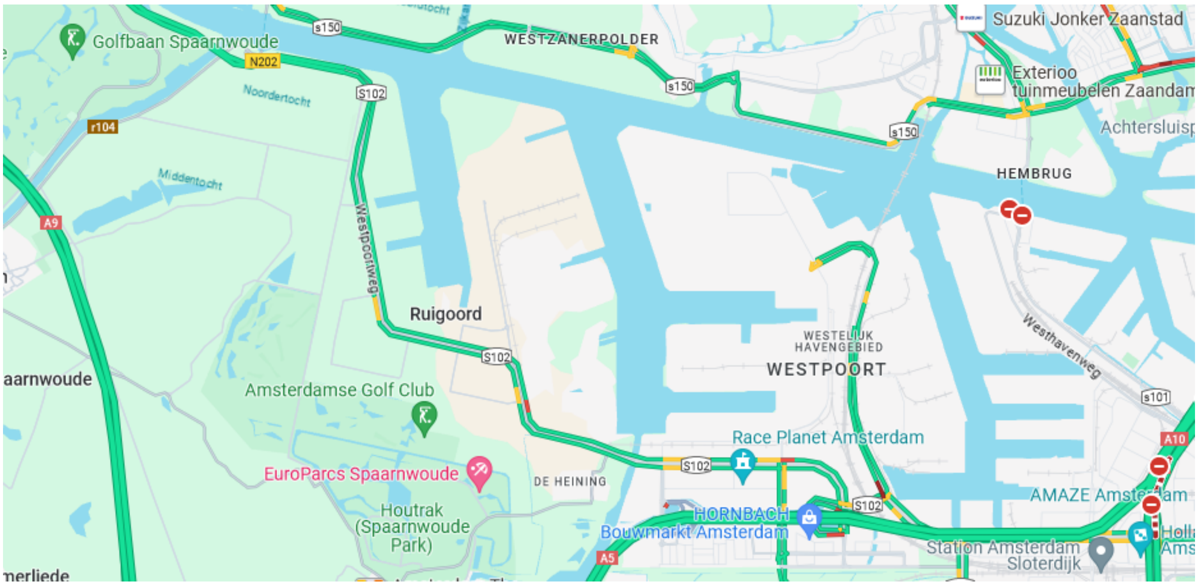

Figure 6.5: Road transport connections Port of Amsterdam (Google, 2024)

6.1.3. Landscape type

Several case-specific constraints on storage design models that can only be realised in certain landscape types are described in Subsection 5.1.2. Most of the constraints are irrelevant because in the conceptual designs of the dual-function, as shown in Section 5.2, only two storage design models remain as feasible: 'Flexible water level management' and 'Storage basin'. The flexible water level management model should be realised in reclamation areas, new urban developments or urban areas (C15). The storage basin model should be realised in reclamation areas or peatland polders (C13).

As discussed in Subsection 3.1.2, a reclamation area, known as a 'droogmakerij' in Dutch, is a clay polder that was originally a lake, other large open water or wetland. As illustrated in Figure 6.6, the soils of the available area in the Houtrakpolder vary in the amount of lime and the coarseness of the clay, but they can all be classified as clay polders.

Figure 6.6: Soil map Houtrakpolder [created by author based on (Ministerie van Infrastructuur & Waterstaat et al., 2024)]

Reclaimed land made Amsterdam the city it is today. The open water between Spaarndammerdijk, Ruigoord and Buitenhuizen was called 't Hout Rack, as shown in Figure 6.7. When the area was drained in 1873, it became the Houtrakpolder, part of a larger land reclamation called the IJpolders (Gemeente Amsterdam, 2024). Therefore, the available area in the Houtrakpolder can be identified as a reclamation area, and no conceptual designs need to be excluded based on the landscape type of the case.

Figure 6.7: Amstelland map with "t Hout Rack' from 1740 (Gemeente Amsterdam, 2024)

6.1.4. Aquifers

Subsequently, 2 constraints related to Aquifer Storage Recovery (ASR) as a dual-function solution are evaluated for the Houtrakpolder case. Firstly, ASR must be implemented in an area with an aquifer of at least 7 metres thick (C29). Secondly, the flow rate at which water can be stored in the aquifer must be greater than the flow rate required to achieve a recovery rate of 50% (C30). For this purpose, a cross section of the soil in the Houtrakpolder area will be analysed. Using a publicly available database, a cross section is made at the solid red line shown in Figure 6.8. The dotted red lines mark the visibility depth of 700m on both sides, which determines the distance from the section line at which measurements and extractions are shown in the section (TNO, 2024).

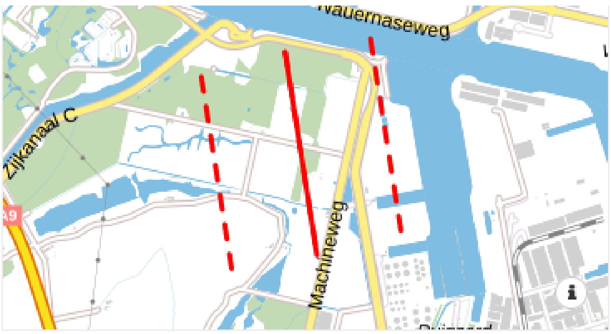

Figure 6.8: Location of cross section soil Houtrakpolder (TNO, 2024)

The cross section is visualised in Figure 6.9 and shows that the soil is composed of several layers of sand and clay. As shown in Figure 4.3, a sand layer between two clay layers can act as an aquifer for an ASR system. Therefore, the closest layer to the surface with these characteristics, the light purple one (KZr3), is identified as a potential aquifer. The layer, known as the Kreftenheye formation, is approximately 20 metres thick, meeting the requirement of 7 metres thickness (C29).

Figure 6.9: Cross section soil Houtrakpolder (TNO, 2024)

The solid red line in Figure 6.9 marks the average brackish-saline boundary for groundwater in the Houtrakpolder area. As the aquifer lies entirely below the brackish-saline boundary, the chloride concentration of the groundwater in this layer is at least 1000 mg/l. In the vicinity of major drainage facilities (rivers and along the reclaimed areas), groundwater flow can locally reach more than 100 m/day. However, in the reclaimed and polder areas the groundwater flow is usually lower, with a maximum of 20 m/year and in many places even less than 10 m/year (van Doorn et al., 2013).

Based on the assumption that chloride concentrations in the Houtrakpolder area are very high and groundwater flow is low, the case is compared with 8 cases analysed by van Doorn et al. (2013) on the suitability of the first aquifer for water storage. It can be concluded that with these soil characteristics the infiltration rate must be greater than 50 cubic meters per hour. According to van Doorn et al. (2013), with a very large Underground Water Storage (UWS) system, as a category shown in Table 6.1, this infiltration rate can be realised to achieve a recovery rate of 60%. Due to the location of the brackish-saline boundary, the chloride concentration is expected to rise well above 1000 mg/L, requiring a very large ASR system to achieve even a 50% recovery rate (C30).

Type of UWS-system	**Infiltration volume per year (especially in winter season)**	**Number of ha required, assuming collection of 200 mm of precipitation per year**	**Global infiltration rate (assuming 150 days per year of infiltration)**
Small	<18,000 m3	<10 ha	<5 m3/h
Medium	18,000 - 36,000 m3	10 - 20 ha	5 - 10 m3/h
Medium-large	36,000 - 90,000 m3	20 - 45 ha	10 - 25 m3/h
Large	90,000 - 180,000 m3	45 - 90 ha	25 - 50 m3/h
Very large	>180,000 m3	>90 ha	>50 m3/h

Table 6.1: Types of underground water storage systems [(van Doorn et al., 2013) adapted by author]

6.1.5. Groundwater level

Finally, the decentralised water management has to be implemented as a dual-function solution by positioning it above the groundwater level (C11). Therefore, the groundwater level in the Houtrakpolder area is analysed. While different soil layers have different groundwater levels, the upper aquifer is analysed, as is the case for ASR systems. Deep, confined aquifers are usually separated from the surface by less permeable layers that restrict the direct downward movement of water from surface infiltration systems. Consequently, while deeper aquifers may contribute to the overall hydrogeology of an area, their interaction with surface-based artificial water buffers (C31) such as infiltration boxes is limited (Water Science School, 2019).

There are only two wells in the Houtrakpolder area from which regular measurements can be assessed. The location of the wells can be found in Figure 6.10. As shown in the measurement series of the first well in Figure 6.11 and the second well in Figure 6.12, the groundwater level in the upper aquifer regularly reaches a level above ground level of -289cm NAP and -323cm NAP at the first and second locations respectively. This has been confirmed by the Province of Noord-Holland, which stated that the Houtrakpolder area has a wet character and (brackish) seepage due to its lower position in relation to the surrounding area. As the artificial water buffers cannot be placed below the groundwater level all year round, decentralised water management as a dual-function solution is not technically feasible and Conceptual design 4 is excluded for the Houtrakpolder case.

Figure 6.10: Groundwater level monitoring well locations (TNO, 2024)

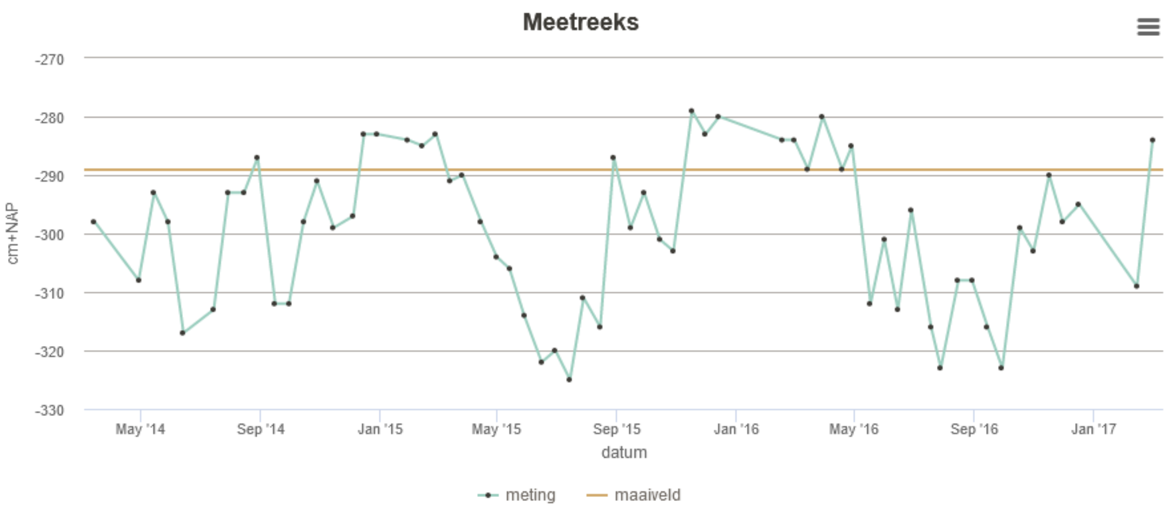

Figure 6.11: Groundwater level Houtrakpolder first monitoring well (TNO, 2024)

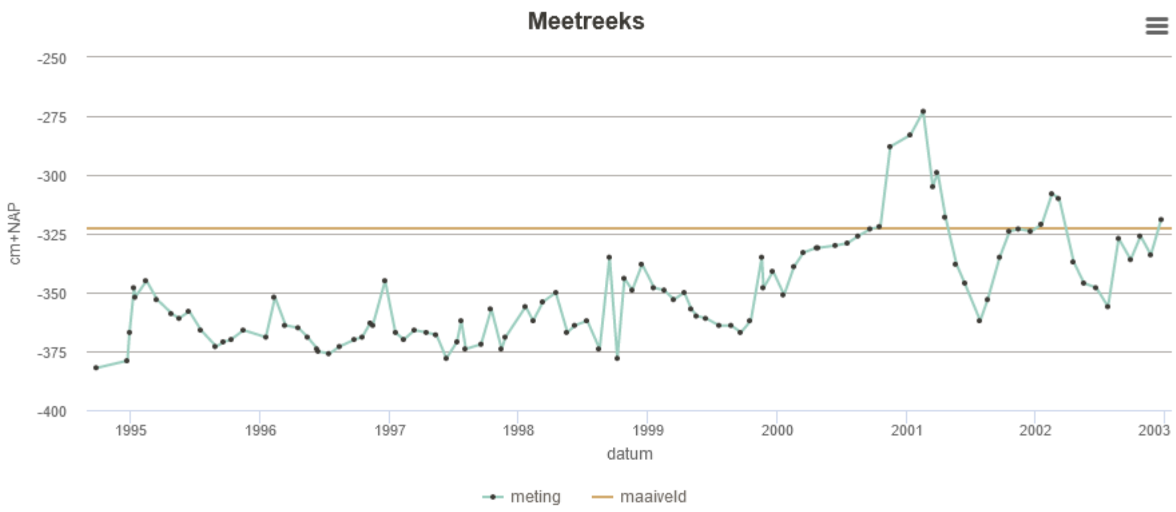

Figure 6.12: Groundwater level Houtrakpolder second monitoring well (TNO, 2024)

6.2. Criteria weights

Based on Subsection 5.3.2, case-specific stakeholders are now defined who act as decision makers in the evaluation of design alternatives. In this section, the decision makers are introduced, after which the Direct Assignment Technique as an MCDM method is performed, as discussed in Subsection 5.3.1. The stakeholders involved in the development of the dual-function in the Houtrakpolder are visualised in Figure 6.13.

As discussed in Subsection 3.5.2, provincial governments play a key role as spatial managers, evaluating and prioritising spatial interests. In the case of the Houtrakpolder, this role is played by the Province of Noord-Holland. The port authority involved is the Port of Amsterdam (PoA). Within the Ministry of IenW, the Directorate-General for Aviation and Maritime Affairs (DGLM) and the Directorate-General for Water and Soil (DGWB) have potentially conflicting interests in the development of the Houtrakpolder and are therefore consulted separately. The Municipality of Amsterdam is involved as the sole shareholder of the Port of Amsterdam and through its role in the spatial development of the city. However, the Houtrakpolder area lies just outside of Amsterdam, in the municipality of Haarlemmermeer.

Rijkswaterstaat West Nederland Noord (RWS-WNN) is the department of RWS that manages the IJsselmeer, the North Sea, the North Sea Canal (NZK) and the Amsterdam-Rhine Canal (ARK). In addition to a number of engineering structures (locks, dams, pumping stations and bridges), RWS-WNN also manages the sea lock of IJmuiden, the North Sea coast and the primary water defences. The 2 water boards involved manage the regional waters, the primary and regional flood defences and the water systems in their own management areas (Werkgroep Water NOVEX NZKG, 2023). Hoogheemraadschap van Rijnland (HvR) manages the water in the area between Velsen and Gouda (Hoogheemraadschap van Rijnland, 2024), which is the regional system on the western side below the NZK. Waterschap Amstel, Gooi en Vecht (AGV) is responsible for the regional system on the east side below the NZK. However, AGV is only responsible for governance, while all tasks have been transferred to Waternet. Waternet, a joint organisation between the municipality of Amsterdam and AGV, also carries out all water-related tasks for the municipality (Waternet, 2024).

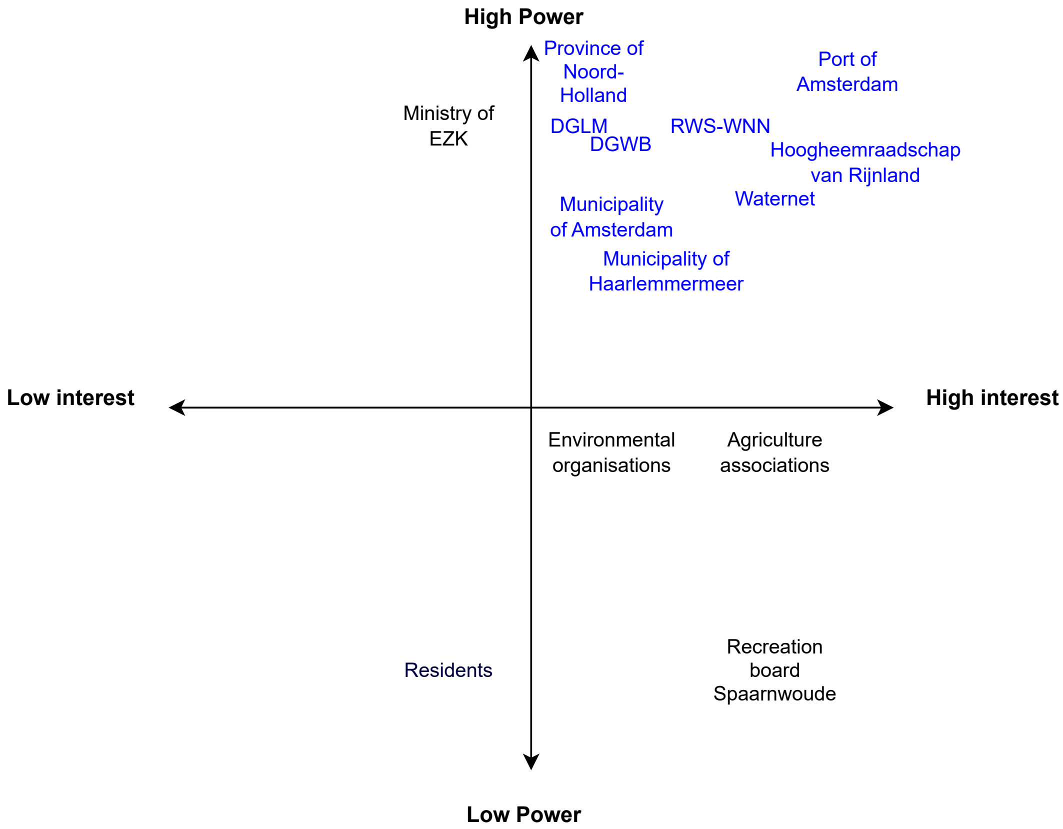

Figure 6.13: Power/interest grid dual-function design Houtrakpolder case [created by author]

A questionnaire was then sent to all the above-mentioned decision-makers to carry out the Direct Assignment Technique (DAT). A situation is outlined where a port terminal - water storage system is to be realised in the Houtrakpolder. The 7 criteria, which refer to the 7 objectives in Subsection 5.1.1, are then described as characteristics of the dual-function system. Moreover, the questionnaire describes the unit in which they are quantified and whether they are maximised or minimised in the most desirable situation. Respondents are then asked to rate each criterion twice on a scale of 0 to 10. Firstly, in an ideal situation, how important the criterion is to the decision-maker's organisation for the optimal functioning of the Houtrakpolder. Secondly, in a realistic situation, how important the criterion is for the optimal but feasible functionality of the Houtrakpolder. The complete questionnaire can be found in Appendix C. The results of the questionnaire, consisting of the points awarded for all criteria, are presented in Table 6.2 and Table 6.3.

It should be noted that no results are given for the Port of Amsterdam, as it was the only stakeholder that chose not to complete the questionnaire. As indicated in the interview, the PoA follows the line regarding the future of the Houtrakpolder as set out in the NOVEX-NZKG development vision (Bestuursplatform NZKG, 2023). For RWS-WNN, the average is calculated from the points awarded by two interviewees from the organisation: a Shipping and Waterways Consultant and a Water Management Strategist.

Organisation	Storage capacity	Storage period	Recovery rate	Physical space	Nautical space	Investment costs	Environmental impact
Province of NH	10	5	1	1	1	10	10
Port of Amsterdam	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DGLM	6	6	8	9	6	8	6
DGWB	8	8	7	0	0	8	8
Mun. Amsterdam	6	6	10	0	0	0	0
Mun. HLM	10	10	10	1	1	1	10
RWS-WNN	8	6.5	5.5	4	4	0.5	2.5
HvR	10	10	5	0	0	8	5
Waternet	10	10	8	1	1	5	8

Table 6.2: Ideal situation: awarded points for criteria

Organisation	Storage capacity	Storage period	Recovery rate	Physical space	Nautical space	Investment costs	Environmental impact
Province of NH	10	5	1	1	1	10	10
Port of Amsterdam	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DGLM	9	10	9	10	3	4	3
DGWB	8	8	6	0	0	8	7
Mun. Amsterdam	6	6	10	0	0	0	0
Mun. HLM	10	10	10	1	1	1	10
RWS-WNN	6	4	3.5	2.5	2.5	0	2.5
HvR	10	0	5	0	0	8	5
Waternet	8	8	7	1	1	5	8

Table 6.3: Realistic situation: awarded points for criteria

To analyse the impact of the two situations outlined in the questionnaire, the points awarded in the ideal situation are subtracted from the points awarded in the realistic situation. The results are shown in Table 6.4, and show that the average importance of the criteria in a realistic situation is only marginally lower than in the ideal situation. Therefore, the ideal situation, which describes how important the criterion is for the optimal functioning of the Houtrakpolder, will be used in the remainder of the MCDM. In this initial phase of the development of the dual-function design, the analysis of the non-bounded interests of the stakeholders is considered to be the most valuable insight. Moreover, the sensitivity of the criteria weights will be analysed in Section 6.5.

Organisation	Storage capacity	Storage period	Recovery rate	Physical space	Nautical space	Investment costs	Environmental impact
Province of NH	0	0	0	0	0	0	0
Port of Amsterdam	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DGLM	3	4	1	1	-3	-4	-3
DGWB	0	0	-1	0	0	0	-1
Mun. Amsterdam	0	0	0	0	0	0	0
Mun. HLM	0	0	0	0	0	0	0
RWS-WNN	-2	-2.5	-2	-1.5	-1.5	-0.5	0
HvR	0	-10	0	0	0	0	0
Waternet	-2	-2	-1	0	0	0	0
Average	-0.1	-1.2	-0.3	-0.1	-0.5	-0.5	-0.4

Table 6.4: Difference ideal and realistic situation: awarded points for criteria

Subsequently, as discussed in Subsection 5.3.1, the MCDM method then asks to normalise the points so that they sum to one and can be used as weights. For this purpose. the formula presented in Equation 6.1 is applied. The normalised criteria weights in the ideal situation are shown in Table 6.5.

$$w_i' = \frac{w_i}{\sum_{j=1}^{n} w_j}$$

s.t.

w_i' := Normalised weight criterion i (6.1)

w_i := Points awarded criterion i

n := Number of criteria

Organisation	Storage capacity	Storage period	Recovery rate	Physical space	Nautical space	Investment costs	Environmental impact
Province of NH	0.26	0.13	0.03	0.03	0.03	0.26	0.26
Port of Amsterdam	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DGLM	0.12	0.12	0.16	0.18	0.12	0.16	0.12
DGWB	0.21	0.21	0.18	0.00	0.00	0.21	0.21
Mun. Amsterdam	0.27	0.27	0.45	0.00	0.00	0.00	0.00
Mun. HLM	0.23	0.23	0.23	0.02	0.02	0.02	0.23
RWS-WNN	0.26	0.21	0.18	0.13	0.13	0.02	0.08
HvR	0.26	0.26	0.13	0.00	0.00	0.21	0.13
Waternet	0.23	0.23	0.19	0.02	0.02	0.12	0.19

Table 6.5: Normalised criteria weights (ideal situation)

Although it is expected that the Port of Amsterdam will be an exception, the resulting normalised weights indicate that storage capacity and storage time play a crucial role in the development of a dual-function system in the Houtrakpolder for all stakeholders. The recovery rate is of high importance for both municipalities, of low importance for the province and of medium importance for other stakeholders. While the Port of Amsterdam is expected to prioritise physical and nautical port space, only the DGLM and Rijkswaterstaat among other stakeholders consider these criteria to be of great importance. Minimising investment costs is not seen as an objective by either the municipalities or Rijkswaterstaat, although the Province places a high value on this criterion. Minimising environmental impact is highly valued by the municipality of Haarlemmermeer and the Province, but is considered to be of low importance by the municipality of Amsterdam and Rijkswaterstaat. In conclusion, the consulted stakeholders agree on the objectives related to water storage in the development of a dual-function system in the Houtrakpolder, while there are considerable differences in the evaluation of the other objectives.

