Computational analysis of water shortage mitigation measures in the IJsselmeer region

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Water Science and Management

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Sint- Michielsgestel

Summary

The increased frequency of droughts due to climate change has prompted national initiatives in the Netherlands to enhance resilience against water-related challenges, with the IJsselmeer region being crucial. To address drought-induced water shortages in the IJsselmeer region, this thesis examined two measures: (1) raising the summer target water level to increase buffer capacity and (2) increasing water supply by connecting the Amsterdam-Rhine Canal (ARK). This thesis evaluated the benefits and drawbacks of these measures, alongside the restoration of the 1980 Rhine riverbed position, which increases water flow to the IJsselmeer region via the IJssel.

The IJsselmeer region, including IJsselmeer and Markermeer, serves key functions: safety (flood prevention), water supply, and nature, which often conflict, particularly between nature and other functions. The ARK supports navigation, discharges excess water, and contributes to water supply. Furthermore, these measures needed to be implemented in a manner that maintained the existing functions of both the IJsselmeer region and the ARK.

This thesis used data on supply and demand for the IJsselmeer region from Delta scenarios Ref 2017 and Steam 2050. Ref 2017 represents current climate and socio-economic situation, while Steam 2050 assumes strong climate change and socio-economic growth. These scenarios were analyzed for two riverbed positions: 1980 and 2018, with the latter reflecting the current state.

The maximum summer target water level increase determined was -0.05 m NAP (from -0.20 m NAP) starting in March, applicable only to the IJsselmeer due to higher flood risks in the Markermeer. Additionally, up to 51 m^3/s of water could be supplied from the ARK to the IJsselmeer region.

The current buffer capacity was sufficient for the Ref 2017 scenario under both riverbed positions. However, for Steam 2050, additional measures were required. With the 1980 riverbed position, either raising the summer water level to -0.05 m NAP or supplying 51 m^3/s from the ARK was sufficient. With the 2018 riverbed position, both measures were necessary.

The thesis's assumptions significantly influenced results. Unchanged dike profiles in the IJsselmeer region limited the ability to increase water levels. Moreover, supplying 51 m^3/s from the ARK was based on a Lobith discharge of 1200 m^3/s; lower discharges would reduce the volume available for diversion.

In conclusion, mitigating water shortages for Steam 2050 with the 2018 riverbed position requires both raising the summer water level to -0.05 m NAP and supplying 51 m^3/s from the ARK.

Key concepts

Dutch	English	Abbreviation
IJsselmeer	IJssel lake	-
Markermeer	Marker lake	-
Klimaatbestendige Zoetwatervoorziening Hoofdwatersysteem	Climate Resilient Freshwater Supply Main Water System	KZH
Deltaprogramma IJsselmeergebied	Delta program IJsselmeer region	-
Deltaprogramma Zoetwater	Delta program freshwater	-
Rijkswaterstaat	Dutch Directorate-General for Public Works and Water Management	RWS
Peilbesluit	Water Level regulation	-
Amsterdam-Rijnkanaal	Amsterdam-Rhine Canal	ARK
Afsluitdijk	Closure Dike	-
Normaal Amsterdams Peil	Normal Amsterdam Level	NAP
Rijn-Maasmonding	Rhine-Meuse estuary	-
Noordzeekanaal	North Sea Canal	NZK
Snelle Waterverdeling Scantool	Quick Water Allocation Scanning Tool	QWAST
Integraal Riviermanagement	Integral River Management	IRM
Verdringingsreeks	Prioritization sequence	-
Beleidstafel Droogte	Policy Table on Drought	-
De Overeengekomen Lage Afvoer	The Agreed Low Discharge	OLA
Landelijk Hydrologisch Model	National Hydrological Model	LHM
Spuisluis	Discharge sluice	-

Note: Certain terms in the table above, such as "Rijkswaterstaat" or "Afsluitdijk" along with Dutch abbreviations like "KZH," were retained in Dutch throughout the thesis. This ensured that the text remains familiar to Dutch readers, particularly for the internship provider, Rijkswaterstaat. Less frequently mentioned terms are presented directly in Dutch, enclosed in brackets, to maintain clarity. Additionally, the word "meer" in IJsselmeer or Markermeer translates to "lake". Finally, "freshwater supply," "water supply," or simply "supply" in this thesis refers to the freshwater supply from surface water.