6.3. Criteria performance

After determining the criteria weights using the Direct Assignment Technique, the next step in MCDM is to evaluate the alternatives' performance on the 7 criteria. Each criterion has been introduced in Subsection 5.1.1 as an objective in the design of a dual-function system. In this section the criteria are evaluated for the three feasible design alternatives for the Houtrakpolder case as defined in Section 6.1. The results are presented in the criteria performance matrix in Table 6.6.

Criterion	Unit	Max/min	Alt. 1: Port lock system	Alt. 2: Floating port	Alt. 3: ASR
Storage capacity	m^3 (million)	max	2.85	0.42	1.18
Storage period	dagen	max	0.66	0.1	183
Recovery rate	%	max	0	0	50
Physical space	hectares	max	160	105	145
Nautical space	hectares	max	50	105	50
Investment costs	€ (million)	min	620.2	1303.2	44.6
Environmental impact	Scale 0-5	min	5	1	3

Table 6.6: Criteria performance matrix

However, as shown in Table 6.6, the criteria are quantified in different units of measurement and are based on an objective that is either maximised or minimised. Therefore, the criteria performance matrix is normalised according to the formula described in Equation 6.2, resulting in the normalised performance matrix in Table 6.7. The remainder of this section describes how the performance of each criterion is derived for each design alternative.

$$x'_k = \begin{cases} \frac{x_k}{\max\{x_i\}} & \text{if } x \text{ is maximised} \\ 1 - \frac{x_k}{\max\{x_i\}} & \text{if } x \text{ is minimised} \end{cases}$$
$$\text{s.t.}$$
$$x'_k = \text{Normalised criterion performance alternative } k$$
$$x_k = \text{Criterion performance alternative } k$$
$$x_i = \text{Performance on all alternatives} \tag{6.2}$$

Criterion	Alt. 1: Port lock system	Alt. 2: Floating port	Alt. 3: Aquifer Storage Recovery
Storage capacity	1.00	0.15	0.41
Storage period	0.00	0.00	1.00
Recovery rate	0.00	0.00	1.00
Physical space	1.00	0.66	0.91
Nautical space	0.48	1.00	0.48
Investment costs	0.52	0.00	0.97
Environmental impact	0.00	0.80	0.40

Table 6.7: Normalised performance matrix

6.3.1. Storage capacity

The storage capacity refers to the first objective (O1) in Subsection 5.1.1. For the three design alternatives of the Houtrakpolder case, the total water storage capacity of the area in cubic metres is now evaluated.

Alt. 1: Port lock system

As in the port lock system alternative water is stored behind the lock, the storage capacity depends on the dimensions of the port basin. Considering the available area in the Houtrakpolder, as shown in Figure 6.2, it is assumed that a new port basin of maximum length would be built parallel to the adjacent port basin and with a similar width as this port basin. This results in a port basin of 50 hectares (1250 metres long and 400 metres wide), visualised in Figure 6.14.

As flexible water level management is applied in this alternative, the storage design model does not limit water level fluctuations. Instead, a comparison is made with the lock system in the Port of Antwerp. As discussed in Section 1.2, parts of the port area have been constructed with dock systems positioned behind locks to cope with the high tidal range of the river leading to the port. This river has a tidal range of 3.5m near the northern part of the port and 5.7m near the city centre (Notteboom et al., 2022). It is therefore assumed that a port basin behind a lock in the Houtrakpolder could cope with water level fluctuations of 5.7 metres. Multiplying the 50 hectares by the water level fluctuations, the first alternative is estimated to have a water storage capacity of 2.85 million cubic metres.

Figure 6.14: Port basin [created by author based on Google (2024)]

Alt. 2: Floating port

The second alternative consists of floating port infrastructure on a body of water as an extension of the main water system. In the case of the Houtrakpolder, a lake of the size of the available area discussed in Figure 6.2 could be created as an extension of the North Sea Canal. The total area of the new lake would be approximately 210 hectares, as visualised in Figure 6.15.

As for the first alternative, flexible water level management is applied, which, as a storage design model, does not limit water level fluctuations. However, as it is assumed that no lock will be used, the water level fluctuations are equal to the fluctuations of the North Sea Canal. According to RWS-WNN, the control margins of the NZK are between -0.30m NAP and -0.50m NAP, resulting in water level fluctuations of 0.20m [Appendix B.1]. Multiplying the 210 hectares by the water level fluctuations, the second alternative is estimated to have a water storage capacity of 0.42 million cubic metres.

Figure 6.15: Port pond [created by author based on Google (2024)]

Alt. 3: Aquifer Storage Recovery

For the ASR alternative, the storage capacity is based on the dimensions of the aquifer used. As discussed in Subsection 6.1.4, the aquifer in the Houtrakpolder is approximately 20 metres thick, and a very large ASR system is required to achieve a 50% recovery rate, given the local soil characteristics. For the very large system, Table 6.1 indicates a minimum capacity of 180,000 cubic metres and a surface area of 90 hectares, assuming 200 mm of precipitation per year.

However, if port functions were to take place in the same area, the presence of industrial activities often result in the introduction of pollutants like heavy metals and organic contaminants into the groundwater system. These contaminants can derive from various industrial discharges and runoff, which potentially degrade water quality and complicate the water recovery process (Chen et al., 2022). If water from outside the area but from the regional water system is stored, there is no need for a 90 hectares area, but port functions in the same area are still expected to contaminate the groundwater. Therefore, for the third alternative of the case, a separate area of 15 hectares to the right of the port basin is designated for underground storage, as shown in Figure 6.16.

The storage capacity is not equal to the total volume of the aquifer, but depends on the porosity of the sand in the soil layer. The Kreftenheye Formation typically consists of yellow-grey to grey-brown, medium to very coarse sand (210-2000 μm) (TNO innovation for life, 2024). Olsthoorn (1997) defines 4 categories of sand with different water storage coefficients based on their porosity. The category with sand between 850 and 1410 μm, which is considered to be the most similar, has an estimated storage coefficient of 36% (Olsthoorn, 1997). Multiplying this coefficient by the dimensions of the aquifer, the ASR system is estimated to have a water storage capacity of 1.08 million cubic metres. Finally, 0.1 million cubic metres of water can be stored in the port basin adjacent to the ASR system, based on a 50-hectares port basin with a water level fluctuation of 0.2m. Therefore, the third alternative is estimated to have a total water storage capacity of 1.18 cubic metres.

Figure 6.16: ASR next to port basin [created by author based on Google (2024)]

6.3.2. Storage period

As discussed in Subsection 5.1.1, the storage period should be estimated based on the solution's storage function and its infiltration flow rate. If the storage area is only used for peak storage, its capacity can be reached in a few hours, and it loses its function until it is emptied again. However, depending on the storage area, water could be stored for a longer period and fulfil a stock storage or seasonal storage function.

Alt. 1: Port lock system

For an alternative fulfilling a peak or emergency storage function, the storage period refers to the time it takes to relieve the system. It is assumed that once the storage capacity is reached, the storage will no longer be able to perform this function. Therefore, the storage capacity for alternatives 1 and 2 is equal to the time it takes to fill the water storage to full capacity. The Hoogheemraadschap van Rijnland (HvR) argued that to be effective as emergency storage from the North Sea Canal, the infiltration rate must be at least 50 cubic metres per second [Appendix B.5]. By dividing the water storage capacity by the infiltration rate, the water storage period of the alternative is estimated to be 15.8 hours, which is equivalent to 0.66 days.

Alt. 2: Floating port

Similar to the first alternative, by dividing the water storage capacity by the infiltration rate, the water storage period of the second alternative is estimated to be 2.3 hours, which is equivalent to 0.1 days.

Alt. 3: Aquifer Storage Recovery

For an alternative with a seasonal storage function, the storage period refers to the entire seasonal period during which it can counteract water shortages and thus fulfil its function. In the Netherlands, the dry season starts around 1 April, when water temperatures rise and plants and trees grow faster, leading to an increased demand for water and thus increasing the likelihood of water shortages (Rijkswaterstaat, 2024c). KNMI's calculation of the potential precipitation deficit is stopped on 30 September each year because in autumn the potential evaporation of the reference crop becomes small and is almost always negligible compared to the amount of rainfall (Ministerie van Infrastructuur en Waterstaat, 2024). Therefore, it is assumed that the period of higher risk of water shortage is approximately from

April to September and an ASR system will operate accordingly. As a result, the water storage period for the third alternative is estimated to be 6 months, which is equivalent to 183 days.

6.3.3. Recovery rate

As discussed in Section 4.3, the recovery rate indicates the proportion of stored water of acceptable quality that can be recovered to combat water shortages.

Alt. 1: Port lock system

By definition, the water in a design alternative that fulfils an emergency water storage function cannot be recovered. Moreover, if it were to be recovered, it would be of unacceptable quality as it would be saline and contaminated water from the NZK, the main water system. Therefore, the recovery rate of the first alternative is set to 0%.

Alt. 2: Floating port

For similar reasons to the first alternative, the recovery rate of the second alternative is set to 0%.

Alt. 3: Aquifer Storage Recovery

As discussed in Section 4.3, recovery rate estimates for ASR systems can be conservatively set at around 50%. In saline environments, scaling up and improving well configurations could be used to improve recovery rates. However, for ASR to be effective, the infiltration flow rate must be greater than the flow rate required to achieve the recovery rate (C30). As described in Subsection 6.1.4, the Houtrakpolder case requires a very large ASR system to achieve a 50% recovery rate. Therefore the recovery rate of the third alternative is set to 50%.

6.3.4. Physical space

As introduced in Subsection 5.1.1, the physical port area refers to the space on land, on or along a quay, for the performance of one of the defined port (sub)functions. As visualised in Figure 6.15, the total space available in the Houtrakpolder for the dual-function system is 210 hectares.

Alt. 1: Port lock system

For the port lock system alternative, the port basin of 50 hectares, as visualised in Figure 6.14, is the only area that cannot be applied for port terminal functions on land. Therefore, the available physical port space for the first alternative is estimated to be 160 hectares.

Alt. 2: Floating port

In the system proposed by the floating port alternative, the defined (sub)functions that are normally performed on land, on or along a quay, are performed on floating platforms. Therefore, the physical space as defined refers to the platform space in this dual-function alternative. As visualised in Figure 6.15, the total area of the new lake would be approximately 210 hectares. It is assumed that half of the water storage area would be used for port infrastructure on floating platforms. Therefore, the available physical port space for the second alternative is estimated to be 105 hectares.

Alt. 3: Aquifer Storage Recovery

Similar to the first alternative, the 50 hectares port basin adjacent to the ASR system, as visualised in Figure 6.16, cannot be used for onshore port terminal functions. In addition, as port (sub)functions are expected to contaminate the groundwater, they cannot be carried out on the surface area of 15 hectares above the aquifer. Therefore, the available physical port area for the third alternative is estimated to be 145 hectares.

6.3.5. Nautical space

As introduced in Subsection 5.1.1, the nautical port space refers to the waterways that can be used to perform the defined port (sub)functions.

Alt. 1: Port lock system

For the lock system alternative, it has been assumed that the nautical space consists of the entire port basin including the lock itself. Therefore, the available nautical port space for the first alternative is estimated to be 50 hectares.

Alt. 2: Floating port

For the floating port alternative, as discussed for the physical space criterion, it is assumed that half of the water storage area would be used for port infrastructure on floating platforms. As a result, the other half consists of open water, as part of the new lake, which can be used for nautical port functions. Therefore, the available nautical port space for the second alternative is estimated at 105 hectares.

Alt. 3: Aquifer Storage Recovery

Similar to the first alternative, the nautical space of the ASR alternative was assumed to be the entire port basin. For this dual-function solution, no lock system is installed. Considering the dimensions of the port basin, the available nautical port space for the third alternative is estimated at 50 hectares.

6.3.6. Investment costs

Before evaluating the specific investment costs of the three design alternatives, the economic value of the land is analysed in the case of the Houtrakpolder, as Massop et al. (2015) identified this value as a decisive factor in whether or not an area should be designated as a water storage area. They argued that urban buildings, infrastructure and greenhouse horticulture, for example, have such a high economic value that they are not considered as storage areas. For this purpose, estimates were made of the economic value of rural land uses in the Netherlands, as shown in Figure 6.17.

LGN code	omschrijving	econ.waarde (€ / ha)	LGN code	omschrijving	econ.waarde (€ / ha)
1	agrarisch gras	2000	24	kale grond in bebouwd gebied	2000
2	mais	2000	25	hoofdwegen en spoorwegen	100000
3	aardappelen	4000	26	bebouwing in buitengebied	2000
4	bieten	3000	28	gras in secundair bebouwd gebied	2000
5	granen	2000	30	kwelders	500
6	overige gewassen	10000	31	open zand in kustgebied	500
8	grastuinbouw	50000	32	duinen met lage vegetatie	500
9	boomgaarden	30000	33	duinen met hoge vegetatie	500
61	boomkwekerijen	40000	34	duinheide	500
62	fruitkwekerijen	25000	35	open stuifzand en rivierzand	500
10	bloembollen	25000	36	heide	500
11	loofbos	500	37	matig vergraste heide	500
12	naaldbos	500	38	sterk vergraste heide	500
16	zoet water	-	39	hoogveen	500
17	zout water	-	40	bos in hoogveengebied	500
18	bebouwing in prim. bebouwd gebied	2000	41	overige moerasvegetatie	500
19	bebouwing in sec. bebouwd gebied	2000	42	rietvegetatie	500
20	bos in prim. bebouwd gebied	2000	43	bos in moerasgebied	500
22	bos in sec. bebouwd gebied	2000	45	natuurgraslanden	500
23	gras in prim. bebouwd gebied	2000			

Figure 6.17: Estimates of the economic value of rural land use forms in the Netherlands (Massop et al., 2015)

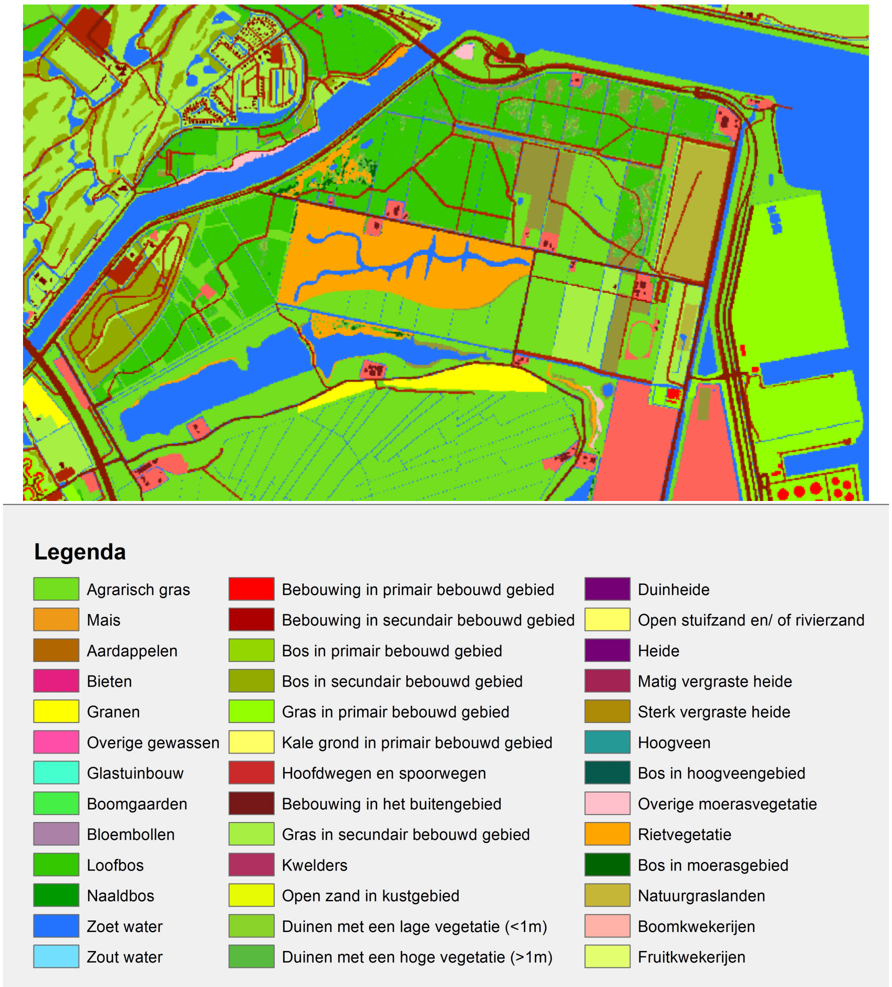

Figure 6.18: Rural land use in the Houtrakpolder [created by author based on Wageningen University & Research (2024a)]

The similar rural land uses in Figure 6.17 are identified in the Houtrakpolder area as visualised in Figure 6.18. Deciduous forest (loofbos) is the dominant rural land use with an economic value of 500 euros/ha. The remaining rural land uses are agricultural grass (2000 euro/hectare), reed (500 euro/hectare) and freshwater (0 euro/hectare). It is therefore assumed that the average economic value of the land in the available area of the Houtrakpolder is 500 euro/hectare, with a total value of 105,000 euro.

It should be noted, however, that this is not an indicator of the purchase price of land in the area. The municipality of Haarlemmermeer, as the owner of the land, emphasises that the land price memorandum is secret in nature (Gemeente Haarlemmermeer, 2024). In view of the municipality's interest, the purchase price is expected to be many times higher than the economic value discussed. In this case, however, it remains unclear whether land should actually be purchased in the Houtrakpolder in order to realise the dual-function. For this reason, and the fact that the total available area of all three design alternatives is similar, the land price is neglected for this case application of the MCDM.

Alt. 1: Port lock system

As discussed in Subsection 5.1.1, the investment costs include the public construction costs of all main infrastructure required for the port function(s) and water storage function(s) of the dual-function solution, as well as the costs of fitting the solution into the area. The total investment costs for the port lock alternative include the investment costs for the lock, the new port basin and dredging. For the sea lock, a comparison is again made with the port of Antwerp, where a lock (De Royerssluis) will be renewed from 2021 to 2026. The contractor will demolish the current lock, construct the enlarged lock chamber, supply and install two lock gates and two bridges as well as electromechanical control of the entire lock (Artes Group, 2024). This new lock, with an investment cost of 280 million euros, can be compared to the Houtrakpolder lock with its length of 36 metres.

In 1993, the Port of Amsterdam (PoA) applied for a loan of 32.3 million euros for the construction of the Afrikahaven and related infrastructure (Rekenkamer Amsterdam, 2005). Taking into account an average inflation rate of 2.12% per year (Alioth LLC., 2024), the value of a €32.3 million investment in 1993 would be approximately €56.9 million in 2024. The Afrikahaven, next to the new basin of the alternative, has a similar width of 400m, but is 1900m long instead of 1250m. Assuming that investment costs are proportional to the length of the basin, the cost of the new port basin is estimated at 37.4 million euros.

As discussed, the control margins of the NZK are between -0.30m NAP and -0.50m NAP. The average ground level in the Houtrakpolder area is -2.89m NAP (TNO, 2024). This means that if the port basin is created in the area and the water is at the lower level of -0.50 NAP, the depth for ships is only 2.39 metres. The North Sea Canal is currently 15 metres deep (-15m NAP) up to Mercuriushaven, which is much further up the canal (Port of Amsterdam, 2024b). Therefore, the port basin created in the Houtrakpolder needs to be dredged to additional depth of at least 12.11 metres in order to enable the general port operations of the Port of Amsterdam. Considering the dimensions of the port basin, 6.055 million cubic metres should be dredged. Due to the new regulations regarding PFAS contamination in the Netherlands, dredging prices per square metre could be as high as 50 euros per cubic metre (Maritiem Nederland, 2024). The cost of additional dredging is therefore estimated at €302.8 million. In total, the investment costs for the first alternative in the Houtrakpolder area are estimated at 620.2 million euros.

Alt. 2: Floating port

The total investment costs for the floating port alternative include the investment costs for the creation of a new lake and additional dredging. It should be noted that the costs of the floating infrastructure are not included as they are assumed to be borne by the terminal operators. As for the other alternatives, based on the assumed landlord port model in Chapter 2, the terminal investments are not for the public port authority but for a private terminal investor. Investment costs for any additional supporting floating infrastructure are neglected.

The creation of a new lake in the Houtrakpolder can be compared to the construction of an inlet polder, but one that is permanently filled. In 2016, the Nieuwe Driemanspolder was built, an inlet polder within the regional water system of the Hoogheemraadschap van Rijnland (HvR). The cost, excluding the purchase of land, was around 40 million euros (Hoogheemraadschap van Rijnland, 2016). Taking into account an average inflation rate of 3.08% per year (Alioth LLC., 2024), the value of a €40 million investment in 2016 would be approximately €51.0 million in 2024. The construction transformed a 350 hectares agricultural area, mainly grassland, into a nature recreation area with peak storage (Hoogheemraadschap van Rijnland, 2016). Assuming that the investment costs are proportional to the area of the inlet polder, the cost of creating the new lake is estimated at 30.6 million euros.

Similar to the port basin, the new lake to be created in the Houtrakpolder needs to be dredged to additional depth of at least 12.11 metres in order to enable the general port operations of the Port of Amsterdam. Considering the dimensions of the lake, 6.055 million cubic metres should be dredged. At a similar dredging price of 50 euros per square metre as for the second alternative, the total dredging costs are estimated at 1271.6 million euros. In total, the investment costs for the second alternative in the Houtrakpolder area are estimated at around 1.3 billion euros.

Alt. 3: Aquifer Storage Recovery

The total investment costs for the Aquifer Storage Recovery (ASR) alternative include the investment costs for a new port basin and the ASR system. Similar to the first alternative, the cost of the new port basin is estimated at 37.4 million euros.

Three urban underground water storage concepts have been identified by STOWA (2016) and their investment costs have been estimated, as visualised in Figure 6.19. As discussed, a very large ASR system, as a category shown in Table 6.1, is required to achieve the 50% recovery rate in the Houtrakpolder. Direct underground storage (Concept 1) processes large volume flows with infiltration rates up to 200 m³/h. This requires different treatment methods than Concepts 2 and Concept 3. Assuming the supply of roof run-off water, a simple pre-treatment consisting of a 'bypass' of the first run-off rainwater and a dirt screen for the pump is sufficient (STOWA, 2016).

Figure 6.19: Estimate of investment costs for three concepts of urban underground water storage (STOWA, 2016)

Therefore, the cost of the ASR system is assumed to be similar to the €80,000 per hectare of the first concept, totalling €1.2 million for the area. However, the costs shown in the Figure 6.19 do not include the cost of redirecting the drainage system to supply the wells, which can add up to €400,000 per hectare (STOWA, 2016). Together with the 6 million euros for disconnection, the total investment costs for the third alternative are estimated at 44.6 million euros.

6.3.7. Environmental impact

As introduced in Subsection 5.1.1, the environmental impact of a design alternative consists of CO2 emissions and the impact on agriculture, nature, biodiversity and a green living environment. For this criterion, one point is awarded for each of these impacts if the negative impact on the environment is significant. The environmental performance is therefore measured on a scale of 0 to 5, with a score of 0 indicating no significant negative impact. This is the only criterion that is measured beyond the boundaries of the Houtrakpolder area, as visualised in Figure 6.2.

Alt. 1: Port lock system

As discussed in Section 4.1, studies, such as those focussing on the port of Incheon, show that lock-related activities, such as vessel transit and post-lock manoeuvring, are major contributors to CO2 emissions in ports (+1). Due to the storage of water from the main system, salinisation and contamination of surface and groundwater are expected to limit agricultural land use in the region. In addition, the emergency storage function does not address water scarcity, which affects agriculture through direct supply or prevention of land subsidence (+1).

As mentioned in Subsection 3.5.2, from a nature conservation perspective, salinisation presents both threats and opportunities. However, in view of the water pollution and the available space, if Alternative 1 is implemented, nature as a spatial function will disappear from the Houtrakpolder area (+1). Due to the construction of a port basin and all the noise and air pollution from the port operations, it is expected that all biodiversity will also disappear from the area (+1).

The Houtrakpolder area is now referred to as 'green and open' due to its large size as a reclamation area and the contrasts between wooded areas and open farmland (Gemeente Haarlemmermeer, 2022). It is expected that with a new port basin, the area will no longer have this green and open character and there will no longer be space for recreation as a spatial function (+1). In conclusion, the port lock system alternative in the Houtrakpolder receives a maximum score of 5 for negative environmental impacts.

Alt. 2: Floating port

As mentioned in Section 4.2, the floating port solution offers some environmental benefits, including lower greenhouse gas emissions, compared to conventional port infrastructure (+0). Similar to the first alternative, salinisation and contamination of surface and groundwater are expected to limit agricultural land use in the region, while the emergency storage function does not address water scarcity (+1).

As discussed in Subsection 3.5.2, managing salinisation by allowing sea level rise and natural water level fluctuations can create opportunities for the emergence of new brackish nature with species that have become rare due to the closure of sea arms (+0). In addition, as mentioned in Subsection 3.1.2, biodiversity can be supported by more closely mimicking natural conditions and contributing to the development of nature-friendly shores (+0).

Finally, as a new lake is created instead of a port basin with onshore infrastructure, the Houtrakpolder area is perceived as maintaining its green and open character (+0). In conclusion, the floating port alternative in the Houtrakpolder receives a score of 1 for negative environmental impacts.

Alt. 3: Aquifer Storage Recovery

Although the ASR alternative does not use a lock system, the CO2 emissions from conventional port infrastructure and the construction of multiple wells for underground storage are expected to result in significant CO2 emissions (+1). As discussed in Section 4.3, ASR systems have been widely applied to agricultural use cases. With its seasonal storage function, the third alternative addresses water scarcity, which can be used for direct agricultural purposes (+0). In addition, long-term water storage can also contribute to buffering towards groundwater or to making areas around the disposal site wetter. In this way, the alternative also contributes to the problems of water scarcity for nature in the Houtrakpolder region (+0).

Similarly to the first alternative, the construction of a port basin and all the noise and air pollution from port operations is expected to result in the loss of all biodiversity in the area (+1). Also, with a new port basin, the area will no longer have its green and open character and there will no longer be space for recreation as a spatial function (+1). In conclusion, the ASR alternative in the Houtrakpolder receives a score of 3 for negative environmental impacts.

6.4. MCDM results

Subsequently, for all three alternatives, the normalised weights in Table 6.5 are multiplied with the normalised performance values in Table 6.7, in accordance with the additive value function in Equation 5.1. The results of the MCDM for the dual-function system are presented in Table 6.8.

	Alt. 1: Port lock system	**Alt. 2: Floating port**	**Alt 3. : Aquifer Storage Recovery**
Province of NH	0,44	0,29	0,66
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,45	0,36	0,77
Ministry of IenW (DGWB)	0,31	0,19	0,75
Municipality Amsterdam	0,27	0,04	0,84
Municipality HLM	0,28	0,26	0,71
RWS-WNN	0,46	0,32	0,72
HHS Rijnland	0,37	0,14	0,76
Waternet	0,33	0,22	0,73

Table 6.8: Results MCDM (ideal situation)

6.4.1. Interpretation

The MCDM results, consisting of the total additive value of the 7 defined criteria for the three design alternatives in Table 6.8, are interpreted in this section. As defined in the dual-function framework, for the Houtrakpolder case a separate MCDM was performed for each stakeholder, based on the criteria weights defined in the questionnaire. As no group decision making method is performed, no conclusion can be drawn regarding the best alternative for the group of stakeholders. However, it should be noted that for each decision maker the Aquifer Storage Recovery alternative (Alt. 3) has the highest overall value and the Port Lock System alternative (Alt. 1) has the second highest value.

Province of Noord-Holland

In the questionnaire, the Province of Noord-Holland assigned a maximum importance score of 10 to the criteria storage capacity, investment costs and environmental impact. In terms of investment costs, Alternative 3 outperforms the other alternatives with relatively very low investment costs, resulting in a normalised performance score of 0.97. In terms of storage capacity and environmental impact, the third alternative performs moderately, while Alternatives 1 and 2 are preferred for maximum storage capacity and environmental impact respectively. Therefore, although Alternative 3 has the highest score, its additive score of 0.66 is relatively low compared to the results for other stakeholders and close to the additive scores of Alternatives 1 and 2. In addition, the Province of Noord-Holland gave the storage period criterion an importance score of 5, while the remaining criteria received a marginal score of 1. Therefore, the storage period of half a year for ASR, compared to a fraction of a day for the other alternatives, also contributes to the Province's preference for the third alternative.

Ministry of IenW

As discussed in Section 6.2, within the Ministry of IenW the Directorate-General for Aviation and Maritime Affairs (DGLM) and the Directorate-General for Water and Soil (DGWB) have potentially conflicting interests in the development of the Houtrakpolder and are therefore consulted separately. The DGWB assigned a minimum importance score of 0 to the port-related criteria physical space and nautical space, while the DGLM assigned a score of 9 and 6 respectively. All other criteria were considered moderately important by both Directorates with scores between 6 and 8. For the DGLM, who is also the commissioner for this study, the questionnaire showed the least difference in importance between the 9 criteria, with the normalised weights of the criteria all between 0.12 and 0.18. As Alternative 3 has the highest performance score for 3 of the 7 criteria and the lowest score for none of the criteria, the ASR alternative is dominant in this case of constant criteria weights. Compared to the DGWB, Alternative 1 scores relatively high for the DGLM due to its maximum relative performance on physical space, and Alternative 2 scores relatively high for the DGLM due to its maximum relative performance on nautical space.

Municipalities

The Municipality of Amsterdam is involved in the development of the Houtrakpolder as the sole shareholder of the Port of Amsterdam and through its role in the spatial development of the city. However, the questionnaire showed that its interest in the development of a dual-function is limited to water storage, with all criteria not related to water storage being given a performance score of 0. Water storage capacity and storage period were considered to be of medium importance, while the recovery rate criterion was given a maximum score of 10. Due to the normalised weights and the fact that Alternative 3 clearly outperforms the other alternatives in terms of storage period and recovery rate, the ASR alternative has the highest additive value for the municipality of Amsterdam (0.84) compared to all other stakeholders. At the same time, Alternative 2 has the lowest overall additive value for the Municipality of Amsterdam (0.04), as the stakeholder assigned a performance score of 0 to the environmental impact criterion. The floating port alternative outperforms the other alternatives in terms of environmental impact, which is of significant importance to all other stakeholders.

As discussed in Section 6.2, the Houtrakpolder is located in the municipality of Haarlemmermeer (HLM). The municipality of HLM assigned a maximum importance score of 10 to the 3 criteria related to water storage and to the environmental impact criterion, while other criteria are neglected. Due to its dominance on the water storage criteria, the ASR alternative is again clearly preferred. The port lock system alternative (Alt. 1) is advantageous due to its maximum relative storage capacity. However, for the municipality of HLM, Alternative 2 scores close to Alternative 1 due to its performance on environmental impact.

Rijkswaterstaat

For RWS-WNN, the criteria weights were based on the average importance rating of two respondents from the organisation: a Shipping and Waterways Consultant and a Water Management Strategist. Rijkswaterstaat's interest in both sides of the dual-function system is demonstrated by the high weights found for the three water storage-related criteria and the medium weights found for the port-related criteria. The criteria investment costs and environmental impact are given a low average importance by RWS through the questionnaire. Similarly to the other stakeholders, Alternative 3 is preferred due to its dominant performance on 2 of the 3 water storage related criteria. However, as storage capacity is perceived as the most important criterion with a normalised weight of 0.26, Alternative 1 has one of the best additive values for RWS-WNN compared to other stakeholders.

Regional water boards

Finally, the regional water boards, Hoogheemraadschap van Rijnland (HvR) and Waternet, assigned minimum importance scores of 1 or 0 to the port-related criteria. As Alternative 3 has the highest performance score for 3 of the other 5 criteria and the lowest score for none, the ASR alternative is again dominant. Both HvR and Waternet assigned a maximum importance score of 10 to storage capacity and storage period. For Waternet, recovery rate and environmental impact are perceived as more important than for HvR. Therefore, Alternative 1 has a relatively moderate additive value to HvR (0.37). For HvR, investment costs are perceived as more important than for Waternet, resulting in a very low additive value (0.14) for the floating port alternative with excessive investment costs.

6.5. Sensitivity analysis

A sensitivity analysis was carried out to explore how adjustments to the criteria weights affect the relative additive value of the design alternatives. For this purpose, the importance values assigned to the criteria in the questionnaire are increased and decreased in experiments. Based on the dominant performance of the third alternative, as discussed in Subsection 6.4.1, the score for each criterion is increased and decreased by 50%. The scores for the other criteria remain constant, and the weights of all criteria are again normalised to ensure that the sum of all criterion weights equals 1. While many studies use more elaborate sensitivity analyses (J. Chang et al., 2019), this method is chosen to limit the number of experiments, considering that the MCDM is already run 8 times for the different decision makers.

The results of the sensitivity analysis can be found in Appendix D. Each table shows the MCDM results for a 50% increase or decrease in the importance of one of the 7 criteria. It can be seen that for all stakeholders, no weight adjustment changes the dominant position of the ASR alternative (Alt. 3). Furthermore, the ranking of the lock system alternative (Alt. 1) and the floating port alternative (Alt. 2) only changes in two experiments. When the importance of the storage capacity criterion is reduced by 50%, Alternative 2 has a higher additive value than Alternative 1 for the municipality of Haarlemmermeer. For the same stakeholder, when the importance score of the environmental impact criterion is increased by 50%, Alternative 2 has a higher additive value than Alternative 1.

6.6. Case study findings

The case study focused on the Amsterdam Houtrakpolder area and applied the design framework for dual-function systems integrating port terminal with water storage functions. The northern part of the Houtrakpolder, identified by the Ministry of IenW, was selected for analysis. This area, located south of the North Sea Canal, serves as a recreational and nature space, but constraints such as the environmental project Het Groene Schip and residential areas limited the available land.

Initially, the study excluded the decentralised water management system as design alternative due to the high groundwater level in the Houtrakpolder, which often exceeds ground level. This condition prevents the placement of artificial water buffers below the groundwater level, making decentralised water management technically infeasible. Water from the North Sea Canal will be stored in both the port lock system and the floating port alternatives, while the ASR system will serve as a seasonal water storage facility, interfacing between the regional and main water management systems. Essential hinterland connectivity was assessed through road and rail networks. The landscape, identified as reclaimed clay polder, was suitable for the proposed storage design models. Additionally, suitable aquifer layers were confirmed for the ASR system, supporting large-scale underground water storage.

The analysis of the normalised weights shows that the storage capacity and period are crucial for the development of a dual-function system in the Houtrakpolder for all stakeholders. The recovery rate is of considerable importance to all stakeholders, with the exception of the Province. The DGLM and RWS are the only stakeholders to prioritise physical and nautical space. Minimising investment costs is highly valued by the Province, but not by the municipalities or Rijkswaterstaat. Minimising environmental impact is crucial for Haarlemmermeer and the Province, but less so for the Municipality of Amsterdam and Rijkswaterstaat. Overall, stakeholders converge on water storage objectives, but diverge significantly on other priorities.

The performance of the three design alternatives against the seven criteria was then assessed. The port lock system involves constructing a port basin with a lock to manage water levels, capable of storing up to 2.85 million cubic meters of water, suitable for peak and emergency storage but with no potential for water recovery due to contamination risks. This design, inspired by existing port infrastructure like the Port of Antwerp, emphasises flexible water level management.

The floating port alternative proposes creating a 210-hectares lake with floating infrastructure for port operations. This system, using flexible water level management with small fluctuations (20 cm), can store 0.42 million cubic meters of water. It emphasises environmental benefits, such as reduced greenhouse gas emissions and potential for new brackish water development. However, it faces significant challenges due to high investment costs (around €1.3 billion) and limited storage capacity.

The ASR system, designed for seasonal storage, stores water in an underground aquifer about 20 meters thick, holding 1.18 million cubic meters of water with a 50% recovery rate. This alternative involves separating port operations to minimise contamination risks while maintaining the polder's existing regional water management functions. It requires the lowest investment cost (€44.6 million) and has a moderate environmental impact, effectively balancing functionality and sustainability.

The ASR alternative emerged as the most preferred option for all stakeholders, balancing economic, environmental, and functional considerations effectively. The port lock system was the second most preferred due to its high storage capacity, despite its high environmental impact and significant investment costs. The floating port alternative was the least favored, mainly due to its high cost and limited storage capacity, despite its lower environmental impact.

A sensitivity analysis was conducted to explore how adjustments to the weighting of the criteria affected the relative value of each design alternative. The results showed that the ASR system consistently remained the preferred alternative for all stakeholders, regardless of the weighting adjustments. This robustness in the ASR system's performance underscores its preference to the stakeholders for integrating port functions with water storage in the Houtrakpolder.

7 Discussion

The Port of Amsterdam chose not to complete the questionnaire and stated that it follows the guidelines concerning the future of the Houtrakpolder as outlined in the NOVEX-NZKG development vision. However, as previously discussed, the ASR alternative is the dominant in the scenario of constant criteria weights. Furthermore, the sensitivity analysis revealed that the alternative ranking shows very low sensitivity to criteria weights. Therefore, even though no separate MCDM was conducted for this stakeholder, it is expected that the ASR system will also be the preferred dual-function system for the Port of Amsterdam.

The Aquifer Storage Recovery (ASR) system clearly is the most preferred dual-function solution for the Houtrakpolder case based on the defined objectives. However, while case-specific constraints are evaluated, its technical feasibility in the Houtrakpolder remains uncertain. In evaluating the design alternative, it has not been clarified how the water stored in the underground aquifer will be retrieved. In assessing the storage capacity, it was noted that a very large underground water storage system would require a surface area of 90 hectares. This requirement is based on the assumption that rainwater runoff will be utilised. However, if port operations are conducted in the same above-ground area, the rainwater will likely be contaminated, meaning that the expected recovery rate may not be achievable.

Alternatively, it is assumed that water from the storage basin system (boezem) is stored in the aquifer, eliminating the requirement for a minimum surface area of 90 hectares. In evaluating investment costs, it is assumed that the direct underground storage concept will be used to process large volume flows with infiltration rates of up to 200 m^3/h. However, these infiltration rates are based on the assumption that only simple pre-treatment is needed for roof runoff water. Alternatively, a catchment basin could be constructed with additional filtration systems. However, it is uncertain whether such a system could achieve an infiltration rate greater than 50 m^3/h.

Assessing the soil characteristics of the area presented another uncertainty in the technical feasibility of an ASR system in the Houtrakpolder. As discussed, this minimum infiltration rate is based on the soil characteristics and the requirement that the infiltration rate should exceed the flow rate needed to achieve the desired recovery rate. The salinity of the groundwater is estimated using a brackish-saline boundary, which only indicates that the aquifer contains more than 1,000 mg cl/L. Based on comparisons with other Dutch sites, it was assumed that the infiltration rate must exceed 50 m^3/h. However, because these assumptions are based on the minimal requirements of extreme cases, it remains uncertain whether this aquifer contains significantly more salt and demands a much higher infiltration rate. Additionally, although in the design alternative port functions are not designated for the surface above the aquifer, port operations in other parts of the Houtrakpolder area could still contaminate the aquifer.

The exclusion of decentralised water management as a dual-function solution in the Houtrakpolder can also be questioned. This conclusion was drawn based on measurements taken over a limited period in two wells in the Houtrakpolder area. To rule out the possibility of creating artificial water buffers, more recent and location-specific measurements need to be conducted.

7.1. Limitations

Looking beyond the case, limitations of the proposed dual-function framework for the Netherlands are identified. First, only 4 conceptual designs based on dual-function solutions found in the scientific literature are included in the framework. It is likely that more innovative solutions exist and that in certain cases other dual-function designs are possible based on specific area characteristics.

In addition to the dual-function solution, each conceptual design consists of at least one feasible port terminal function, a terminal sub-function, a water storage function, a water management system and a storage design model. As visualised in the morphological charts, multiple options remain feasible at some levels of the design, also when applied to a case. While flexibility in design is shown in green in the morphological chart, it is not included as a preference for conceptual design in its evaluation. In addition to flexibility, the framework also ignores the benefits of combining different design choices on one level in the morphological chart. For example, in the conceptual design, the lock system could potentially combine liquid and dry bulk port functions, while the ASR could potentially combine storage and seasonal water storage functions. Moreover, the framework does not allow for combinations of the dual-function solutions themselves, such as a port lock system together with an ASR system.

In addition, the terminal sub-functions are not thoroughly specified in the conceptual designs, resulting in undefined design implications. Considering 'dry bulk' as a port function and 'storage' as a sub-function, this could refer to the storage of empty dry bulk carriers in the dual function area. If only this port function is applied, the draught requirements for the vessels could change, and therefore the water storage capacity and the investment costs for dredging. Further levels would need to be added to the morphological charts to adapt the framework to further stages of development of these conceptual designs.

Other limitations of the framework relate to the 7 defined objectives, most of which were identified on the basis of the stakeholder interviews. As these interviews were conducted with stakeholders in the Amsterdam Houtrakpolder case and the case was used to understand their interests in the development of a dual-function, this may have resulted in a selection bias. As a result, the objectives may not be representative of the general interests of stakeholders in the development of the dual-function in the Netherlands. Other objectives in this development could be operational costs or economic impact.

Initially, 'environmental port space' was also included as an objective in the framework. When environmental port space is applied to an area, it means that this area is specifically reserved for the negative environmental impacts of the port. The transition in port operations from fossil fuels to biofuels, synthetic fuels and hydrogen is expected to take place towards 2050 and these new materials are expected to require more environmental space. However, in the current framework, this objective is redundant as the small area available must be fully reserved for environmental space when a port terminal is realised. In addition, the correlation between the different objectives has not been checked. If the objectives and thus the criteria were highly correlated, the evaluation method could neglect certain aspects of the design by overemphasising others.

As no such dual-function system has been implemented in the Netherlands, there is uncertainty in the identification of stakeholders and their position in the power/interest grid. Although the framework describes that the exact position of the stakeholders in the grid does not indicate that there are significant differences in power or interest between them, it is used as a tool for identifying the decision-makers to be consulted for the design evaluation. As the Ministry of IenW commissioned the research, the power of public government parties may have been over-represented, while private port-related stakeholders were not consulted.

The Direct Assignment Technique was chosen to assign weights in the MCDM, as the simplicity of this method was considered essential to ensure stakeholder participation and to avoid misinterpretation. However, as the method does not require the decision maker to rank the importance of the entire set of criteria and absolute scores are used, the importance scores are assigned in the questionnaire without reference to any particular reference point. It can be argued that a reference point is required for decision makers to make quantitative comparisons, and alternatively decision makers will use their best judgement to define what a particular score means (Ezell et al., 2021). As the 0-10 scale does not have a clearly defined meaning, the validity of comparisons of criteria weights between different stakeholders is limited. Furthermore, although the questionnaire describes the unit in which the criteria are quantified and whether they are maximised or minimised in the most desirable situation, the range of performance values is not shared. The magnitude of this range could also affect the importance scores given to specific criteria by stakeholders (Ezell et al., 2021), calling into question the validity of this weighting method.

8 Conclusion

In Chapter 1 the following research question was defined to achieve the research objective: **How can a dual-function system framework for incorporating water storage with container, liquid bulk and dry bulk cargo, and offshore wind energy terminal operations in the Netherlands, be developed, and validated in the context of the Houtrakpolder?**.

To answer this question, a systems analysis was first carried out to understand how different forms of water storage and the defined types of port terminals are designed and operated (**Sub-question 1**). In Chapter 2, terminal operations were categorised into three functional systems: seaside operations, yard operations and landside operations. The functional distinction allowed a detailed analysis and comparison of the specific sub-functions inherent in different types of terminals. In Chapter 3 four main functions of water storage were delineated, along with their relevance to water management systems and storage design models. Furthermore, the potential for implementing water storage functions in different landscape types in the Netherlands was explored.

Subsequently, initial solutions are explored for incorporating water storage with port operations at container, liquid bulk, dry bulk, and offshore wind energy terminals (**Sub-question 2**). In Chapter 4, four innovative dual-function solutions are introduced: port lock systems, floating ports, aquifer storage recovery (ASR), and decentralised water management. Moreover, benefits, potential risks, and limitations are identified, which affect their ability to fulfill the sub-functions defined in Chapter 2 and Chapter 3.

The first part of the framework aims to evaluate the technical feasibility of the dual-function solutions (**Sub-question 3**). For this purpose, based on system analysis and stakeholder interviews, requirements are defined in Figure 5.1, consisting of 32 constraints and 7 objectives. Part of the constraints are used to generate four technically feasible conceptual designs. In addition to the dual-function solution, each conceptual design includes at least one feasible port terminal function, a terminal sub-function, a water storage function, a water management system, and a storage design model.

The interviews have been the primary input for defining the interests of stakeholders in port and water management systems during the development of dual-function solutions (**Sub-question 4**). Requirements that have been repeatedly emphasized are identified as objectives in the framework and used to evaluate design alternatives. The framework proposes a separate evaluation based on Multi-Criteria Decision-Making (MCDM) for each decision maker. Due to its simplicity and flexibility, the Direct Assignment Technique (DAT) is incorporated as the method for assigning weight to criteria. Finally, the framework identifies the stakeholders who are considered to have the highest interest and influence in both functional systems combined, and these stakeholders should be consulted for the DAT.

To assess which dual-function solution is feasible and in line with the interests of the stakeholders in the Houtrakpolder (**Sub-question 5)**, design alternatives are generated. In Chapter 6, the case-specific constraints defined in the design framework are evaluated for the Houtrakpolder area. The region-specific water management systems, hinterland connections, landscape types, aquifers and groundwater levels are evaluated. This results in alternatives based on the conceptual designs in the framework, but limited in terms of terminal sub-functions, water storage functions and water management systems. Based on the assessed groundwater level, decentralised water management as a dual-function solution is excluded for the Houtrakpolder case.

The case-specific stakeholders are then defined and consulted through a questionnaire for the DAT. The objectives of the framework are translated into criteria and quantified based on the input from the case. Using the criteria weights and the performance matrix, the additive weighted value of each alternative for each stakeholder is presented. It can be concluded that the ASR dual-function system has the highest overall value and the port lock system alternative has the second highest value among all stakeholders consulted for the Houtrakpolder case. As the ASR system performs best on three of the seven defined objectives and not worst on any of them, it is also preferred in a scenario with constant criteria weights. The MCDM results and sensitivity analysis showed that differences in the perceived value of the design criteria considered have a limited impact on the dominant position of the ASR system relative to the other systems considered. Therefore, it can be concluded that only the ASR solution in the Houtrakpolder as a dual-function system is in line with stakeholder interests.

Although the Port of Amsterdam did not complete the questionnaire, it is expected that the ASR system will also be the preferred dual-function solution for this stakeholder. This does not mean that all stakeholders involved in this case have the same priorities. Overall, stakeholders converge on water storage objectives, but diverge significantly on other priorities. However, if the design were to be developed to a level with more functional detail, it is expected that interests related to water storage will also conflict. Moreover, as discussed in Chapter 7, when assessing the performance values of the ASR alternative, it was found that water would have to be captured outside the Houtrakpolder area. It was also found that it is uncertain whether such an underground water storage system of this size and with the soil characteristics of the Houtrakpolder area would achieve the desired infiltration rate to be effective. Therefore, it cannot be concluded that the ASR system is technically feasible as a dual-function system in the Houtrakpolder. Combined with the results of the MCDM, it can be concluded that at this stage in the development cycle of the dual-function designs, there is no system combining the port and water storage functions that is technically feasible and in line with the interests of the stakeholders in the Houtrakpolder.