Content

1. Introduction

1.1 Background

As the concentration of greenhouse gases and the temperature at the Earth's surface increase, the global mean rates of precipitation and evaporation also rise, leading to an alteration in the planet's water cycle (Manabe, 2019). This alteration, along with other impacts, is considered to be part of global climate change. The alteration in the planet's water cycle has numerous implications, such as an increased frequency of droughts in Europe and worldwide (Mukherjee et al.,2018). Even under moderate climate scenario (e.g., RCP4.5), droughts are projected to become increasingly frequent and severe across the entire European continent, particularly in the Mediterranean area, Western Europe, and Northern Scandinavia, with the exception of Iceland (Spinoni et al, 2018).

These climate change impacts present challenges for water managers, who must balance the need to ensure water safety (flood prevention) during storms with the necessity of maintaining adequate water supplies during prolonged dry periods, while also considering the needs of nature and other water users. In the Netherlands, droughts have been experienced in recent years (Mukherjee et al., 2018). Like the droughts of the years 2018-2020 and 2022 which had significant societal and economic consequences. These droughts not only led to water shortage but also deteriorated water quality and additional subsidence due to low groundwater levels, affecting buildings. This affected various sectors and water-using functions such as nature, agriculture, navigation, and drinking water production (Bartholomeus et al, 2023).

At the same time, floods still occur, such as the one in southern Netherlands in 2021, and are also projected to increase with rising temperatures (KNMI, 2023). These phenomena emphasize the need for water management capable of addressing the consequences of drought and flooding, while maintaining water safety and limiting impacts on water quantity and quality. For decades, water management in the Netherlands has focused on implementing flood prevention policies, mostly prompted by specific events like the floods in 1953. The occurrence of droughts however did not lead to similarly significant transitions in water management. (van der Wiel et al., 2021, 2022; Aalbers et al., 2022; Blauhut et al., 2022; Gessner et al., 2022).

To ensure adequate freshwater availability, national initiatives aim to make the Netherlands resilient to water-related challenges by 2050. The Delta Program, for example, focuses on freshwater supply, water safety, and spatial adaptation. For water supply, the goal is to limit water shortages occurrence to once every twenty years (Delta Program Freshwater, 2023). Current research, therefore, emphasizes developing water management strategies that mitigate the impacts of drought-induced water shortages while also addressing the potential for floods. The Climate Resilient Freshwater Supply Main Water System initiative (Klimaatbestendige Zoetwatervoorziening Hoofdwatersysteem, henceforth KZH) was introduced in 2019 to further enhance the country's resilience to drought conditions. The primary mission of KZH is to efficiently allocate freshwater among users both before and during drought periods, thereby reducing the impacts of water shortages (Delta Program, 2024). Additionally, Integrated River Management (IRM) represents a collaboration among the national government, provinces, water boards, and municipalities. The goal of IRM is to ensure the four key elements (nature, freshwater supply, navigability, and flood prevention) of the major rivers catchments (Rhine and Meuse) within the context of sediment management/riverbed positioning, storage and discharge capacity (Asselman et al., 2022). The IRM is conducting a comprehensive examination of changes in riverbed positioning within the Rhine branches, as these changes significantly impact the freshwater distribution of the Rhine River (Asselman et al., 2022).

An important surface water resource currently being studied, is the IJsselmeer region (including, IJsselmeer and Markermeer). As the country's largest freshwater basin, the IJsselmeer region is crucial, with more than 30% of the Netherlands approximately 12,950 km² relying either directly or indirectly on it for their water supply (Delta Program, 2023). Ensuring a reliable freshwater supply also supports various economic sectors, emphasizing the need for effective water management strategies (Bartholomeus et al., 2023).

Considering the fundamental importance of IRM, Delta program freshwater and KZH for water management in the IJsselmeer region, this thesis considers these frameworks for further analyses.

1.2 Problem description

During periods of water shortages, the freshwater supply from surface water (hereafter referred to as "water supply" or "supply") is reduced or completely cut off for many users, depending on the severity of the shortage, in order to safeguard critical functions (Kort et al., 2020). This reduction/cutting follows a prioritization sequence (Appendix A). However, limiting the water supply significantly impacts the economy, particularly the agricultural sector, due to the lack of sufficient irrigation water (Beleidstafel Droogte, 2019).