8.1. Recommendations

As discussed in Chapter 7, in order to ensure the technical feasibility of an ASR system in the Houtrakpolder, at least 90 hectares of land without port functions are required for the collection of non-contaminated rainwater. Therefore, the two spatial functions are clearly in conflict with each other in the case of the most preferred design alternative and are limited by the small area available. The floating port alternative requires expensive and polluting dredging to implement an innovative technology, mainly developed for offshore use, in an urban environment. Alternatively, floating platforms could be used for offshore terminals, potentially reducing vessel movements and operational pollution in the port area and the city of Amsterdam. In addition, the framework assumed that the dual-function system would be implemented in an inland area adjacent to the main shipping route of an existing port, and that the vessel movements associated with the port functions would also be to or from this main route. As a result, any solution using flexible water level management, including port lock systems and floating port systems, is limited to the storage of saline and polluted water from the main system.

As dual-function systems are clearly limited by the scale of the area and little synergy is expected between the two functions, a systems approach is recommended for further development of the framework. This approach is also expected to address the limitations of the framework discussed in Section 7.1, allowing for the combination of different design choices on a level in the morphological charts, the combination of dual-function solutions, and the addition of levels to the morphological charts. The systems approach should be at the level of the main water management system for water storage and the whole port area for port terminal functions. As mentioned in Appendix B.1, the water system in the case of the Houtrakpolder, which runs from the sea locks in IJmuiden to the canal terraces in Utrecht, is a fragile network with little room for error. When looking at the system as a whole, water storage can be seen in the context of a wider range of (technical) solutions to relieve the pressure of excess water (Appendix B.1, Appendix B.8, Appendix B.5). There is already an initiative in this direction. The Delta Programme Central Holland, with RWS and Hoogheemraadschap van Rijnland as pioneers, involves all six water boards in the ARK-NZK system and the provinces of Noord-Holland and Utrecht (Appendix B.5).

Looking at the Houtrakpolder within the ARK-NZK system, it could have potential for the creation of new marshes as a design model for water storage due to the brackish seapage in the area. Together with an offshore port terminal, a 'dual-function system' could be realised, which is expected to have more water storage capacity, more physical and nautical port space, be cheaper and have less environmental impact. The systems approach should be able to analyse a larger area and effectively reserve environmental space, while other areas are allocated for nature conservation or residential development. In addition, the Houtrakpolder has recently been designated as an area for a transformer station due to the congestion of the Dutch electricity grid. In order to include spatial functions outside the dual-function system in the framework, for example as a constraint on the physical space available, a system-level approach is also seen as essential. Furthermore, at a more detailed design level, sub-functions of a port terminal that are less in conflict with the water storage function should be explored. For example, as discussed in Section 7.1, the storage of empty bulk carriers, which have a shallower draft compared to laden carriers, in a water storage area could be explored. These sub-functions are worth exploring as they are expected to change the requirements in the framework and therefore have a significant impact on the output, which consists of technical feasibility and stakeholder design preferences.

At a later stage in the development of the dual-function design, it is also recommended to change the method of design evaluation. As discussed, the simplicity of the current method was considered essential to ensure stakeholder participation and to avoid misinterpretation. As the design alternatives become more detailed and thus more imaginative for stakeholders, a method of evaluating design alternatives rather than criteria could be incorporated into the framework. For this purpose, the technical feasibility of the proposed alternatives should also be subject to less uncertainty, for example when soil measurements or simulations have been carried out.

In addition, future research is strongly recommended to focus on the governance and ownership structure involved in the implementation of a dual-function design. As discussed in Section 7.1, as no such dual-function system has been implemented in the Netherlands, there is uncertainty in the identification of stakeholders and the extent of their power and interest. Moreover, if the design were to be developed to a level with more functional detail, it is expected that interests related to water storage will also conflict. Within the Delta Programme Central Holland the parties seem to have conflicting interests when it comes to discharging excess water into the canal and infrastructure ownership (Appendix B.3). Central Holland's ambition is to look not only at the water system, but also at the link with spatial planning and spatial functions. However, it is emphasised that there are many issues even beyond the scope of Central Holland (Appendix B.5). Furthermore, the Central Holland initiative does not include an administrative authority. In the 'Ruimte voor de Rivieren' programme, RWS is also looking for space for water storage, but does not have the policy instruments to specifically designate water storage areas for canal systems (Appendix B.3). Finally, Waternet points out that while the water system now looks at the whole area on a large scale and in the long term, this vision is lacking for port development in the Netherlands (Appendix B.5).

Therefore, new governance structures focusing on a systems approach, policy instruments and infrastructure ownership need to be explored. Consideration should be given to including the Port of Amsterdam in the Central Holland programme, following the example of Rotterdam, where the port authority is part of the local equivalent of Central Holland. As highlighted in Chapter 4, the main challenges and opportunities in designing a system of systems lie in the interfaces between different systems. The interfaces must be robust and efficient, facilitating the transfer and management of resources, information and operations between the two systems.

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A

Scientific paper

A Framework for Combining Port Functions with Water Storage in the Netherlands: Application to the Amsterdam Houtrakpolder Case

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Abstract

The Netherlands faces significant spatial challenges that necessitate major social and spatial interventions, including the need for new housing, renewable energy infrastructure, climate adaptation, agricultural constraints, and biodiversity conservation. This study proposes a framework for combining port functions with water storage in the Netherlands, specifically applied to the Amsterdam Houtrakpolder case. By focusing on the technical feasibility of dual-function solutions and the interests of stakeholders, the framework evaluates the potential integration of water storage systems prioritizing water retention. The analysis encompasses four types of port terminals: container, liquid bulk, dry bulk, and offshore wind energy terminals. The study utilizes Systems Engineering (SE) to define objectives and constraints, generate conceptual designs, and evaluate alternatives through Multi-Criteria Decision Making (MCDM). The results indicate that the Aquifer Storage Recovery (ASR) system is the preferred dual-function solution for the Houtrakpolder case, aligning with stakeholder interests. However, technical feasibility remains uncertain, suggesting that a systems approach at the main water management and port area levels is recommended for further development.

Keywords: Dual-function framework, Water storage, Port functions, Systems Engineering, Multi-Criteria Decision Making

1. Introduction

The Netherlands faces significant spatial challenges, including the need for new housing, renewable energy infrastructure, climate adaptation, agricultural constraints, and biodiversity conservation. These are tasks that require major social and spatial interventions, while utility, aesthetics, and future sustainability should be balanced. Moreover, they all claim space, while the territory is limited. In response, the Dutch national government outlined three guiding principles in The National Environmental Vision (NOVI): prioritising multifunctionality over single-use, focussing on regional characteristics, and avoiding burden-shifting. Moreover, it emphasises the steering role of the water system in environmental planning (Planbureau voor de Leefomgeving, 2023).

In the National Environmental Vision Extra programme (NOVEX), all levels of government are collaborating in sixteen focus areas. The provinces work together with water boards and municipalities to convert national objectives and goals into spatial terms which can be incorporated into provincial plans. Amsterdam Noordzeekanaalgebied (NZKG) is one of the NOVEX areas where several functions come together, but available space is limited. Required functions of space include, but are not limited to, the Amsterdam port area, the energy transition, the transition to a circular economy, housing and water storage (De Nationale Omgevingsvisie, 2023).

The Houtrakpolder is a large polder on the southern side of the Noordzeekanaal mainly used for recreational purposes. In the masterplans of the Municipality of Amsterdam (Gemeente Amsterdam, 2020) and Bestuursplatform NZKG (Stuurgroep Visie Noordzeekanaalgebied, 2013) the area has been strategically reserved for expansion of the port area of Amsterdam. However, according to the new development perspective of NOVEX-NZKG, the reservation may be lifted as an option. If there are alternative port development possibilities, the Houtrakpolder should be reserved for other spatial functions, especially energy functions (such as a transformer station) and also (peak) water storage functions. As both functions are of high social and economic importance, possibilities in combing water storage and port functions should be explored.

The dual-function port terminal - water storage, has not been subject of scientific literature explicitly. However, in reality many seaports are already forced to integrate water management in their strategies. The Port of Antwerp implements a multifaceted approach to water management, focussing on conservation, recycling, and quality maintenance (Port of Antwerp Bruges, 2023). Historically, significant portions of the port area have been constructed with dock systems positioned behind locks. Due to high tidal changes on the river leading to the port, its design is intended to maintain a stable water depth for vessels at berth. However, during the 1990s, the Port of Antwerp initiated the development of river-based terminals, recognizing the time-sensitive nature of container ship operations and the potential risks and delays associated with lock operations, including collision hazards (Notteboom et al., 2022).

Innovative water storage techniques are scientifically researched, but not compared with each other nor applied to a port basin. For instance, decentralised stormwater management solutions are applied in the urban context, including measures such as green roofs and tree pits with a focus on water infiltration (Dickhaut and Richter, 2020). Furthermore, the spatial challenges in the Netherlands lead to various initiatives in the research area of floating infrastructure. The studies depict a hopeful scenario wherein a certain portion of the port infrastructure and operations will be relocated to the sea. It is however unclear if and how these promising innovations can be applied within a port, aiming to combine its functions with water storage. Furthermore, literature falls short in comparing potential water storage techniques in various port contexts and in considering their function in a water management system.

This study proposes a framework for incorporating water storage techniques with port functions in the Netherlands, forming a dual-function system. The framework focuses on the technical feasibility of dual-function solutions and the interests of stakeholders involved in both systems. Considering water storage, this study will concentrate on functions prioritising water retention over drainage, with a specific focus on the unique water management environment of the Netherlands. In the analysis of port operations this study focuses on four types of terminals: container, liquid bulk, dry bulk, and offshore wind energy terminals. The framework will be empirically validated through application to the Amsterdam Houtrakpolder case, assessing which dual-function solution is technically feasible and in line with stakeholder interests.

2. Literature review

2.1. Port terminal functions

A seaport consists of various terminals that serve as critical links between sea and land transport, with the capacity of the port determining the volume of cargo it can handle in a given period of time. Port terminals are the physical interfaces between these sea and land modes of transport, capable of handling different types of cargo, including containers, bulk and roll-on/roll-off (Ro-Ro) cargo, within specified timeframes (Bassan, 2007). As mentioned, this study will focus on four main types of port terminals. In general, the functions of a port terminal can be divided into three sub-functions: Storage; Transport, transhipment and transfer; and Value-added logistics (Dohmen, 2016).

Storage and transport are considered the primary functions of a terminal, while value-added logistics such as blending, tank-to-tank transfers, or the addition of additives are seen as secondary. In addition to these primary and secondary sub-functions, ensuring safety through supporting activities is essential. Alternatively, terminal operations can be categorised into three functional systems: seaside operations, yard operations, and landside operations (Dohmen, 2016). This functional distinction is advantageous as it allows for a detailed analysis and comparison of the specific sub-functions inherent to different types of terminals. Additionally, the physical location of a port terminal function (seaside, yard, or landside) is crucial when evaluating potential dual-function solutions. The delineation of port functions visualised in Figure 1 will be used for the functional analysis of the four port terminal types.

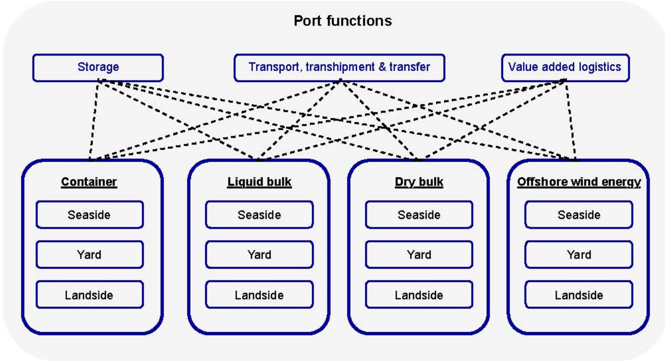

Figure 1: Port terminal functional systems [created by author]

2.1.1. Container terminals

A container terminal is a specialised facility for the transshipment, handling and temporary storage of containers between at least two modes of transport. It consists of various areas, including quays, yards and equipment such as cranes, together with supporting facilities such as administration and maintenance buildings and warehouses (Notteboom et al., 2022). Container terminals rely heavily on quays, yards, cranes and (automated) equipment for efficient operation. The docking area, known as the berth, is where a container ship docks, and technical specifications such as length and draught are critical. These specifications have become increasingly challenging in recent decades due to the growth in the size of container ships (Rodrigue, 2020).

2.1.2. Liquid bulk terminals

Liquid bulk terminals play a vital role in global supply chains, facilitating the movement of a wide range of commodities including oil, gas, chemicals, renewable energy and food products. With the increasing shift towards renewable and sustainable energy sources, these terminals are becoming even more critical for transporting the fuels of the future (Royal Haskoning DHV, 2024). Liquid bulk terminals emphasise the importance of berthing facilities, loading arms, hoses and pumps, as well as strict safety measures for hazardous materials. Modern liquid bulk terminals prioritise environmental sustainability by capturing and recovering hydrocarbon vapours or volatile organic compounds (VOCs) to reduce emissions (Notteboom et al., 2022).

2.1.3. Dry bulk terminals

Dry bulk terminals play a crucial role in port operations, facilitating the movement of loose dry materials between suppliers and users in the global transport chain (Schott and Lodewijks, 2007). These terminals typically handle two main categories of dry bulk commodities: major bulk commodities, which include coal, iron ore, grain, bauxite/alumina and phosphate rock, and minor bulk commodities, such as fertilisers, agricultural products, cement, sand, petroleum coke and scrap metal. Major bulk commodities often have different grades and applications, resulting in different trade patterns and terminal designs for export and import terminals. In general, dry bulk terminals require specific infrastructure such as stackers and reclaimers for loading and unloading, and the implementation of dust control measures to minimise environmental impact (Notteboom et al., 2022).

2.1.4. *Offshore wind energy terminals*

As key energy hubs, ports not only facilitate the import and export of traditional energy products, but also play a key role in the transport networks for sustainable energy sources such as hydrogen. Hydrogen is essential for decarbonising maritime transport and connecting continental energy networks with offshore energy generation facilities (Saborit et al., 2023). Offshore wind energy terminals perform various functions related to offshore wind energy, including construction, operation, maintenance and energy integration (Lammers et al., 2023). By accommodating larger components, vessels and increased activities, they provide comprehensive support throughout the lifecycle of offshore wind turbines (WindEurope, 2017). These terminals require facilities for the assembly and shipment of large components, with a focus on storage space, a high capacity quay, component manufacturing facilities and repair workshops (Akbari et al., 2017).

2.2. *Water storage functions*

Water storage, is defined as the temporary collection of (rain)water in natural and artificial landscapes such as soil, ditches, streams, rivers, lakes, ponds and designated water storage areas (Rijksoverheid, 2024). Prioritising water retention, four main functions of water storage can be delineated: stock storage, seasonal storage, peak storage and emergency storage. These functional categories and their implications are presented in Table 1. This section examines the strategies associated with these main functions and discusses their relevance to water management systems and storage design models. It will also explore the potential for implementing water storage functions in different landscape types in the Netherlands.

water storage function	**solution for...**	**strategy**	**occurrence**	
			frequency (number/year)	**duration**
Stock storage	water shortage	the local retention of precipitation, in particular summer showers, in order to postpone the inflow of (area-foreign) water for as long as possible	many times a year	several days to weeks
Seasonal storage	water shortage	storing water surpluses in the winter aimed at reducing water shortages for agriculture and nature reserves in the summer	annual cycle	many months
Peak storage	flooding	the temporary storage of water aimed at preventing flooding elsewhere	annually - 1:100	a few days
Emergency storage	flooding	the temporary storage of water aimed at preventing calamities/disasters	1:100 - 1:10,000	several days to weeks

Table 1: Water storage main functions [(Habiforum, 2002) adapted by author]

2.2.1. *Stock storage*

Stock storage involves the retention of water to be used strategically (Massop et al., 2015). It serves as a proactive measure against water shortages by locally capturing precipitation, especially from summer showers. The aim is to postpone dependence on external water sources by extending local water availability by several days to weeks, as required several times a year (Habiforum, 2002).

Stock storage is primarily about storing water within the local water management system, focusing on capturing and storing rainwater where it falls. This strategy is essential to meet the challenges of spatial pressure and increasing urbanisation. In urban areas, intensified land use and increased impervious surfaces lead to rapid runoff, preventing rainwater from naturally infiltrating into the ground. Various measures can be taken to counteract these effects and increase water storage capacity. These include increasing the absorption capacity of the soil by reducing surface cover, using rain barrels or local water basins, installing green roofs, creating additional space in the capillaries of the system such as ditches, and constructing tree pits (Werkgroep Water NOVEX NZKG, 2023).

The design model **'Widened watercourses'** plays a crucial role in both stock storage and peak storage. By widening watercourses and providing terraced or gradually sloping banks, a significant increase in water storage capacity is achieved. Water level fluctuations are typically between 0.5 and 1 metre (Habiforum, 2002). The model also has a positive impact on a range of soil-related issues such as drought and waterlogging, which affect the carrying capacity of the soil and therefore its usability for other activities. In addition, the model supports biodiversity by more closely mimicking natural conditions and contributes to the development of nature-friendly shorelines (Rijksinstituut voor Volksgezondheid en Milieu (RIVM), 2011). This storage design model can be applied to different landscape types, including both peat bogs and clay polders. Particularly in clay polders, widened watercourses contribute significantly to stock storage and peak storage functions (Habiforum, 2002).

Allowing groundwater levels to fluctuate can increase the storage capacity of the soil during heavy rainfall. This makes **'Flexible water level management'** a cost-effective model for addressing unnatural groundwater system configurations in both rural and urban areas. Flexible groundwater levels are often associated with flexible surface water levels (Rijksinstituut voor Volksgezondheid en Milieu (RIVM), 2011). Most water systems operate with fixed summer and winter water levels. This system can be moved to a flexible water level management system where water levels can vary within a range. Flexible surface water level management is an important strategy for dealing with water shortages and surpluses throughout the year (Gemeente Haarlemmermeer and Hoogheemraadschap van Rijnland, 2015) and is therefore also applicable to seasonal storage and peak storage.

The **'New marshes'** design model focuses on the creation of new marshes as an effective method of retaining local water, thereby directly supporting stock storage. Clean, local water is essential to this model as it promotes more natural groundwater fluctuations, increasing the overall water storage capacity of the area while maintaining the ecological integrity of the marshes. These marshes also provide additional capacity for peak water storage by capturing excess rainwater from the polder. New marshes can be created in areas where groundwater naturally emerges. Deep reclaimed areas, depending on their soil, can act as magnets for groundwater, making the creation of new marshes unviable (Habiforum, 2002). A reclamation area, known in Dutch as a 'droogmakerij', is a clay polder that was originally a lake, other large open water or a wetland. New marshlands can also be created in peatland polders by strategically raising the water level to stop further subsidence and stimulate new peat growth (Habiforum, 2002).

The design model **'Storage polder in urban edges'** focuses on the storage of urban water and emphasises the importance of maintaining water quality through the integration of a recirculating water system. By circulating the water through the storage polder, the water quality is further improved before being released into the urban waterways. This model includes various types of storage, including stock, seasonal and peak storage, with water level fluctuations of 0.5 to 0.8 metres, primarily for managing urban water. It is particularly effective for peak water storage at the edge of the city, where the built environment does not have sufficient capacity to internally manage extreme rainfall (Habiforum, 2002). The implementation of storage polders in beach ridge landscapes is feasible, but presents challenges due to the permeability of the sandy soil (Habiforum, 2002). However, in low lying areas prone to rapid flooding, construction is generally less advisable due to the high risk of damage and casualties. Therefore, from a risk zoning perspective, reserving the lowest lying areas primarily for water storage appears to be a preferable future strategy (Pieterse et al., 2009).

The design model **'Storage basin'**, called 'bergingsboezem' in Dutch, is a main model for seasonal water storage. However, it can also be used for stock and peak storage. This model primarily uses the grasslands along the dams and is designed for the retention of water specific to the area, functioning independently of the main water storage basin system or 'boezem'. Its importance lies in its central role in seasonal storage, capturing rainwater and seepage to maintain optimum water levels in nearby polders during periods of drought. The design typically accommodates water level fluctuations of up to 1 metre. In addition, the capacity of a storage basin can be increased by incorporating a floodplain, known in Dutch as 'uiterwaard'. In reclamation areas (clay polders) with a groundwater suction effect, the reservoir model can mitigate this effect. In addition, this model can be adapted to the peatland polder landscape (Habiforum, 2002).

2.2.2. Seasonal storage

Seasonal storage stands out as a key strategy for managing water scarcity by bridging the gap between abundant water supplies in winter and the shortages experienced by agriculture, nature reserves and industry in summer. This method involves storing water for several months each year, making the most of natural variations in water availability (Habiforum, 2002)(Werkgroep Water NOVEX NZKG, 2023). It also plays a crucial role in maintaining water levels during dry periods to prevent damage to infrastructure, and in cleaning the water system to reduce salinisation caused by brackish infiltration (Bremer et al., 2004). Seepage in this context refers to the process by which groundwater is forced to the surface under pressure (Waterschap Rivierenland, 2024). To distinguish water with different salinities, the categories fresh water (less than 150 mg chloride/l), brackish water (between 150 and 1000 mg chloride/l) and salt water (more than 1000 mg chloride/l) are traditionally used (Geologische Dienst Nederland, onderdeel van TNO, 2024).

In water management practice, seasonal storage is mainly associated with the regional water system. This strategy integrates the concept of water storage with different spatial functions, where the inundation depth is generally kept at a minimum level, except in the case of very deep polders (Werkgroep Water NOVEX NZKG, 2023). The term 'inundation depth' refers to the depth of water after deliberate flooding of a region (STOWA, 2017). The regional water system is managed by the regional water boards. Compared to peak storage the implementation of seasonal storage within the regional system requires significantly larger areas (Werkgroep Water NOVEX NZKG, 2023).

In addition, the interface between the regional and main water systems provides additional opportunities for seasonal storage. This intermediate zone can act as a water conservation reservoir. The aim of these storage areas is to reduce the demands on the regional system without putting excessive pressure on the main system. The main system is managed by Rijkswaterstaat. The water stored in these intermediate areas is predominantly fresh, as opposed to the more saline water of the primary system (Werkgroep Water NOVEX NZKG, 2023).

The **'New ponds'** design model with variable water levels provides another innovative method of seasonal water storage. The presence of a permanent body of water positions seasonal storage as a primary function, although peak storage remains a viable option. These ponds, which can accommodate water level fluctuations of 1 to 1.5 metres, are able to utilise water from both local sources and the storage basin system. In clay polders where the clay layer is thin and the underlying sand is not too fine, the process of sand extraction can facilitate the formation of these ponds. In the context of beach ridge landscapes, the creation of new ponds can mitigate desiccation within dune valleys. In general, the high quality and increased volume of inflowing dune water makes this type of landscape particularly suitable for water storage (Habiforum, 2002).

As discussed in Subsection 2.2.1, the flexible water level management model, the storage polder in urban edges model, and the storage basin model, can also be applied for the seasonal water storage function.

2.2.3. Peak storage

Peak storage serves as a critical solution for flood control (Habiforum, 2002), involving the temporary storage of water to prevent flooding in other areas (Massop et al., 2015). This function of water management is aimed at accommodating excess water during periods of heavy rainfall or runoff, with the frequency of such peak storage events varying from once every one to one hundred years. The water is stored for a short period, typically a few days (Habiforum, 2002). The peak storage function is becoming increasingly important in the context of climate change, sea level rise, land subsidence and urbanisation, all of which contribute to the increased risk of high water levels in water bodies and the potential for flood-related disasters. Peak storage is often directly related to the pumping capacity of water bodies. When increasing pumping capacity through technical solutions is no longer a viable option to address the above challenges, the establishment of water storage sites for peak storage during extreme rainfall becomes imperative (van Kruiningen et al., 2004).

Similar to the seasonal water storage function, the peak storage function includes storage in the regional water management system as well as in the areas between the regional and the main water management systems. The effects of water storage in these systems on water quality, quantity and spatial functions can be found in Subsection 2.2.2.

The design model **'Inlet polder'**, also known as an overflow polder, plays an important role in the Dutch water management system. This design is a part of a larger agricultural polder, surrounded by dikes and adjacent to the storage basin system (boezem), which is specially designed for the temporary storage of excess water. It is mainly used for peak and emergency water storage and shows great promise for supporting dual purposes, especially in agriculture. Farmers are usually compensated for the temporary use of their land for water storage. This compensation helps to offset any potential loss in land value and repair any damage caused by the water after a peak storage event. The amount of water that these inlet polders can hold varies, with water levels potentially fluctuating between 1 and 2.5 metres. The frequency with which an inlet polder is used can range from once a year to once a century, or even less frequently in cases where it is designed for emergency storage. The water held in these polders is usually sourced from the storage basin system, which helps to ensure that the water quality is suitable throughout the storage period. The inlet polder model is particularly compatible with peatland polders and areas of deep reclamation (Habiforum, 2002).

The **'Inner polder'** design model is another strategic method of peak storage management. In this approach, a section of a polder, surrounded by dikes and located at a lower elevation, is used specifically for the temporary storage of surplus water from neighbouring polders. Acting as a buffer, the inner polder captures peak water flows until conditions allow the water to be released back into the storage basin system (boezem). Fluctuations in water levels of 1 to 1.5 metres are expected, with the frequency of use varying from annually to once a century. This model of water storage is compatible with landscapes characterised by deep reclamation (clay polders) (Habiforum, 2002).

As discussed in Subsection 2.2.1 and Subsection 2.2.2, the widened watercourses model, the flexible water level management model, the new marshes model, the storage polder in urban edges model, the storage basin model, and the new ponds model, can also be applied for the peak water storage function.

2.2.4. Emergency storage

Finally, emergency storage is identified as a critical water storage function to prevent flooding and avert catastrophes or disasters. This function involves the temporary storage of water to mitigate extreme and infrequent hydrological events that may occur once every 100 to 10,000 years. Emergency storage may also be required in urgent situations due to system failures or pumping problems. The duration for which water is held in emergency storage can vary from several days to weeks (Habiforum, 2002).

Emergency storage in water management primarily involves the storage of water in and out of the main system. Storage in the main system involves the adjustment of water levels in the main system to temporarily store water above normative levels. These adjustments have a significant impact on the surrounding environment, including potential obstructions to navigation, the need to close locks more frequently and an increased risk of sewer overflows. As a result, drainage from these systems may need to be diverted, requiring increased discharge capacity from smaller canals and pumping stations. In addition, a higher water level in the main system requires adjustments to quays and building heights along the canal (Werkgroep Water NOVEX NZKG, 2023). In addition to storage in the main system, during extreme weather conditions with limited discharge options, adjacent polders can be used as reservoirs to manage high water levels in the main system. However, the use of these polders, especially for emergency storage, often leads to disruption of inland use due to the brackish and polluted nature of the stored water, making regular agriculture impossible and posing a risk of further salinisation of adjacent areas (Werkgroep Water NOVEX NZKG, 2023).

As discussed in Subsection 2.2.1 and Subsection 2.2.3, the flexible water level management model and the inlet polder model can also be applied for the emergency water storage function.

2.3. Dual function solutions

In the search for a comprehensive framework for the implementation of dual-function port terminal and water storage systems, the literature suggests that port lock systems or Aquifer Storage Recovery (ASR) systems could be a promising solution.

2.3.1. Port lock system

Port lock systems, traditionally used to manage ship traffic and water levels, offer opportunities for innovative water storage. Figure 2 shows the port lock system in the South Korean port of Incheon, which, like Antwerp, has to cope with high tidal fluctuations.

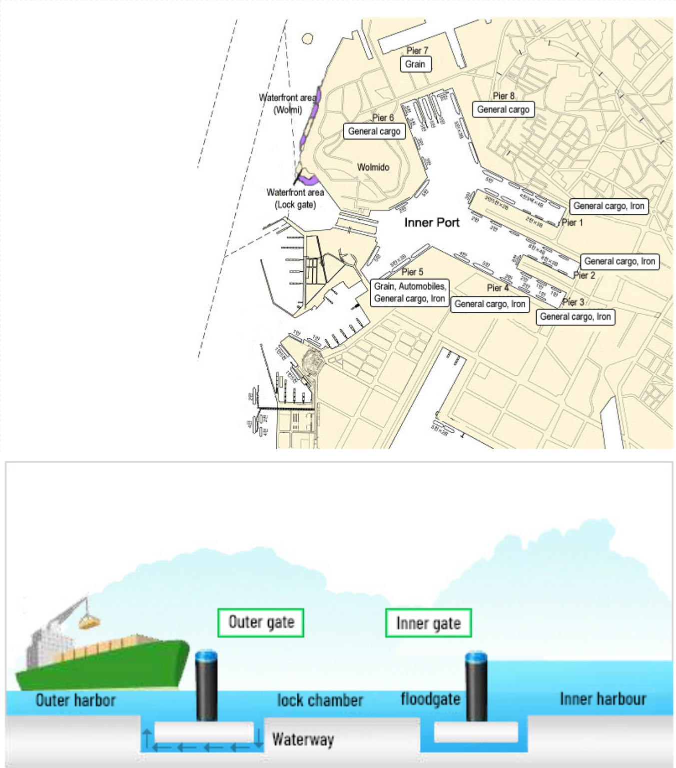

Figure 2: Port lock system Port of Incheon (Ministry of Oceans and Fisheries, 2024)

High tides in ports present operational challenges, and locks are used to maintain water levels. However, the operation of these locks often leads to water loss in the port basin. To overcome this, the port basin can be filled naturally at high tide outside of the port. However, it is argued that this process leads to complex scheduling challenges. Optimising lock operations involves a number of stakeholders, including vessels, port authorities and environmental agencies. Each of these stakeholders brings different priorities and decision-making processes that affect the overall scheduling and operation of lock systems (Schindler et al., 2020). Moreover, the environmental impact of lock systems should not be neglected, particularly in terms of greenhouse gas emissions. Studies, such as those focusing on the Port of Incheon, show that lock-related activities, such as vessel transit and post-lock manoeuvring, are major contributors to CO2 emissions in ports (Chang et al., 2013).

2.3.2. *Aquifer Storage Recovery*

Aquifer Storage Recovery (ASR) is an innovative water management technique in which excess water is infiltrated into underground aquifers and extracted when water is needed. Infiltration of excess freshwater is done through wells or infiltration ponds, while extraction is mainly done through wells. This method allows dual use of land, with the surface being used for residential, commercial and natural areas, while the subsurface is used for water storage. ASR has been successfully applied in various sectors, including the drinking water industry and agriculture, particularly for storing rainwater for irrigation in greenhouses. A schematic representation of ASR for greenhouse water supply is shown in Figure 3. More recently, its use has been extended to urban water management and climate adaptation measures to reduce flood risks and maintain freshwater availability during dry periods (Bremer et al., 2004)(STOWA, 2019).

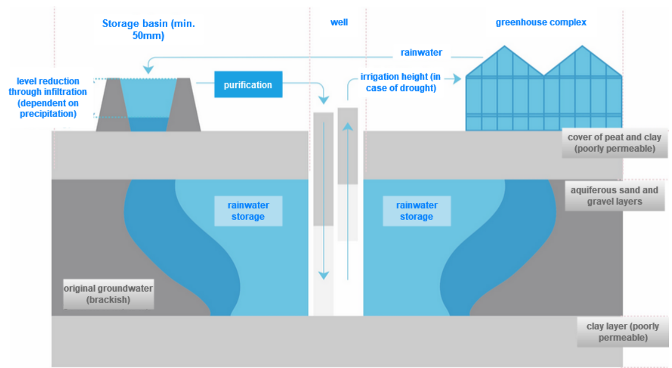

Figure 3: ASR schematic visualisation [(STOWA, 2019) adapted by author]

An ASR system is only effective if the flow rate at which water can be stored in the aquifer is greater than the flow rate required to achieve the recovery rate. The recovery rate measures the efficiency of ASR systems by indicating the proportion of stored water that can be recovered with acceptable quality. While recovery efficiencies can be conservatively estimated at around 50%, this value can vary depending on aquifer characteristics and the quality of the injected water. The complexity of the recovery process requires advanced modelling to accurately predict results, taking into account the interaction between injected water and native groundwater. In saline environments, scaling up and improving well configurations could be used to improve recovery rates. Injected freshwater that cannot be recovered still contributes to the desalination of water in the aquifer. (Bremer et al., 2004)(Lowry and Anderson, 2006)(STOWA, 2019)(van Doorn et al., 2013).

In addition, the success of ASR projects is highly dependent on local geological and hydrological conditions, such as the chloride content and flow rates of the groundwater and the geological structure of the subsurface. If the groundwater is saline, the injected fresh water will move to the surface due to the difference in density with the saline groundwater. Rapid groundwater flow causes the fresh water bubble to drain. As a result, the stored water mixes with saltier water and may also contain unwanted metals or other contaminants. Finally, a minimum aquifer thickness of 7 metres has been mentioned for underground water storage to be effective (van Doorn et al., 2013).

3. Methodology

3.1. *Stakeholder analysis*

Once the main concerns and components of a project have been identified, a stakeholder analysis can identify the parties that may be affected, followed by an assessment of their level of interest and influence (Brugha and Rvasovszky, 2000). It is expected that the implementation of dual-function solutions will involve a diverse group of public and private sector stakeholders whose interests may conflict. In order to design a comprehensive framework, it will be necessary to identify stakeholders involved in both functions, as well as potential new parties resulting from the merger, and to assess their level of interest and influence. In addition, the stakeholder analysis will provide valuable perspectives on which industry experts to interview.

Because it is possible to identify individuals who occupy key positions in relation to the research question, interviews are used as a method of data collection. Interviews may be preferred to questionnaires not only because of the depth of insight they provide, but also because of the reluctance of key informants to complete questionnaires. Interviews are used to gather factual information or to gain insight into opinions, attitudes, experiences, processes, behaviours or predictions (Rowley, 2012). This in-depth understanding is considered essential to the creation of the desired framework. Insights from industry experts will be used primarily to assess the feasibility and impact of dual-function solutions. Due to the limited availability of information on the solutions, as suggested by Chetouani et al. (2023), this research uses semi-structured interviews.

3.2. Design framework

Design studies are used to design a visualisation system that supports the solution of a specific real-world problem, validate the design, and reflect on the lessons learned in order to refine visualisation design guidelines (Sedlmair et al., 2012). This is in line with the aim of this research to develop and empirically validate a comprehensive framework for the integration of port and water storage systems. Systems Engineering (SE) is an interdisciplinary design approach that focuses on defining customer needs and required functionality early in the development cycle (International Council on Systems Engineering (INCOSE), 2023). For this research, SE allows the comparison of different design alternatives, links the contexts of different disciplines to system performance, and includes both qualitative and quantitative measures (Soudian and Berardi, 2021).

Using SE, and based on the input from the literature review and the interviews conducted, a framework for the design of a dual-function system consisting of both port and water storage functions is proposed. The framework defines requirements, consisting of objectives and constraints, based on the analysis of the two separate functions and the stakeholder analysis. The framework introduces conceptual designs based on the analysis of the dual-function solutions, limited in design by the concept-specific constraints. The conceptual designs are used to generate design alternatives based on case input on site characteristics and case-specific constraints. The final step of the framework is an evaluation of the design alternatives through Multi-Criteria Decision Making (MCDM), using the objectives as the main input. Dual-function technical feasibility is assessed during both the generation and evaluation of design alternatives. The design framework is visualised in Figure 4. It should be noted that the framework is subject to two design assumptions. Firstly, the dual-function system will be implemented in an inland area adjacent to the main shipping route of an existing port. Secondly, the vessel movements associated with the port functions will also be to or from this main route.

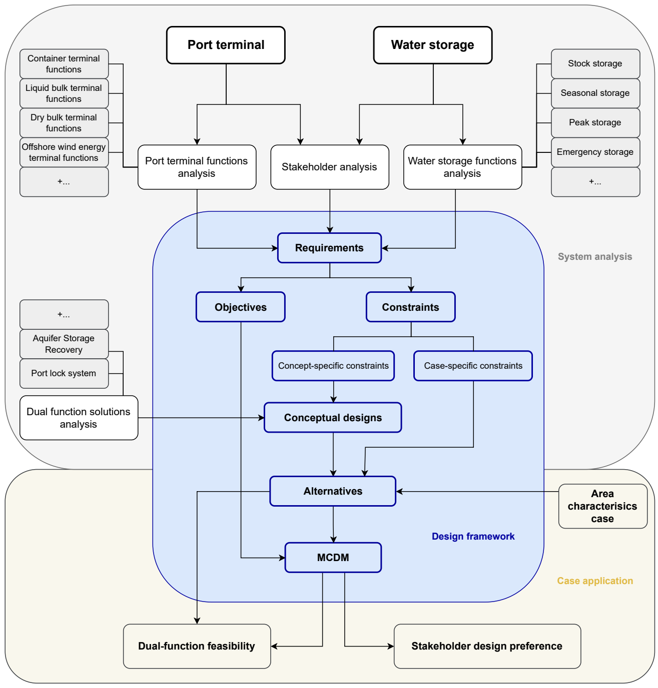

Figure 4: Dual-function design framework for port terminal and water storage functions [created by author]

3.2.1. Objectives

The requirements that are defined as objectives in the dual-function framework are mainly based on the stakeholder interviews in Appendix B of the thesis report (Voorkamp, 2024). As illustrated in Figure 4, all objectives are used to evaluate design alternatives. The objectives are translated into criteria and quantified in Chapter 4 based on input from the case. The objectives and their dependencies are discussed in more detail in the remainder of this section.

O1: Storage capacity. The first objective is to maximise the total water storage capacity of the area. Water storage usually replaces or supplements a certain amount of pumping capacity. The required pumping capacity depends on the water management systems involved and the desired level of flood protection. The amount of storage capacity, for example in cubic metres, indicates how much of this pumping capacity can be filled by the water storage capacity. For surface storage, the storage capacity can be estimated by multiplying the dimensions of the water storage area by the maximum water level fluctuations of the storage design model used. For underground storage, the dimensions of the aquifer or infiltration box and its physical properties should be considered.

O2: Storage period. The second objective states that the storage time for water in the area should be maximised. If the storage area is only used for peak storage, its capacity can be reached in a few hours, and it loses its function until it is emptied again. However, depending on the storage area, water could be stored for a longer period and fulfil a stock storage or seasonal storage function. Therefore, the storage period should be estimated based on the solution's storage function and its infiltration flow rate.

O3: Recovery rate. The third objective is to maximise the amount of water that can be recovered and used to combat water shortages. More evaporation and less rainfall in the summer months are expected to reduce the supply of fresh water in the Netherlands. At the same time, the demand for clean fresh water is expected to increase due to population growth, economic growth and more intensive land use. This includes expected water shortages for the energy transition, shipping, and peatland irrigation to prevent subsidence and CO_2 emissions. For surface water storage, the recovery rate is heavily influenced by evaporation and contamination. For underground water storage, the recovery rate depends on the thickness and permeability of the aquifer, the salinity of the groundwater, the rate of any background flow and the sealing of the aquifer.

O4: Physical space. The next objective states that the available physical space for port terminal operations in the area should be maximised. Physical port space refers to space on land, on or alongside a quay, for the performance of one of the defined port (sub)functions. The demand for physical port space in the Netherlands is subject to new factors such as the transition from fossil fuel terminals, the increasing containerisation of logistics or the development of offshore wind energy terminals. In addition, the demand for housing, other business premises and the expansion of the electricity grid are putting strong pressure on the physical space in the ports. The amount of physical space available in the area is directly dependent on the structural design of the dual-function solution.

O5: Nautical space. The next objective is to maximise the available nautical space for port terminal operations in the area. The nautical port space refers to waterways which can be used for the performance of on the defined port (sub)functions. The amount of nautical port space has impact on the efficiency and safety of nautical port operations and is directly dependent on the structural design of the dual-function solution.

O6: Investment costs. The next objective is to minimise the total investment costs for the dual-function solution. In this case, investment costs include the public construction costs of all main infrastructure needed for the port function(s) and water storage function(s) of the dual-function solution, as well as the costs for fitting the solution into the area. The latter category of costs refers to land prices, and costs water treatment requirements and environmental compliance. The design framework does not consider the operational or lifecycle costs of the dual-function solution.

O7: Environmental impact. The final objective is to minimise the environmental impact of the dual-function solution, consisting of CO_2 emissions and the impact on agriculture, nature, biodiversity and a green living environment. These potential negative impacts of realising a dual-function system are based on the interests of the community stakeholders. These interests are only included as an objective in the design framework, while the other stakeholders with more decision making influence will be consulted directly in the evaluation phase of the design framework.

3.2.2. Constraints

Constraints are modelled as the initial and boundary conditions of concept ideation in a design study (Liu et al., 2019). For a system consisting of both port and water storage functions, 32 constraints are defined and presented in Table 2. As visualised in Figure 4, some constraints are used to generate the conceptual designs in Subsection 3.2.3, while others are case-specific and are used to generate design alternatives.

#	Constraint
C1	Based on the terminal type, its standard vessel dimensions have to fit in the approach channel of the port basin.
C2	A liquid bulk terminal has to be flexible for unpredictable arrival rates.
C3	A liquid bulk terminal has to comply with contractual agreements with its customers for ensuring quick loading and unloading operations.
C4	In a liquid bulk terminal vapor recovery systems must be installed to limit external contamination.
C5	A liquid bulk terminal should be connected to the hinterland either via road or rail.
C6	In a dry bulk terminal dust control systems must be installed to limit external contamination.
C7	A dry bulk terminal should be connected to the hinterland either via rail or waterways.
C8	An offshore wind energy terminal has to ensure overhead and horizontal clearances to ensure safe passage of vessels carrying turbine components.
C9	An offshore wind energy terminal has to ensure substantial load-bearing capacity for its quay wall, staging area and storage area.
C10	An offshore wind energy terminal should be connected to the hinterland via road.
C11	Stock storage should be implemented by storing water in the local water management system.
C12	Stock storage should be implemented by creating a storage basin, widened watercourses, flexible water management, new marshes or a storage polder in urban edges.
C13	The storage basin model should be realised in reclamation areas or peatland polder landscapes.
C14	The widened watercourses model should be realised in peatland polder or clay polder landscapes.
C15	The flexible water level management model should be realised in reclamation areas, new urban developments or urban areas.
C16	The new marshes model cannot be realised in deep reclamation areas.
C17	The storage polder in urban edges model cannot be realised in beach ridge landscapes with high soil permeability.
C18	Seasonal storage should be implemented by storing water in the regional water management system or in the interface between the regional and main system.
C19	Seasonal storage should be implemented by creating a storage basin, new ponds, flexible water management or a storage polder in urban edges.
C20	The new ponds model should be realised in clay polders where the clay layer is thin and the underlying sand is not overly fine, or in beach ridge landscapes.
C21	Peak storage should be implemented by storing water in the regional water management system or in the interface between the regional and main system.
C22	The inlet polder model should be realised in deep reclamation areas or peatland polder areas.
C23	The inner polder model should be realised at a lower elevation next to another polder.
C24	The inner polder model should be realised in deep reclamation areas.
C25	Emergency storage should be implemented by storing water in or from the main water management system.
C26	Emergency storage should be implemented by creating flexible water management or an inlet polder.
C27	Floating port as a dual-function solution has to be implemented by incorporating a terminal sub-function with limited dynamic operations to ensure dynamic stability.
C28	Aquifer Storage Recovery as a dual-function solution, by definition, has to recover stored water, fulfilling a stock storage or seasonal storage function.
C29	ASR has to be implemented in an area with an aquifer of at least 7 metres in thickness.
C30	For ASR, the flow rate at which water can be stored in the aquifer has to be greater than the flow rate which is required to achieve a recovery rate of 50%.
C31	Decentralised water management as a dual-function solution, can only be implemented by using artificial water buffers, fulfilling a stock storage function.
C32	Decentralised water management has to be implemented by positioning the storing elements above the groundwater level.

Table 2: Constraints

3.2.3. Conceptual designs

Based on the dual-function solutions presented in Section 2.3 and the constraints in Subsection 3.2.2, two conceptual designs for a dual-function system are defined. In addition to the dual-function solution, each conceptual design consists of at least one feasible port terminal function, a terminal sub-function, a water storage function, a water management system and a storage design model. This section discusses the constraints that have shaped each conceptual design and uses morphological charts to visualise them.

The first conceptual design, visualised in Figure 5, is based on the port lock system solution as defined in Subsection 2.3.1. As it is assumed that no inner port lock will be large enough to accommodate the standard container terminal type vessel, a combination with a container terminal function is excluded (C1). The operation of a lock system is also expected to limit flexibility to unpredictable arrival rates (C2). While this constraint has been highlighted for liquid bulk terminals, 'transport, transhipment & transfer' is excluded as a sub-function for all main functions in this conceptual design. This sub-function is also excluded because it is considered that a lock system cannot ensure rapid loading and unloading operations (C3). Furthermore, the dimensions of a port lock do not allow sufficient horizontal clearance to include functions for an offshore wind energy terminal (C8). In this concept, water from the main water management system is transferred to the harbour basin behind the lock when the ships lock and the water reservoir is filled. Since water from the main system is stored, it can only be used for the emergency storage function (C25). As the harbour basin will be permanently filled, the design uses the flexible water level management storage design model (C26).

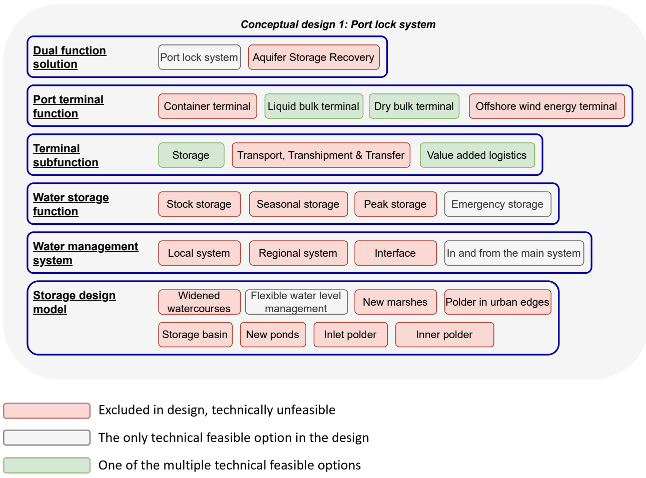

Figure 5: Morphological chart of conceptual design 1 [created by author]

The second conceptual design, visualised in Figure 6, is based on the Aquifer Storage Recovery solution as defined in Subsection 2.3.2. In this dual-function design, an ASR system is installed anywhere in the port area adjacent to a new port basin. As described, an ASR system is subject to potential aquifer contamination and clogging of pipes. As vapour recovery systems must be installed to limit external contamination in liquid bulk terminals (C4) and dust control systems in dry bulk terminals (C6), these port functions present too high a risk to combine with underground water storage. The same applies to value added logistics as a sub-function of all port terminal functions, where operations could pollute the air and surface or groundwater. By definition, an ASR system recovers stored water, fulfilling a storage or seasonal storage function (C28). Finally, this conceptual design uses the storage basin design model (C12, C19). Although underground, the aquifer functions independently of the 'boezem' and captures rainwater to maintain optimum water levels during periods of drought. However, unlike an above-ground storage basin model, the storage capacity depends on the size of the aquifer and is not limited to water level fluctuations of up to 1 metre.

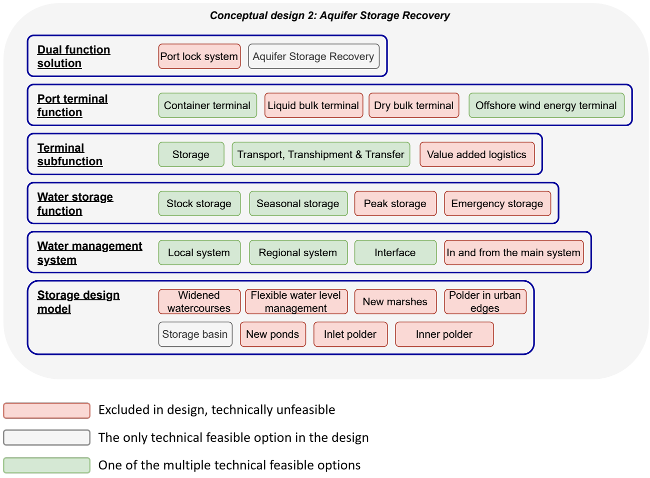

Figure 6: Morphological chart of conceptual design 2 [created by author]

3.2.4. *Design evaluation*

Decision making can be defined as the identification and selection of an alternative from a set of alternatives based on the preferences of the decision maker(s). Different decision makers value the criteria involved differently (Rezaei, 2016). While there are more complex methods for group decision making, this framework proposes a separate evaluation based on MCDM for each decision maker. It is assumed that at this stage in the development of the dual-function solution, the main objective of the evaluation should be to identify the differences in the preferences of each stakeholder, rather than to decide on an overall optimal design alternative.

The goal of MCDM is to select the alternative with the best overall value. The total value of an alternative can be obtained using a simple additive weighted value function (Equation 1), which is the underlying model for most MCDM methods. The crucial aspect here, and what sets apart various MCDM methods, is the method by which the criteria weights are determined (Rezaei, 2015). For the dual-function framework, it is assumed that the seven objectives for the two conceptual designs can be quantified by reasoned estimation and used as criteria and alternatives, respectively, in the additive weighted value function.

$$
\begin{aligned}
&V_i = \sum_{j=1}^{n} w_j p_{ij} \\
&\quad \text{s.t.} \\
&\quad V_i := \text{Value of alternative } i \\
&\quad n := \text{Number of criteria} \\
&\quad w_j := \text{Weight of criteria } j \\
&\quad p_{ij} := \text{Normalised score of alternative } i \text{ on criteria } j
\end{aligned}
\tag{1}
$$

The Direct Assignment Technique (DAT) asks users to assign points directly to the criteria. The MCDM method then asks to normalise the points so that they sum to one and can be used as weights. One approach to scoring is to provide a finite range of possible scores and ask decision makers to assign a score to each criteria according to its importance. In this case, criteria of higher importance receive a higher score than those of lower importance (Ezell et al., 2021). The framework suggests a range from 0 to 10, with a score of 0 indicating that the criterion does not play a role in the evaluation of the conceptual designs.

DAT is a straightforward method of assigning weights to criteria that does not require the decision maker to rank the importance of the entire set of criteria. The number of questions required to assign weights using the Direct Assignment Technique is limited to the number of criteria (Ezell et al., 2021). At this early stage in the development of the dual-function design, the simplicity of this method is essential to ensure stakeholder participation and to avoid misinterpretation. By using absolute scores, rather than letting decision makers divide a fixed pot of points, new criteria could be added or old ones removed (Ezell et al., 2021). This makes the framework evaluation step flexible enough to adapt to further development stages of the dual-function designs.

3.2.5. *Decision makers*

As discussed in the previous section, the MCDM is performed using the Direct Assignment Technique, separately for each decision maker. The decision makers are defined in the framework based on the analysis of stakeholders in the literature review and interviews. The stakeholders considered to have the highest interest and power in both functional systems combined should be consulted for the DAT and are marked with a blue colour in the combined power/interest grid in Figure 7. It should be noted that the precise position of these blue stakeholders in the diagram does not indicate that there are any significant differences in power or interest between them. The power/interest grid is only a tool for the identification of decision makers to be consulted for the design evaluation. Stakeholders marked with a black colour in the grid are considered to have less power in the development of a dual-function design, but their interest is represented in the Environmental Impact Objective (O7) as discussed in Subsection 3.2.1.

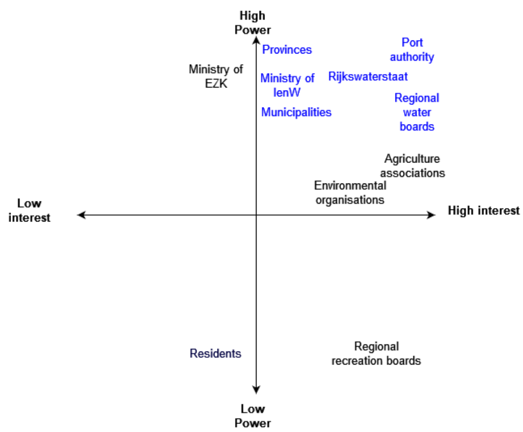

Figure 7: Power/interest grid dual-function design [created by author]

4. Case study

The northern part of the Houtrakpolder in Amsterdam has been identified as a potential area for the dual-function by the Dutch Ministry of Infrastructure & Water Management. The area is located south of the North Sea Canal and is used for recreation and nature with mainly grass and forest. In the western part of the polder is the village of Spaarndam, while in the eastern part are the industrial areas of the port of Amsterdam (Hoogheemraadschap van Rijnland, 2024). However, the entire northern part of the Houtrakpolder is not available for the design of a dual-function system. As a natural boundary between the port operations and the Spaarnwoude green buffer zone, 'Het Groene Schip' was initiated in this area in 2012. This project involved the incorporation of approximately 3 million square metres of secondary building materials (Afvalzorg, 2024). It is therefore considered that the risk of environmental damage is too great to allow this area to be rezoned as part of a dual-function system. In addition, the residential area that forms part of the village of Spaarnwoude is excluded, and it is assumed that a contiguous area is required for both port operations and water storage. Therefore, Figure 8 shows the available area in the Houtrakpolder for the dual-function system, which will be the input for the further application of the framework.

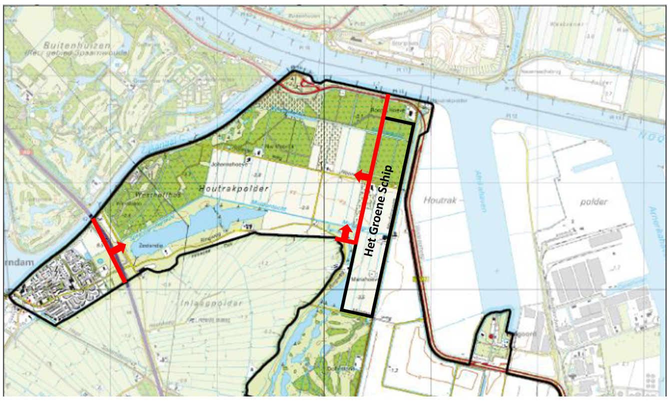

Figure 8: Houtrakpolder available area [created by author based on van der Dussen and Buijs-Heine (2019)]

To begin the application of the dual-function framework, the two conceptual designs introduced in Subsection 3.2.3 are evaluated based on the properties of the case. The constraints that are case-specific and used to generate design alternatives are checked.

4.1. Hinterland connection

Considering the connection of the potential new port area to the hinterland, 3 constraints are described in Subsection 3.2.2 which are evaluated for the case. Firstly, a liquid bulk terminal should be connected to the hinterland either via road or rail (C5). Secondly, a dry bulk terminal should be connected to the hinterland either via rail or waterways (C7). Thirdly, an offshore wind energy terminal should be connected to the hinterland via road (C10).

As visualised in Figure 9, 15 terminals in the port of Amsterdam are connected to the rail network. These include terminals for intermodal (container) transport, dry bulk and wet bulk. The rail network in the port of Amsterdam consists of two main railway stations: Westhaven and Aziëhaven, which are both equipped with overhead lines for electric locomotives and can accommodate trains up to 750 metres long. The port's rail network will be further expanded in the coming years (Port of Amsterdam, 2024). It is therefore expected that a new port terminal on the available land in the Houtrakpolder could easily be connected to this existing rail network.

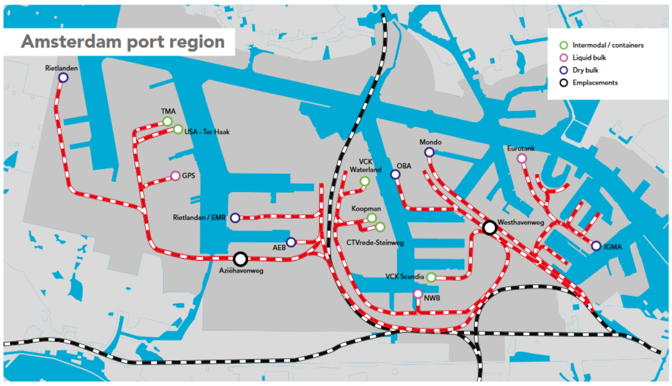

Figure 9: Rail transport connections Port of Amsterdam (Brenninkmeijer and Smit, 2020)

The port of Amsterdam also has excellent road connections due to its strong hub function. Schiphol Airport and the city of Amsterdam can be reached within 15 minutes (Port of Amsterdam, 2024). As the new terminal is expected to be connected through the hinterland by rail and road as part of the dual-function system, no port terminal functions need to be excluded for the Houtrakpolder case on the basis of the constraints discussed.

4.2. Landscape type

Several case-specific constraints on storage design models that can only be realised in certain landscape types are described in Subsection 3.2.2. Most of the constraints are irrelevant because in the conceptual designs of the dual-function, as shown in Subsection 3.2.3, only two storage design models remain as feasible: 'flexible water level management' and 'storage basin'. The flexible water level management model should be realised in reclamation areas, new urban developments or urban areas (C15). The storage basin model should be realised in reclamation areas or peatland polders (C13).

As discussed in Subsection 2.2.1, a reclamation area, known as 'droogmakerij' in Dutch, is a clay polder that was originally a lake, other large open water or wetland. The soil of the available area in the Houtrakpolder varies in the amount of lime and coarseness of the clay, but it can all be categorised as clay polder (Ministerie van Infrastructuur & Waterstaat et al., 2024). Furthermore, the open water known as 't Hout Rack, was drained in 1873, and then became the Houtrakpolder, part of a larger land reclamation called the IJpolders (Gemeente Amsterdam, 2024). Therefore, the available area in the Houtrakpolder can be identified as a reclamation area, and no conceptual designs need to be excluded based on the landscape type.

4.3. Aquifers

Subsequently, two constraints related to ASR as a dual-function solution are evaluated for the Houtrakpolder case. Firstly, ASR must be implemented in an area with an aquifer of at least 7 metres thick (C29). Secondly, the flow rate at which water can be stored in the aquifer must be greater than the flow rate required to achieve a recovery rate of 50% (C30). For this purpose, a cross section of the soil in the Houtrakpolder area will be analysed. Using a publicly available database, a cross section is made at the solid red line shown in Figure 10. The dotted red lines mark the visibility depth of 700m on both sides, which determines the distance from the section line at which measurements and extractions are shown in the section (Geologische Dienst Nederland, onderdeel van TNO, 2024).

Figure 10: Location of cross section soil Houtrakpolder (Geologische Dienst Nederland, onderdeel van TNO, 2024)

The cross section is visualised in Figure 11 and shows that the soil is composed of several layers of sand and clay. As shown in Figure 3, a sand layer between two clay layers can act as an aquifer for an ASR system. Therefore, the closest layer to the surface with these characteristics, the light purple one (KZr3), is identified as a potential aquifer. The layer, known as the Kreftenheye formation, is approximately 20 metres thick and therefore meets the requirement of 7 metres thickness (C29).

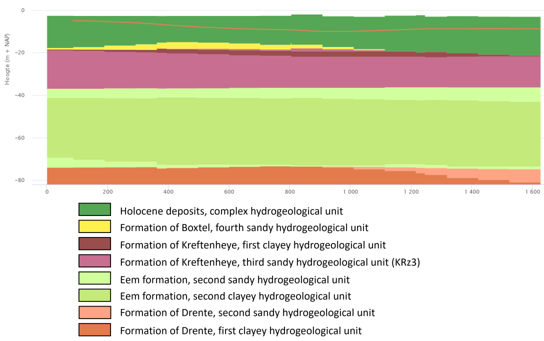

Figure 11: Cross section soil Houtrakpolder (Geologische Dienst Nederland, onderdeel van TNO, 2024)

The solid red line in Figure 11 marks the average brackish-saline boundary for groundwater in the Houtrakpolder area. As the aquifer lies entirely below the brackish-saline boundary, the chloride concentration of the groundwater in this layer is at least 1000 mg/l. In the vicinity of major drainage facilities (rivers and along the reclaimed areas), groundwater flow can locally reach more than 100 m/day. However, in the reclaimed and polder areas the groundwater flow is usually lower, with a maximum of 20 m/year and in many places even less than 10 m/year (van Doorn et al., 2013).

Based on the assumption that chloride concentrations in the Houtrakpolder area are very high and groundwater flow is low, the case is compared with 8 cases analysed by van Doorn et al. (2013) on the suitability of the first aquifer for water storage. It can be concluded that with these soil characteristics the infiltration rate must be greater than 50 cubic meters per hour. According to van Doorn et al. (2013), with a very large Underground Water Storage (UWS) system, this infiltration rate can be realised to achieve a recovery rate of 60%. Due to the location of the brackish-saline boundary, the chloride concentration is expected to rise well above 1000 mg/L, requiring a very large ASR system to achieve even a 50% recovery rate (C30).

5. Results

5.1. Criteria weights

Based on Subsection 3.2.5, case-specific stakeholders were defined who act as decision makers in the evaluation of design alternatives. A questionnaire, which can be found in Appendix C of the thesis report (Voorkamp, 2024), was sent to all the case-specific decision-makers to carry out the Direct Assignment Technique (DAT). A situation is outlined where a port terminal - water storage system is to be realised in the Houtrakpolder. It should be noted that no results are given for the Port of Amsterdam, as it was the only stakeholder that chose not to complete the questionnaire. As indicated in the interview, the PoA follows the line regarding the future of the Houtrakpolder as set out in the NOVEX-NZKG development vision (Bestuursplatform NZKG, 2023). The resulting normalised criteria weights are shown in Table 3.

Organisation	Storage capacity	Storage period	Recovery rate	Physical space	Nautical space	Investment costs	Environmental impact
Province of NH	0.26	0.13	0.03	0.03	0.03	0.26	0.26
Port of Amsterdam	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DGLM	0.12	0.12	0.16	0.18	0.12	0.16	0.12
DGWB	0.21	0.21	0.18	0.00	0.00	0.21	0.21
Mun. Amsterdam	0.27	0.27	0.45	0.00	0.00	0.00	0.00
Mun. HLM	0.23	0.23	0.23	0.02	0.02	0.02	0.23
RWS-WNN	0.26	0.21	0.18	0.13	0.13	0.02	0.08
HvR	0.26	0.26	0.13	0.00	0.00	0.21	0.13
Waternet	0.23	0.23	0.19	0.02	0.02	0.12	0.19

Table 3: Normalised criteria weights

While it is expected that the Port of Amsterdam would be an exception, the resulting normalised weights indicate that storage capacity and storage period plays a crucial role in the development of a dual-function system in the Houtrakpolder for all stakeholders. The recovery rate holds high importance for both municipalities, is of low significance to the province, and is of medium importance to other stakeholders.

While the Port of Amsterdam is anticipated to prioritise physical and nautical port space, only DGLM and Rijkswaterstaat among other stakeholders consider these criteria substantially important. Minimising investment costs is not perceived as an objective by both municipalities and Rijkswaterstaat, although the province values this criterion highly. The minimisation of environmental impact is highly valued by the municipality of Haarlemmermeer and the Province, but is deemed of low importance by the municipality of Amsterdam and Rijkswaterstaat.

In conclusion, the consulted stakeholders align on objectives related to water storage in the development of a dual-function system in the Houtrakpolder, while there is considerable variation in the valuation of other objectives.

5.2. Criteria performance

Subsequently, for the two feasible design alternatives in the Houtrakpolder area, performance on each criteria is evaluated, based on their method of estimation discussed in Subsection 3.2.1. However, the criteria are quantified in different units of measurement and are based on an objective that is either maximised or minimised. Therefore, the criteria performance matrix is normalised, resulting in the normalised performance matrix in Table 4.

Criterion	Alt. 1: Port lock system	Alt. 2: Aquifer Storage Recovery
Storage capacity	1.00	0.41
Storage period	0.00	1.00
Recovery rate	0.00	1.00
Physical space	1.00	0.91
Nautical space	1.00	1.00
Investment costs	0.00	0.93
Environmental impact	0.00	0.40

Table 4: Normalised performance matrix

5.3. MCDM

Subsequently, for both alternatives, the normalised weights in Table 3 are multiplied with the normalised performance values in Table 4, in accordance with the additive value function in Equation 1. The results of the MCDM for the dual-function system are presented in Table 5.

	Alt. 1: Port lock system	Alt 3. : Aquifer Storage Recovery
Province of NH	0.32	0.67
Port of Amsterdam	N/A	N/A
Ministry of IenW (DGLM)	0.43	0.83
Ministry of IenW (DGWB)	0.21	0.74
Municipality Amsterdam	0.27	0.84
Municipality HLM	0.28	0.72
RWS-WNN	0.52	0.79
HHS Rijnland	0.26	0.75
Waternet	0.28	0.74

Table 5: Results MCDM

As no group decision making method is performed, no conclusion can be drawn regarding the best alternative for the group of stakeholders. However, it should be noted that for each decision maker the Aquifer Storage Recovery alternative has the highest overall value.

6. Discussion

The Port of Amsterdam chose not to complete the questionnaire and stated that it follows the guidelines concerning the future of the Houtrakpolder as outlined in the NOVEX-NZKG development vision. However, the ASR alternative is also dominant in the scenario of constant criteria weights. Furthermore, a sensitivity analysis revealed that the alternative ranking shows very low sensitivity to criteria weights. Therefore, even though no separate MCDM was conducted for this stakeholder, it is expected that the ASR system will also be the preferred dual-function system for the Port of Amsterdam.

However, the technical feasibility in the Houtrakpolder remains uncertain, even though the case-specific constraints have been evaluated. The evaluation of the design alternative did not clarify how the water stored in the underground aquifer would be extracted. If rainwater run-off is used, port operations will take place in the same above-ground area and the rainwater is likely to be contaminated, which means that the expected recovery rate may not be achievable. Alternatively, if water from the storage basin system (boezem) were to be stored in the aquifer, it is uncertain whether such a system could achieve the required infiltration rate to be effective. The assessment of the soil characteristics is another uncertainty, as the method uses a brackish-saline boundary and comparisons with other Dutch sites. As these assumptions are based on the minimum requirements of extreme cases, it remains uncertain whether this aquifer contains significantly more salt and requires a much higher infiltration rate. In addition, although the design does not provide for alternative port functions on the surface above the aquifer, port operations in other parts of the Houtrakpolder area could still contaminate the aquifer.

6.1. Limitations

Looking beyond the case, only two conceptual designs based on dual-function solutions are included in the framework. It is likely that more innovative solutions exist and that in certain cases other dual-function designs are possible based on specific area characteristics. Within each conceptual design, as visualised in the morphological charts, multiple options remain feasible at some levels of the design, which is also possible when applied to a case. While flexibility in design is shown in green in the morphological chart, it is not included as a preference for conceptual design in its evaluation. In addition to flexibility, the framework also ignores the benefits of combining different design choices on one level in the morphological chart. Moreover, the framework does not allow for combinations of the dual-function solutions themselves. Finally, the terminal sub-functions are not thoroughly specified in the conceptual designs, resulting in undefined design implications. Further levels would need to be added to the morphological charts to adapt the framework to further stages of development of these conceptual designs.

The Direct Assignment Technique was chosen, as the simplicity of this method was considered essential to ensure stakeholder participation and to avoid misinterpretation. However, as the method does not require the decision maker to rank the importance of the entire set of criteria and absolute scores are used, the importance scores are assigned in the questionnaire without reference to any particular reference point. It can be argued that a reference point is required for decision makers to make quantitative comparisons, and alternatively decision makers will use their best judgement to define what a particular score means (Ezell et al., 2021). As the 0-10 scale does not have a clearly defined meaning, the validity of comparisons of criteria weights between different stakeholders is limited. Furthermore, the range of performance values is not shared. The magnitude of this range could also affect the importance scores given to specific criteria by stakeholders (Ezell et al., 2021), calling into question the validity of this weighting method.

7. Conclusion

In the case of the Houtrakpolder, the ASR dual function system has the highest additive value for all stakeholders consulted. The ASR system performs best on five of the seven defined objectives. Furthermore, the MCDM results and the sensitivity analysis showed that differences in the perceived value of the design criteria considered have a limited impact on the relative dominance of the ASR system. Therefore, it can be concluded that an ASR solution in the Houtrakpolder as a dual-function system is in line with stakeholder interests.

This does not mean that all stakeholders involved in this case have the same priorities. The consulted stakeholders align on objectives related to water storage, while there is considerable variation in the valuation of other objectives. If the design were to be developed to a level with more functional detail, it is expected that interests related to water storage will also conflict.

When assessing the performance values of the ASR alternative, it was found that water would have to be captured outside the Houtrakpolder area. It was also found that it is uncertain whether such an underground water storage system of this size and with the soil characteristics of the Houtrakpolder area would achieve the desired infiltration rate to be effective. Therefore, it cannot be concluded that the ASR system is technically feasible as a dual-function system in the Houtrakpolder. Combined with the results of the MCDM, it can be concluded that at this stage in the development cycle of the dual-function designs, there is no system combining the port and water storage functions that is technically feasible and in line with the interests of the stakeholders in the Houtrakpolder.

7.1. Recommendations

As dual-function systems are clearly limited by the scale of the area and little synergy is expected between the two functions, a systems approach is recommended for further development of the framework. This approach is also expected to address the limitations of the framework, allowing for the combination of different design choices on a level in the morphological charts, the combination of dual-function solutions, and the addition of levels to the morphological charts. The systems approach should be at the level of the main water management system for water storage and the whole port area for port terminal functions.

Looking at the Houtrakpolder within the ARK-NZK system, it could have potential for the creation of new marshes as a design model for water storage due to the brackish seapage in the area. Together with an offshore port terminal, a 'dual-function system' could be realised, which is expected to have more water storage capacity, more physical and nautical port space, be cheaper and have less environmental impact. The systems approach should be able to analyse a larger area and effectively reserve environmental space, while other areas are allocated for nature conservation or residential development. In addition, the Houtrakpolder has recently been designated as an area for a transformer station due to the congestion of the Dutch electricity grid. In order to include spatial functions outside the dual-function system in the framework, for example as a constraint on the physical space available, a system-level approach is also seen as essential. Furthermore, at a more detailed design level, sub-functions of a port terminal that are less in conflict with the water storage function should be explored. For example, as discussed in Section 6.1, the storage of empty bulk carriers, which have a shallower draft compared to laden carriers, in a water storage area could be explored. These sub-functions are worth exploring as they are expected to change the requirements in the framework and therefore have a significant impact on the output in terms of technical feasibility and stakeholder design preferences.

Finally, future research is strongly recommended to focus on the governance and ownership structure involved in the implementation of a dual-function design. As no such dual-function system has been implemented in the Netherlands, there is uncertainty about the identification of stakeholders and the extent of their power and interests. Furthermore, if the design were to be developed to a more functional level, it is expected that interests related to water storage will also conflict. Therefore, new governance structures focusing on a systems approach, policy instruments and infrastructure ownership need to be explored. Consideration should be given to getting port authorities involved in the Dutch Delta Programmes.

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B

Interviews

B.1. Rijkswaterstaat (RWS): Strategic Water Manager and Shipping Advisor

- Datum: 18 januari 2024
- Duur: 11:00 - 12:00 uur
- Locatie: Rijkswaterstaat Hoofdkantoor, Haarlem
- Geïnterviewden: Strategisch Watermanager RWS, Adviseur Scheepvaart RWS
- Interviewer: Tijn Voorkamp

Dit interview is afgenomen met twee experts van Rijkswaterstaat (RWS) West-Nederland Noord: een Strategisch Watermanager, verantwoordelijk voor het toekomstige waterbeheer, en een Adviseur Scheepvaart, wiens werk zich richt op de combinatie van waterbeheer en scheepvaart. Het gesprek vond plaats op 18 januari en was vooral gericht op de uitdagingen in het Noordzeekanaalgebied, mogelijke oplossingen in waterbeheer en de interactie met de scheepvaart. De belangrijkste onderwerpen die besproken zijn, omvatten:

1. **Piekwaterberging:** Er heerst geen enthousiasme binnen RWS voor piekwaterberging van water uit het Noordzeekanaal. Het beeld is dat deze oplossing het water uit vier verschillende waterschappen moeten opslaan, terwijl de hoeveelheid water die een polder zoals de Houtrakpolder kan bergen minimaal is. Het gebied zou binnen een uur weer leeg kunnen worden gepompt. Bovendien is er twijfel over de haalbaarheid van het vasthouden van water voor een periode van twee dagen, refererend naar de piekperiode.
2. **Systeemaanpak:** Er is een voorkeur voor een bredere aanpak waarbij water langer in de waterschappen wordt vastgehouden alvorens het naar het hoofdsysteem wordt geleid. Het landschap moet weer als spons worden gebruikt, zoals bijvoorbeeld gedaan wordt in De Onlanden in Groningen. RWS en de waterschappen werken samen in het instituut 'Slim Watermanagement'. Het systeem loopt van de Zeesluizen in IJmuiden tot aan de terrassen van de grachten in Utrecht, een fragiel netwerk met weinig ruimte voor fouten. Ecologische overwegingen zijn belangrijk, gezien het brakwater systeem en de aanwezige flora en fauna.
3. **Seizoensberging:** Het Noordzeekanaal als gebied lijkt te geavanceerd en met teveel ruimtelijke toepassingen om seizoensberging te realizeren. Er wordt wel een voorbeeld in Friesland genoemd van succesvolle seizoensberging. Ook wordt de potentie van ondergrondse waterberging benadrukt met het inzicht dat de duinen in Noord-Holland meer water vasthouden dan het IJsselmeer.
4. **Relatie met scheepvaart:** De interactie tussen waterbeheer en scheepvaart in NZKG betreft drie raakvlakken: peilbeheer, spuien en spuibeperking in de buitenhaven, en verziltingsproblematiek. Als in IJmuiden moet worden gepompt heeft dit invloed op de scheepvaart omdat de buitenhaven dan niet te bereiken is. Hier zou piekwaterberging dus wellicht een functie voor zowel watermanagement als de scheepvaart kunnen verichten. Verder is verzilting door schutten van

schepen een groot probleem. Het zout is schadelijk voor de natuur, drinkwater voorzieningen en de landbouw in het systeem. Bij extreme droogte is er is niet genoeg water om via het gemaal te malen en wordt het kanaal steeds zouter. Als gevolg worden dan ingrepen gedaan aan het schutbedrijf: beperkingen en vertragingen. Het Noordzeekanaal is een belangrijke ecologische verbindingszone voor vis, waar ook een commerciel belang speelt. De rol van waterberging in waterbelang zou meetbaar gemaakt kunnen worden aan de hand van doelstellingen op het gebied van waterkwaliteit, waterkwantiteit en waterveiligheid.

5. **Bestuur:** Er zijn wekelijkse overleggen over waterpeil en zoutgehalte tussen RWS en alle waterschappen. Op directie niveau is er een ontwikkelingsprogramma Water binnen RWS. In tijden van droogte of van veel regen is er een overleg op nationaal niveau, en wordt het Landelijke Coördinatiecommissie Waterverdeling (LCW) actief met een opschalingsmechanisme. Het Nationaal Deltaprogramma is recentelijk ook uitgebreid naar het NZKG.
6. **Toekomstgerichte uitdagingen** Niet alleen op piekmoment zijn er de afgelopen jaren meer uitdagingen in het syteem, maar ook door het jaar heen. Een van de uitdagininingen ligt bij het peilbeheer, waar de marges waarop gestuurd wordt liggen tussen de -0.30 and -0.50NAP. Bij de ondergrens kunnen schepen het kanaal niet opkomen. Bij de bovengrens is de waterstand zo hoog dat je het risico loopt op een situatie waarbij het riool omgekeerd gaat werken. Ook kan de waterlinie bij Amsterdam moeten worden gesloten, waarmee de bereikbaarheid van de stad op het spel staat. Er wordt nu een toegespitst waterbeleid voor NZKG gemaakt met alle problemen en knoppen waar aan gedraaid kan worden. Waterberging is een van die knoppen.

B.2. Directoraat-generaal Water en Bodem (DGWB): Senior Policy Coordinator

- Datum: 25 januari 2024
- Duur: 11:00 - 12:00 uur
- Locatie: Rijkskantoor Den Haag
- Geïnterviewden: Senior Beleidscoordinator
- Interviewer: Tijn Voorkamp

Dit interview is afgenomen met een senior beleidscoördinator binnen het Directoraat-Generaal Water en Bodem (DGWB) van het Ministerie van Infrastructuur en Waterstaat. De expert bekleedt de functie van beleidscoördinator op de afdeling Waterkwaliteit en Waterkwantiteit en is nauw betrokken bij het Deltaprogramma Zoetwater. Het gesprek vond plaats op 25 januari en richtte zich voornamelijk op het watersysteem in het NZKG en het plaatsen van waterberging in dit systeem als een instrument voor watermanagement. De belangrijkste onderwerpen die besproken zijn, omvatten:

1. **Deltaprogramma's:** DGWB is betrokken bij het Deltaprogramma Zoetwater, waarbij de nadruk ligt op het vasthouden van water. De nadruk werd gelegd op de vraag naar aanzienlijk meer bergingsmogelijkheden in de waterschappen, en er werd gepleit voor een klimaatadaptieve benadering bij alle nieuwe bouwprojecten. Ook werd er gesproken over een regionaal Deltaprogramma Light, genaamd Centraal Holland. Er is echter geen bestuurlijk gezag is in dit uitgestrekte gebied, wat wel vijf novexgebieden omvat.
2. **Noordzeekanaal als systeem:** Het Amsterdam-Rijnkanaal/Noordzeekanaal (ARK/NZK) wordt beschouwd als het meest kwetsbare punt voor wateroverlast in Nederland. Vanwege intensief en divers ruimtegebruik wordt er een enorme economische schade verwacht in dit gebied bij wateroverlast. Het gehele systeem is afhankelijk van het sluizencomplex in IJmuiden. Het afvoeren van water naar het Markermeer wordt gezien als een noodoplossing, maar is niet in alle situaties mogelijk.
3. **Piekwaterberging:** De Houtrakpolder werd genoemd als een potentiële inlaatpolder, vooral van belang wanneer gemalen niet langer kunnen worden gebruikt. Er zijn zeven gemalen in het NZKG, waarvan er vijf nieuw zijn en twee oud. Het advies luidt om deze niet één op één te vervangen, maar om rekening te houden met een stijging van de zeespiegel tot één meter. Het spuien van water uit het kanaal naar zee onder vrij verval is al niet meer mogelijk bij een zeespiegelstijging van 10 cm. Als reactie zal de pompcapaciteit moeten toenemen. Bovendien wordt een marge van slechts 10 cm op het Noordzeekanaal genoemd.
4. **Seizoensberging:** Er wordt verwacht dat al het water in de ondergrond bij de Houtrakpolder brak zal zijn. Een seizoensgebonden berging, waarbij ondergronds een zoetwaterbel wordt gecreëerd, wordt gezien als een goede oplossing om water langer vast te houden. Er moet echter rekening worden gehouden met het feit dat wanneer er voor het volgende seizoen wordt opgeslagen, deze ruimte niet beschikbaar zal zijn voor piekberging.
5. **Toekomstgerichte uitdagingen:** Er werd gewezen op nieuwe KNMI-scenario's die wijzen op warmer weer en veranderende neerslagpatronen, wat kan leiden tot meer verdamping in de zomer en meer neerslag in de winter. Dit heeft gevolgen voor de afvoer van rivieren en kan leiden tot meer verzilting in het Noordzeekanaalgebied. Daarbij wordt verwacht dat de vraag naar schoon zoet water zal toenemen door bevolkingsgroei, economische groei en intensiever landgebruik. Het is dan de vraag welke prioriteit de scheepvaart heeft binnen dit systeem wat aan haar grenzen zit.

B.3. Rijkswaterstaat (RWS): Project Leader Future-proof Water System

- Datum: 31 januari 2024
- Duur: 10:00 - 10:30 uur
- Locatie: Telefonisch
- Geïnterviewden: Projectleider Toekomstbestendig Watersysteem RWS
- Interviewer: Tijn Voorkamp

Dit interview is afgenomen met een projectleider Toekomstbestendig watersysteem (TB) Amsterdam-Rijnkanaal/Noordzeekanaalgebied (ARK/NZK) binnen Rijkswaterstaat (RWS) West-Nederland Noord. In het programma Slim Watermanagement werken de waterschappen en RWS al samen aan optimaliseren van het operationeel watersysteem optimaliseren, om tekort aan of overlast van water te voorkomen. Waar Slim Watermanagement echter kijkt naar het dagelijks waterbeheer, kijkt TB ArK/NZK maar liefst tot 2100 Slim Watermanagement, 2024. Het gesprek vond plaats op 31 januari en de belangrijkste onderwerpen die besproken zijn, omvatten:

1. **Noordzeekanaal als systeem:** Bij wateroverlast kan de toegang tot het Noordzeekanaal vanuit het Amsterdam-Rijnkanaal worden afgesloten. Dit resulteert in de beperking van de toevoer van rivierwater naar het systeem, waarbij enkel water vanuit de waterschappen nog wordt toegelaten. Vanwege de toenemende druk op het watersysteem wordt er breed gezocht naar ruimte voor waterberging in het Noordzeekanaalgebied, waarbij al snel de Houtrakpolder als geschikt gebied is aangewezen.
2. **Piekwaterberging:** De aanvankelijk voorgestelde oplossing voor piekwaterberging om overtollig water eerst vanuit de boezem naar het hoofdsysteem te malen, om vervolgens terug te laten stromen naar de polder, heeft geleid tot onduidelijkheid over de richting waarvandaan de Houtrakpolder tijdens een piekperiode zou worden gevuld. Er moet samen met Waterschap Rijnland worden onderzocht wat de meest efficiënte route is om overtollig water vanuit het waterschap naar de HRP te leiden. Hoewel er al water vanuit het kanaal naar de Haarlemmermeer wordt geleid om het te verbrakken, is dit gericht op natuurontwikkeling en niet op waterberging.
3. **Bestuur:** In het programma Ruimte voor de Rivieren, zoekt RWS naar ruimte voor waterberging, maar beschikt niet over de beleidsinstrumenten om specifiek waterberginggebieden voor kanaalsystemen aan te wijzen. Hierdoor zijn er politiek-bestuurlijke risico's aan verbonden. Centraal Holland is een nieuw orgaan waarin de waterschappen, RWS en de provincie gezamenlijk problemen buiten hun eigen beheergebied kunnen bespreken. Deze partijen kunnen echter tegenstrijdige belangen hebben als het gaat om het afvoeren van overtollig water naar het kanaal.

B.4. Municipality of Amsterdam: Port Account Holder

- Datum: 13 februari 2024
- Duur: 16:00 - 17:00 uur
- Locatie: Stadhuis Amsterdam
- Geïnterviewden: Accounthouder Haven Gemeente Amsterdam
- Interviewer: Tijn Voorkamp

Dit interview is afgenomen met een Accounthouder Haven van de gemeente Amsterdam. Het gesprek vond plaats op 15 februari en was vooral gericht op de ontwikkeling van de Haven van Amsterdam en gerelateerde vraag naar fysieke ruimte. De belangen van havenuitbreiding voor de gemeente, het havenbedrijf en de ondernemersvereniging werden inzichtelijk. De belangrijkste onderwerpen die besproken zijn, omvatten:

1. **Oorsprong van de havenbekkenreservering:** De oorsprong van de reservering voor havenuitbreiding richting de Houtrakpolder, zoals vastgelegd in de Visie NZKG 2040 Stuurgroep Visie Noordzeekanaalgebied, 2013, werd besproken. De gemeente geeft aan dat in 2012 een voorspelling voor 2020 werd gedaan, waarbij een ladingstroom van ongeveer 125 miljoen ton achter de sluis werd verwacht. Deze aanzienlijke toename in ladingstroom was gebaseerd op een verwachte groei van fossiele brandstoffen en een groei van de containeroverslag.
2. **Huidige vraag naar ruimte:** De stagnatie van de groei van fossiele brandstoffen en de snelle schaalvergroting van containerschepen hebben ertoe geleid dat de grote rederijen de voorkeur geven aan Rotterdam en Antwerpen voor hun containeroverslag. De toenemende containerisatie van de logistiek werkt niet in het voordeel van de Amsterdamse haven. Een aanzienlijk deel van de overslag van agrarische producten vindt steeds meer plaats met behulp van containers. Hoewel Amsterdam de grootste cacaohaven ter wereld is, komt de meeste cacao niet meer rechtstreeks via het Noordzeekanaal, maar via containers uit Rotterdam en Antwerpen. In combinatie met de afname van kolen en de verwachte afname van benzine en diesel lijkt de groei van het havenbedrijf te stagneren. Bovendien stelt de gemeente dat als de beoogde Havenstad van 650 hectare wordt gerealiseerd, dit niet volledig gecompenseerd hoeft te worden met nieuw haventerrein elders. Havenstad betreft voor het grootste deel terreinen van de gemeente Amsterdam waar kantoren en stadsgebonden bedrijven zijn gevestigd. Een benodigde compensatie van hooguit 100 hectare voor haventerrein werd genoemd.
3. **Ruimte voor de energietransitie:** De gemeente benadrukt dat er in de toekomst wel veel ruimte nodig is voor het assembleren en onderhouden van windmolens op de Noordzee. De doelstelling om tegen 2050 70 gigawatt aan windenergie op zee te hebben, zal resulteren in een groot tekort aan terrein. Er wordt verwacht dat er een onderscheid zal worden gemaakt tussen haventerreinen voor de bladen van windmolens en haventerrein voor andere assemblage- en onderhoudswerkzaamheden vanwege de enorme afmetingen van de bladen.
4. **Economisch betekenis:** De gemeente geeft aan geen direct economisch belang te hebben bij havenuitbreiding. De Havenmonitor laat zien dat de directe werkgelegenheid die voortkomt uit de haven sinds 2012 redelijk stabiel is gebleven. De havenindustrie is in Amsterdam geen grote werkgever in vergelijking met de technologiesector. Bovendien zou de automatisering in het havenbedrijf steeds meer invloed hebben op de vraag naar personeel. Geschat wordt dat de economie van de haven nog geen 5% bijdraagt aan de totale Amsterdamse economie, terwijl dit in Rotterdam misschien wel 30 tot 40% is.
5. **Ondernemersvereniging:** ORAM is het grootste netwerk van bedrijven in de Metropoolregio Amsterdam en fungeert als belangenbehartiger en netwerkpartner ORAM, 2024. De gemeente beschrijft dat deze partij een sterke voorstander is van havenuitbreiding. Daarnaast is er algemene behoefte aan bedrijventerreinen in de stad vanwege de overgang naar woon-werkgebieden. Deze behoefte omvat zowel droge bedrijventerreinen als haventerreinen, waarbij ORAM geen onderscheid lijkt te maken tussen beide.

B.5. Waternet, Hoogheemraadschap van Rijnland, Rijkswaterstaat

- Datum: 14 februari 2024
- Duur: 11:30 - 12:30 uur
- Locatie: Microsoft Teams
- Geïnterviewden: Strategisch Adviseur Waternet, Beleidsadviseur HR, Adviseur Klimaatbestendig Waterbeheer RWS
- Interviewer: Tijn Voorkamp

Dit interview is afgenomen met drie experts binnen het watersysteem NZKG, werkzaam bij Waternet, Hoogheemraadschap van Rijnland en Rijkswaterstaat. Alle drie de experts adviseren op het gebied van waterbeheer in en rondom het Noordzeekanaal en zijn vanuit hun eigen organisatie betrokken bij het NOVEX programma in het gebied. Het gesprek vond plaats op 14 februari en de belangrijkste onderwerpen die besproken zijn, omvatten:

1. **Waterbergingsvraag:** Rijnland benadrukt dat het vaststellen van een gewenst beschermingsniveau in ARK/NZK essentieel is voor het bepalen van de benodigde capaciteit voor waterberging. Het huidige integrale onderzoek zal uitmonden in een bestuurlijk gesprek over de nationale ambities, met betrokkenheid van RWS en IenW in het 'beleidsdoelentraject'. Rijnland geeft aan dat voor de NZK/ARK een aanzienlijke hoeveelheid water moet worden afgevoerd, waarbij naast het plaatsen van extra pompen, het verhogen van waterpeilen, het 'tijdelijk parkeren' van water een optie is. De zoektocht is naar een combinatie van deze maatregelen. Om een substantiële bijdrage te leveren aan de oplossing voor het NZK, is een eerste schatting gemaakt van minimaal 10 miljoen kubieke meter aan benodigde waterberging. Aangezien er in de HRP 3 miljoen kubieke meter past, zullen er nog meer diepe polders nodig zijn. Rijnland geeft aan dat de Haarlemmermeerpolder en Driemanspolder al als piekwaterberging worden gebruikt, met een kleinere capaciteit van respectievelijk 1 miljoen en 2 miljoen kubieke meter.
2. **Watervraag:** Waternet lichtte toe dat de watervraag in het gebied sterk toeneemt, gedreven door woningbouw, de noodzaak om verzilting tegen te gaan, en strategieën voor het vernatten van veenweidegebieden om bodemdaling en CO2-uitstoot te voorkomen. Ook speelt de watervraag vanuit de industrie, aangedreven door de energietransitie en de circulaire economie, een grote rol. Waternet heeft al een industriewater-net, maar doet onderzoek naar capaciteitsuitbreiding. Waterbergingen op kleinere schaal, om water langer vast te houden, zouden wellicht ook een oplossing bieden.
3. **Bestuur:** Het Deltaprogramma Centraal Holland, met RWS en Rijnland als kwartiermakers, betrekt alle 6 waterschappen in NZKG en de provincies Noord-Holland en Utrecht. Er wordt toegewerkt naar een voorkeursstrategie, maar uiteindelijk worden de beslissingen door het rijk of de provincie genomen. De provincie heeft hierin een belangrijke rol als ruimtelijk ordenaar die ook functies toewijst aan een bepaald gebied. De ambitie van Centraal Holland is heel nadrukkelijk om niet alleen naar het watersysteem te kijken, maar juist de combinatie met ruimtelijke inrichting en ruimtelijke functies. Er wordt echter benadrukt dat er genoeg vraagstukken zijn die buiten het bereik van Centraal Holland vallen. Bovendien geeft Waternet aan dat waar voor het watersysteem nu wel op grote schaal en voor de lange termijn naar het gehele gebied wordt gekeken, deze visie wordt gemist voor de ontwikkeling van de havens in Nederland.
4. **Houtrakpolder als waterberging:** De Houtrakpolder, onderdeel van het Hoogheemraadschap van Rijnland, wordt beschouwd als een potentieel gebied voor waterberging, mede vanwege de recreatieve en natuurlijke ambities. RWS benadrukt dat er een sterke voorkeur is om water vanuit de waterschappen in de waterschappen te bergen, in lijn met het 'water en bodem sturend' beleid van het ministerie. Waternet merkt op dat in tegenstelling tot veel hoofdwatersystemen, zoals die met uiterwaarden langs een rivier, er in het hoofdwatersysteem van NZKG geen natuurlijke berging aanwezig is. RWS suggereert om wellicht eerst te kijken naar de meest geschikte functie voor dagelijks beheer van waterberging in de HRP en vervolgens te overwegen of dit gebied ook kan dienen als noodberging (airbag). Dit vanwege de extreme afhankelijkheid van technische middelen in het systeem. Rijnland benadrukt dat het gaat om het bergen van water gedurende enkele dagen. Om effectief te zijn, moet de capaciteit vanuit het NZK minstens 50 kubieke meter per seconde bedragen. Vanuit het perspectief van Rijnland betekent dit dezelfde tijdsduur maar met een kleinere capaciteit.

B.6. Port of Amsterdam (PoA): Strategic Advisor and Department Head

- Datum: 15 februari 2024
- Duur: 09:00 - 10:00 uur
- Locatie: Microsoft Teams
- Geïnterviewden: Strategisch Adviseur Government Relations PoA, Afdelingshoofd Ruimte, Milieu & Geoinfo PoA
- Interviewer: Tijn Voorkamp

Dit interview is afgenomen met twee experts van het havenbedrijf van Amsterdam. Het werk van de Strategisch Adviseur is gericht op regionale samenwerking en ruimtelijke ordening binnen NZKG. De adviseur is betrokken bij de voorbereidingen voor het Bestuursplatform NZKG en de interne trekker van het NOVEX programma wat hieronder valt. De afdeling Ruimte, Milieu & Geoinfo, en daarmee het afdelingshoofd, is gefocust op ruimtelijke ordening, ruimtelijke functies die grenzen aan de industrie, en alle milieudossiers (luchtkwaliteit, geluid, stikstof etc.). Het gesprek vond plaats op 15 februari en de belangrijkste onderwerpen die besproken zijn, omvatten:

1. **Transitie kolenterminals:** PoA benoemd meerdere variabelen met betrekking tot de ontwikkeling van de vraag naar (fysieke) ruimte, waaronder de transitie van kolenterminals. De ambitie om tegen 2030 kolenvrij te zijn als haven is vergevorderd. Klanten werden al vroegtijdig aangemoedigd om hun kolenactiviteiten te diversifiëren richting non-fossiele activiteiten. PoA tracht de zittende bedrijven zo goed mogelijk te faciliteren in hun transitie naar deze non-fossiele activteiten en ziet dat in de meeste gevallen kolenactiviteiten worden vervangen zonder dat de gevestigde bedrijven vertrekken.
2. **Havenstad:** De Havenstad transformatie is vastgesteld en PoA houdt hier ook rekening mee. De havengebieden in het Havenstad programma zijn: Minervahaven, Alfadriehoek en de Coen-Vlothaven. De Minvervahaven en Alfradriehoek transformeren als eerst, conform de planning van de gemeente. Hier zit geen mogelijke verplaatsingsopgave van haventerrein voor PoA. De Coen-Vlothaven (+/- 100ha haven- en industriegebied) transformeert na 2040 en kent mogelijk wel een verplaatsingsopgave. De nautische ruimte in zowel de Minervahaven als in de Coen-Vlothaven is ook na de tranformatie van belang voor PoA om de nautische operatie vlot en veilig te kunnen uitvoeren.
3. **Energietransitie:** Derde variabele is de energietransitie an sich (waaronder de transitie van liquid terminals). De overgang van fossiele brandstoffen naar biobrandstoffen, synthetische brandstoffen en waterstof lijkt richting 2050 plaats te gaan vinden. Verwacht wordt dat deze nieuwe stoffen meer milieuruimte of omgevings-veiligheidsruimte zullen vereisen. Er wordt op dit moment gewerkt aan nieuw beleid (Beleid Omgevingsveiligheid havengebied Westpoort) door de provincie, gemeente Amsterdam en PoA. Dit is een herziening van het beleid uit 2009 en gericht op de energietransitie.
4. **Ruimtevraag:** Deze milieuruimte, die nodig is om de fysieke ruimte optimaal te benutten, wordt gezien als een prioriteit. PoA geeft aan dat om de energietransitie goed te kunnen faciliteren, milieuruimte uitgebereid moet worden, over de Houtrakpolder heen. Bovendien wordt opgemerkt dat vanwege de verschillende tijdspaden van bovengenoemde variabelen en het ontbreken van nieuw beleid op het gebied van externe veiligheid, het moeilijk is om de ruimtevraag te voorspellen. PoA legt uit dat in de Visie NZKG (2013) onder voorwaarden een reservering is opgenomen voor mogelijke havenuitbreiding in de Houtrakpolder. Op dit moment zoekt het PoA echter niet actief naar fysieke ruimte. De druk op milieuruimte en nautische ruimte is op dit moment in de tijd groter en urgenter dan de fysieke ruimtedruk. Zoals gezegd kan dit na 2040 mogelijk veranderen door havenstad. Let wel, ook qua fysieke ruimte is het havengebied beperkt.

B.7. Rijkswaterstaat (RWS): Climate-proof Water Management Consultant and Strategic Advisor

- Datum: 15 februari 2024
- Duur: 14:00 - 15:00 uur
- Locatie: Microsoft Teams
- Geïnterviewden: Adviseur Klimaatbestendig Waterbeheer RWS, Strategisch Adviseur RWS
- Interviewer: Tijn Voorkamp

Dit interview is afgenomen met twee experts van Rijkswaterstaat (RWS) West-Nederland Noord: een Adviseur Klimaatbestendig Waterbeheer en een Strategisch Adviseur, wiens werk zich richt op waterkwantiteit en waterveiligheid. Het gesprek vond plaats op 15 februari en was vooral gericht op kwantificering van de vraag naar waterberging, soorten waterberging en de interactie met de scheepvaart. De belangrijkste onderwerpen die besproken zijn, omvatten:

1. **Kwantificatie van de waterbergingsvraag:** Er is besproken dat de benodigde hoeveelheid waterberging wordt berekend door een samenspel tussen de afname van de spuicapaciteit in een gebied en de hoeveelheid opslagruimte die nodig is om extra benodigde pompcapaciteit op te vangen. De beschikbare bergingscapaciteit van een polder wordt geschat op basis van oppervlakte en diepte, maar deze capaciteit is ook afhankelijk van de omstandigheden op het moment van gebruik. Daarnaast werd besproken dat de vraag naar waterberging afhankelijk is van beleidskeuzes, met name de verhouding tussen technische oplossingen (zoals een extra gemaal) voor de extra belasting van het watersysteem en oplossingen volgens de 'vasthouden, bergen en afvoeren'-tactiek.
2. **Piekwaterberging:** Volgens RWS moet piekwaterberging als volgt worden beschouwd: als het waterpeil in het kanaal te hoog is, kan RWS bepalen dat het waterschap geen water mag lozen op het kanaal, zoals vastgelegd in het waterakkoord. In deze situatie is het wenselijk om een locatie te hebben waar water tijdelijk kan worden opgeslagen. Dit betreft water van de waterschappen, maar het verlicht ook de druk op het hoofdsysteem.
3. **Seizoensberging:** Zowel in het hoofdsysteem als in de boezems van de waterschappen is het waterbeheer momenteel nog sterk gericht op snelle afvoer. Onderzoek naar seizoensgebonden berging wordt aangemoedigd. Het langdurig vasthouden van water kan ook bijdragen aan buffering richting grondwater of aan het natter maken van gebieden rondom de berging. Het is echter belangrijk op te merken dat de situatie bij het Noordzeekanaal niet te vergelijken is met die in Zuid-Holland, waar sprake is van zandgronden. Bovendien moet rekening worden gehouden met een aanzienlijk verdampingsverlies.
4. **Centraal inzetbare berging:** Het concept van centraal inzetbare berging met structurele opslag en de mogelijkheid om deze gedeeltelijk te legen bij een hoge wateraanvoer werd besproken als een logische oplossing. Op dit moment wordt dit al toegepast op het kanaal door het waterpeil lager te houden wanneer zware regenval wordt verwacht, waardoor er meer opslagcapaciteit in het kanaal zelf beschikbaar is.
5. **Relatie met scheepvaart:** Diverse raakvlakken tussen waterbeheer en scheepvaart zijn besproken, waaronder schade aan tunnels en bruggen. Daarnaast fungeren sluizen als primaire waterkeringen en moeten ze worden gesloten als het waterpeil aan de buitenzijde te hoog is. De wateraanvoer die de scheepvaart nodig heeft om de verzilting tegen te gaan, komt van het Amsterdam-Rijnkanaal, dat het zoute water richting IJmuiden stuwt. Waterberging in de Houtrakpolder heeft geen directe invloed op deze dynamiek; dit betreft zoutbeheer, niet waterpeilbeheer. Schepen mogen niet worden geschut als de sluis bij Utrecht niet openstaat, niet omdat het waterpeil laag is. Als het water extreem hoog staat, kunnen schepen niet onder de bruggen door varen. Dit is ook een argument om water in de regio op te slaan in plaats van op het kanaal. Vanaf het kanaal kan water naar zee worden afgevoerd door zowel pompen als spuien. Bij vooral spuien ontstaat er veel stroming, wat problemen kan opleveren voor de scheepvaart. Daarom kunnen ze een beperking op het spuien aanvragen. Dit kan worden afgewezen als er niet genoeg kan worden gepompt en het spuien echt noodzakelijk is.

B.8. Province of Noord-Holland: Program Manager Seaports

- Datum: 6 maart 2024
- Duur: 10:00 - 11:00 uur
- Locatie: Microsoft Teams
- Geïnterviewden: Programmamanager Zeehavens Provincie Noord-Holland
- Interviewer: Tijn Voorkamp

Dit interview is afgenomen met de programmamaker Zeehavens van de provincie Noord-Holland. De geïnterviewde is ook verantwoordelijk voor de provinciale input aan het NOVEX ontwikkelingstraject in het NZKG. Het gesprek vond plaats op 6 maart en was vooral gericht op de ruimtelijke ontwikkelingen in het NZKG en de rol van de provincie als ruimtelijk regisseur. De belangrijkste onderwerpen die besproken zijn, omvatten:

1. **Havenuitbreiding:** De provincie Noord-Holland geeft aan dat de initiële reservering voor havenuitbreiding in 2013 gebaseerd was op een groeiprognose die een overslag van boven de 125 miljoen ton voorspelde. Deze prognose leidde tot de conclusie dat nieuwe ruimte noodzakelijk was. Echter, de verwachte groei in containeroverslag heeft zich niet gerealiseerd, en de vraag naar benzine en kolen daalt. De provincie concludeert dat, puur op basis van volumes, de haven geen extra ruimte nodig zal hebben. Verwacht wordt dat havenfuncties en energiefuncties kunnen toegepast worden op bestaande terreinen.
2. **Klimaatverandering:** De gevolgen van klimaatverandering, geïllustreerd door simulaties en de effecten in Limburg, de Ardennen en Duitsland, zijn duidelijker in beeld gekomen. Specifiek voor het NZKG wijst de provincie op twee belangrijke uitdagingen: de stijgende zeespiegel, die het gebruik van spuien voor afwatering binnen 30 tot 70 jaar vrijwel onmogelijk maakt, en de toename van hevige piekbuien, die een snellere afvoer van water noodzakelijk maken. Dit onderstreept de noodzaak om water meer ruimte te geven in de ruimtelijke planning.
3. **Ruimtelijke regie:** Als regisseur in de ruimte stelt de provincie Noord-Holland alle ruimtelijke belangen op een rij. Terwijl de vraag naar ruimte voor goederenstromen afneemt, neemt de vraag naar ruimte voor de energietransitie en water juist toe. Er is duidelijk een tekort aan ruimte; er is ongeveer 1,5 keer de oppervlakte van Noord-Holland nodig om aan alle behoeften te voldoen. Daarom is het essentieel dat functies gecombineerd worden of dat er keuzes gemaakt worden. Water speelt in het NZKG een cruciale rol, niet alleen vanwege de enorme hoeveelheid benodigde ruimte maar ook vanwege de beperkte locatiekeuze die geschikt is voor waterberging. Ten slotte wordt opgemerkt dat er steeds meer vraag is naar groene recreatie door de groei van Amsterdam, en dat deze functie zich makkelijk laat combineren met waterberging.
4. **Houtrakpolder:** Geschat wordt dat minimaal 10 miljoen kubieke meter berging nodig is in het NZKG, bij voorkeur verdeeld over gebieden ten noorden en ten zuiden van het Noordzeekanaal. De Houtrakpolder wordt gezien als een geschikt gebied voor het watersysteem aan de zuidkant en heeft een capaciteit van ongeveer 3 miljoen kubieke meter. De diepte van de polder en de huidige functie als brak verzilt natuurgebied maken het een interessante locatie voor waterberging zonder dat dit onmiddellijke desastreuze gevolgen heeft. De provincie ziet de Houtrakpolder niet langer alleen als een havenlocatie, gezien de noodzaak om ruimte te vinden voor waterberging, landschap en recreatie, en de energietransitie.
5. **Type waterberging:** Waterberging vanuit het hoofdsysteem (het kanaal) wordt gezien als een van de scenario's waarin de Houtrakpolder nodig zal zijn. De voorkeur wordt gegeven aan waterberging op de locatie waar het water valt, maar er zijn noodscenario's waar je niet anders kunt. In dit geval moet rekening worden gehouden met vervuilende stoffen die vanuit het kanaal meestromen. De provincie staat ook positief tegenover een combinatie van piek- en seizoens-/voorrraadberging. Ten slotte verwacht de provincie dat er voor de totale waterbergingsopgave combinaties gezocht moeten worden met andere technische oplossingen (pompcapaciteit, flexibel peilbeheer, infiltratiekratten).

B.9. Municipality of Haarlemmermeer: Deputy Mayor/Alderman

- Datum: 6 maart 2024
- Duur: 11:00 - 11:30 uur
- Locatie: Microsoft Teams
- Geïnterviewden: Locoburgemeester en Wethouder Gemeente Haarlemmermeer
- Interviewer: Tijn Voorkamp

Dit interview is afgenomen met een wethouder van de gemeente Haarlemmermeer, wiens portefeuille onder andere bestaat uit ruimtelijke ontwikkeling, havenzaken en woningbouw. Het gesprek vond plaats op 6 maart en was vooral gericht op de gemeentelijke visie op de Houtrakpoldercase. De belangrijkste onderwerpen die besproken zijn, omvatten:

1. **Ruimtelijke ontwikkeling:** De gemeenteraad van Haarlemmermeer is unaniem tegen alle ontwikkelingen in de Houtrakpolder die niet in lijn zijn met het behoud van een 'groen en open karakter'. Hiermee is de gemeente duidelijk tegen een uitbreiding van het haventerrein in de Houtrakpolder. Er wordt opgemerkt dat niet alle ruimtelijke functies in het NZKG gerealiseerd kunnen worden. Zelfs als de Houtrakpolder een havengebied zou worden, passen nog steeds niet alle ruimtelijke opgaven erin, en zullen er keuzes gemaakt moeten worden. De gemeente geeft ook aan dat er meer aandacht zou moeten zijn voor leefbaarheid op de lange termijn, naast de korte termijnfocus op het oplossen van bijvoorbeeld woningtekorten. Er wordt gesuggereerd om havenactiviteiten naar de buitenkant van het kanaal te verplaatsen (op het terrein van Tata Steel), wat zowel operationeel als financieel een voordelige oplossing kan zijn.
2. **Waterberging:** De gemeente Haarlemmermeer staat positief tegenover een waterberging in de Houtrakpolder als daarmee de havenreservering komt te vervallen. Er wordt erkend dat piekwaterberging in het gebied nodig is. De piekberging in de Driemanspolder is mooi ingepast en past binnen het gewenste groene en open karakter. Een ruimtelijke toewijzing op basis van klimaatverandering en zeespiegelstijging wordt gezien als een 'no-regret'-beslissing. Bij havenontwikkeling, woningbouw en de energietransitie is dit niet het geval en is er meer keuzevrijheid. Ten slotte wordt de wens uitgesproken om met de Houtrakpolder aansluiting te vinden bij recreatieschap Spaarnwoude. Dit ook gezien de groeiende behoefte van (Metropoolregio) Amsterdam aan groen recreatiegebied.

C

Survey

1 Voor welke organisatie bent u werkzaam?

2 Wat is uw functie binnen deze organisatie?

Situatie:

- Stel dat er in de Houtrakpolder een dubbel functioneel waterberging - haventerminal systeem wordt gerealiseerd,
- Het gaat hierbij om een systeem waarbij beide ruimtelijke functies gecombineerd worden in één gebied.
- Mogelijke havenfuncties kunnen zijn: container hub, bulk opslag, onderhoud voor wind op zee etc.
- Mogelijke havenfuncties kunnen zijn: piekberging, seizoensberging etc.
- 10 criteria worden beschreven als eigenschappen van een potentieel dubbel functioneel systeem in de Houtrakpolder.
- Bij elk criterium staat de eenheid vermeld waarin dit criterium wordt gekwantificeerd.
- Bij elk criterium staat of het gemaximaliseerd (max.) of geminimaliseerd (min.) wordt in de meest wenselijke situatie.

Opdracht:

Waardeer elk criterium **2x** op een schaal van **0 tot 10 (sterren)**. Door het overslaan van de vraag (0 sterren) kan worden aangegeven dat het criterium **geen** rol speelt voor uw organisatie.

- **Vraag 3-10:**

Ideale situatie: Hoe belangrijk is het criterium voor uw organisatie voor optimale (dubbel)functionaliteit van de Houtrakpolder?

Figure C.1: Survey for determining criteria weights (page 1) [created by author based on Survio (2024)]

• **Vraag 11-18:**

Reële situatie: Hoe belangrijk is het criterium voor uw organisatie voor optimale, maar haalbare, (dubbel)functionaliteit van de Houtrakpolder?

3 Totale capaciteit van een waterbergingsysteem in de Houtrakpolder

Vraag instructies: *Ideale situatie - m^3 – max*

☆☆☆☆☆☆☆☆☆☆ ☐ / 10

4 De periode dat water kan worden geborgen/vastgehouden in een waterbergingsysteem in de Houtrakpolder

Vraag instructies: *Ideale situatie - dagen – max*

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5 De hoeveelheid geborgen water die teruggewonnen kan worden voor het bestrijden van watertekorten in het NZKG

Vraag instructies: *Ideale situatie - % – max*

☆☆☆☆☆☆☆☆☆☆ ☐ / 10

6 Beschikbare fysieke havenruimte in de Houtrakpolder (bijv. kades)

Vraag instructies: *Ideale situatie - m^2 – max*

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7 Beschikbare nautische havenruimte in de Houtrakpolder (bijv. ligplaatsen)

Vraag instructies: *Ideale situatie - m^2 – max*

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Figure C.2: Survey for determining criteria weights (page 2) [created by author based on Survio (2024)]

8 Beschikbare milieuruimte in de Houtrakpolder (bijv. geluidsruimte)

Vraag instructies: *Ideale situatie - m^2 – max.*

☆☆☆☆☆☆☆☆☆☆ ☐ / 10

9 Totale investeringskosten voor een waterberging - haventerminal systeem in de Houtrakpolder

Vraag instructies: *Ideale situatie - € – min.*

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10 Milieu-impact van een waterberging - haventerminal systeem in de Houtrakpolder (CO2, landbouw, natuur, biodiversiteit, groene leefomgeving)

Vraag instructies: *Ideale situatie - Schaal 1-5 – min.*

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Let op: **Vraag 11-18:**

Reële situatie: Hoe belangrijk is het criterium voor uw organisatie voor optimale, maar haalbare, (dubbel)functionaliteit van de Houtrakpolder?

11 Totale capaciteit van een waterbergingsysteem in de Houtrakpolder

Vraag instructies: *Reële situatie - m^3 – max.*

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12 De periode dat water kan worden geborgen/vastgehouden in een waterbergingsysteem in de Houtrakpolder

Vraag instructies: *Reële situatie - dagen – max.*

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Figure C.3: Survey for determining criteria weights (page 3) [created by author based on Survio (2024)]

13 De hoeveelheid geborgen water die teruggewonnen kan worden voor het bestrijden van watertekorten in het NZKG

Vraag instructies: *Reële situatie - % – max*

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14 Beschikbare fysieke havenruimte in de Houtrakpolder (bijv. kades)

Vraag instructies: *Reële situatie - m^2 – max*

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15 Beschikbare nautische havenruimte in de Houtrakpolder (bijv. ligplaatsen)

Vraag instructies: *Reële situatie - m^2 – max*

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16 Beschikbare milieuruimte in de Houtrakpolder (bijv. geluidsruimte)

Vraag instructies: *Reële situatie - m^2 – max*

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17 Totale investeringskosten voor een waterberging - haventerminal systeem in de Houtrakpolder

Vraag instructies: *Reële situatie - € – min.*

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18 Milieu-impact van een waterberging - haventerminal systeem in de Houtrakpolder (CO2, landbouw, natuur, biodiversiteit, groene leefomgeving)

Vraag instructies: *Reële situatie - Schaal 1-5 – min.*

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Figure C.4: Survey for determining criteria weights (page 4) [created by author based on Survio (2024)]

D

Sensitivity analysis

As discussed in Section 6.5, a sensitivity analysis was carried out to explore how adjustments to the criteria weights affect the relative additive value of the design alternatives for the Houtrakpolder case. The importance values assigned to each criterion in the questionnaire were increased and decreased by 50% in 14 experiments. The adjusted MCDM results, consisting of the additive values for each alternative for each stakeholder, are presented in Table D.1 to Table D.14.

	Alt. 1: Port lock system	**Alt. 2: Floating port**	**Alt 3. : Aquifer Storage Recovery**
Province of NH	0,51	0,28	0,63
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,48	0,35	0,75
Ministry of IenW (DGWB)	0,38	0,19	0,72
Municipality Amsterdam	0,36	0,05	0,79
Municipality HLM	0,35	0,25	0,68
RWS-WNN	0,52	0,30	0,69
HHS Rijnland	0,45	0,14	0,72
Waternet	0,40	0,21	0,70

Table D.1: Sensitivity analysis: Storage capacity +50%

	Alt. 1: Port lock system	**Alt. 2: Floating port**	**Alt 3. : Aquifer Storage Recovery**
Province of NH	0,36	0,32	0,70
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,41	0,37	0,79
Ministry of IenW (DGWB)	0,23	0,20	0,79
Municipality Amsterdam	0,16	0,02	0,91
Municipality HLM	0,19	0,27	0,75
RWS-WNN	0,38	0,34	0,77
HHS Rijnland	0,28	0,14	0,81
Waternet	0,24	0,23	0,78

Table D.2: Sensitivity analysis: Storage capacity -50%

	Alt. 1: Port lock system	**Alt. 2: Floating port**	**Alt 3. : Aquifer Storage Recovery**
Province of NH	0,41	0,27	0,68
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,42	0,34	0,78
Ministry of IenW (DGWB)	0,28	0,18	0,77
Municipality Amsterdam	0,24	0,04	0,86
Municipality HLM	0,25	0,23	0,74
RWS-WNN	0,41	0,29	0,75
HHS Rijnland	0,33	0,13	0,79
Waternet	0,29	0,20	0,76

Table D.3: Sensitivity analysis: Storage period +50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,47	0,31	0,64
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,48	0,38	0,75
Ministry of IenW (DGWB)	0,35	0,22	0,72
Municipality Amsterdam	0,32	0,05	0,81
Municipality HLM	0,32	0,29	0,67
RWS-WNN	0,51	0,35	0,69
HHS Rijnland	0,43	0,17	0,72
Waternet	0,37	0,25	0,70

Table D.4: Sensitivity analysis: Storage period -50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,43	0,29	0,67
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,42	0,33	0,79
Ministry of IenW (DGWB)	0,29	0,18	0,77
Municipality Amsterdam	0,22	0,03	0,87
Municipality HLM	0,25	0,23	0,74
RWS-WNN	0,42	0,29	0,74
HHS Rijnland	0,35	0,14	0,77
Waternet	0,30	0,20	0,76

Table D.5: Sensitivity analysis: Recovery rate +50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,45	0,30	0,66
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,49	0,39	0,75
Ministry of IenW (DGWB)	0,34	0,21	0,73
Municipality Amsterdam	0,35	0,05	0,79
Municipality HLM	0,32	0,29	0,67
RWS-WNN	0,50	0,35	0,69
HHS Rijnland	0,40	0,15	0,74
Waternet	0,36	0,24	0,71

Table D.6: Sensitivity analysis: Recovery rate -50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,45	0,30	0,67
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,50	0,38	0,78
Ministry of IenW (DGWB)	0,31	0,19	0,75
Municipality Amsterdam	0,27	0,04	0,84
Municipality HLM	0,29	0,26	0,71
RWS-WNN	0,49	0,34	0,73
HHS Rijnland	0,37	0,14	0,76
Waternet	0,34	0,23	0,74

Table D.7: Sensitivity analysis: Physical space +50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,43	0,29	0,66
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,39	0,33	0,75
Ministry of IenW (DGWB)	0,31	0,19	0,75
Municipality Amsterdam	0,27	0,04	0,84
Municipality HLM	0,27	0,25	0,71
RWS-WNN	0,42	0,29	0,71
HHS Rijnland	0,37	0,14	0,76
Waternet	0,32	0,22	0,73

Table D.8: Sensitivity analysis: Physical space -50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,44	0,30	0,66
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,45	0,40	0,75
Ministry of IenW (DGWB)	0,31	0,19	0,75
Municipality Amsterdam	0,27	0,04	0,84
Municipality HLM	0,28	0,27	0,71
RWS-WNN	0,46	0,36	0,71
HHS Rijnland	0,37	0,14	0,76
Waternet	0,33	0,23	0,73

Table D.9: Sensitivity analysis: Nautical space +50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,44	0,28	0,67
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,45	0,32	0,79
Ministry of IenW (DGWB)	0,31	0,19	0,75
Municipality Amsterdam	0,27	0,04	0,84
Municipality HLM	0,28	0,25	0,71
RWS-WNN	0,46	0,27	0,74
HHS Rijnland	0,37	0,14	0,76
Waternet	0,33	0,21	0,74

Table D.10: Sensitivity analysis: Nautical space -50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,45	0,26	0,70
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,46	0,33	0,78
Ministry of IenW (DGWB)	0,33	0,18	0,77
Municipality Amsterdam	0,27	0,04	0,84
Municipality HLM	0,28	0,26	0,71
RWS-WNN	0,46	0,31	0,72
HHS Rijnland	0,39	0,13	0,78
Waternet	0,34	0,21	0,75

Table D.11: Sensitivity analysis: Investment costs +50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,43	0,26	0,70
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,44	0,33	0,78
Ministry of IenW (DGWB)	0,29	0,18	0,77
Municipality Amsterdam	0,27	0,04	0,84
Municipality HLM	0,28	0,26	0,71
RWS-WNN	0,46	0,31	0,72
HHS Rijnland	0,36	0,13	0,78
Waternet	0,32	0,21	0,75

Table D.12: Sensitivity analysis: Investment costs -50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,39	0,35	0,63
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,42	0,38	0,75
Ministry of IenW (DGWB)	0,28	0,25	0,72
Municipality Amsterdam	0,27	0,04	0,84
Municipality HLM	0,25	0,32	0,68
RWS-WNN	0,44	0,34	0,71
HHS Rijnland	0,35	0,18	0,74
Waternet	0,30	0,27	0,71

Table D.13: Sensitivity analysis: Environmental impact +50%

	Alt. 1: Port lock system	Alt. 2: Floating port	Alt 3. : Aquifer Storage Recovery
Province of NH	0,51	0,22	0,70
Port of Amsterdam	N/A	N/A	N/A
Ministry of IenW (DGLM)	0,48	0,33	0,79
Ministry of IenW (DGWB)	0,35	0,13	0,79
Municipality Amsterdam	0,27	0,04	0,84
Municipality HLM	0,32	0,19	0,75
RWS-WNN	0,48	0,30	0,73
HHS Rijnland	0,40	0,10	0,78
Waternet	0,36	0,16	0,77

Table D.14: Sensitivity analysis: Environmental impact -50%