Rijkswaterstaat is committed to ensuring freshwater availability across the entire main water system to all users. As part of this commitment, the KZH team at Rijkswaterstaat is evaluating various measures to assess their benefits and drawbacks comprehensively to lessen the need to implement the prioritization sequence. This evaluation is slated to result in a definitive course of action by 2026, determining which measures will be implemented or abandoned and their respective implementation strategies, with the IJsselmeer region seen as crucial (Rijkswaterstaat, 2018). Furthermore, the KZH measures must be examined in conjunction with other measures being developed that significantly impact the IJsselmeer region, such as the IRM measures that involve changing the riverbed position of the Rhine branches to address the increased erosion of the Waal. This erosion affects the discharge distribution at the Waal/Pannerdensch Canal and IJssel/Nederrijn (Asselman et al., 2022). Since the IJssel is the primary water supplier to the IJsselmeer region (Rijkswaterstaat, 2018), the higher erosion rate of the Waal leads to a reduced water supply to the IJssel, thereby decreasing the water availability for the IJsselmeer region (Asselman et al., 2022). Restoring the riverbed to the 1980 position or achieving similar water distribution through infrastructure would increase water flow to the IJssel and, consequently, to the IJsselmeer region (Asselman et al., 2022).

A freshwater stress test conducted in May 2021 indicated that the probability of water shortages in the IJsselmeer might be significantly higher than previously estimated (Appendix B&C) (Rijkswaterstaat, 2021). This uncertainty must be addressed through KZH measures. Two of these measures were examined in this thesis:

(1) **increasing buffer capacity in the IJsselmeer region by increasing the summer target water level** and (2) **creating new inflow through the Amsterdam-Rhine Canal (ARK)**.

However, the effects of these two measures on safety, freshwater supply, and nature, in combination with other functions such as agriculture and navigation, are currently unclear.

1.3 Research aim and questions

This thesis is focused on analyzing the effects of the two measures considering fresh water supply, safety, and nature in combination with other functions of the IJsselmeer region and the ARK.

1.Increasing the IJsselmeer summer target water level: the current upper and lower water level limits in the IJsselmeer region are -0.10 m NAP and -0.30 m NAP, respectively, with an emergency lower limit set at -0.40 m NAP. The summer target level is set at -0.20 m NAP, providing a buffer capacity of 0.20 m. This buffer capacity represents the difference between the upper and lower water level limits in the IJsselmeer region. Raising the summer target water level increases this buffer capacity, making more water consistently available.

2.Establishing a secondary supply route via the ARK: currently, the IJssel is the primary supply route to the IJsselmeer. One option is to create an additional supply route from the Waal via the ARK through the Markermeer to the IJsselmeer .This approach would enhance the water supply to the IJsselmeer region, thereby reducing the required buffer capacity to mitigate water shortages.

The aim of this project is to gain insight into the drawbacks (negative impacts) and benefits (positive impacts) of these two measures.

This thesis addresses two main research questions and their associated sub-questions, focusing on (1) increasing the summer target water levels in the IJsselmeer region and (2) connecting the Amsterdam-Rhine Canal, respectively:

Main research question 1: What are the impacts of increasing the summer target water levels in the IJsselmeer region to mitigate water shortages, under both the current climate and socioeconomic conditions (Ref2017), and the worst-case climate and socioeconomic scenario projected for the year 2050 (Steam 2050)?

The first main research question is further specified according to these three sub questions:

1.1 What is the required buffer capacity in the IJsselmeer region to mitigate water shortages under the Delta Scenarios (Ref 2017 and Steam 2050), considering each scenario in combination with both the 2018 (current) and 1980 riverbed positions?
1.2 What are the impacts of increasing the summer target water level on safety, nature, and other functions of the IJsselmeer region?
1.3 What is the maximum possible rise in summer target water level in the IJsselmeer region, considering safety, nature and the other functions?

Main research question 2: What are the impacts of connecting the Amsterdam-Rhine Canal to mitigate water shortages in the IJsselmeer region, under both the current climate and socioeconomic conditions (Ref2017), and the worst-case climate and socioeconomic scenario projected for the year 2050 (Steam 2050)?

The second main research question is further specified according to these two sub questions:

2.1 What are the impacts of connecting the Amsterdam-Rhine Canal to the IJsselmeer region on water quality in both the canal and the IJsselmeer region, and on navigation and safety in the canal?
2.2 What is the maximum possible additional inflow from the Amsterdam-Rhine Canal to the IJsselmeer region, considering the impacts under the Delta Scenarios (Ref 2017 and Steam 2050), and taking into account each scenario in combination with both the 2018 and 1980 riverbed positions?

2.Theory

2.1 IJsselmeer region functions

The IJsselmeer region shown in Figure 1 (A) below has three main functions:

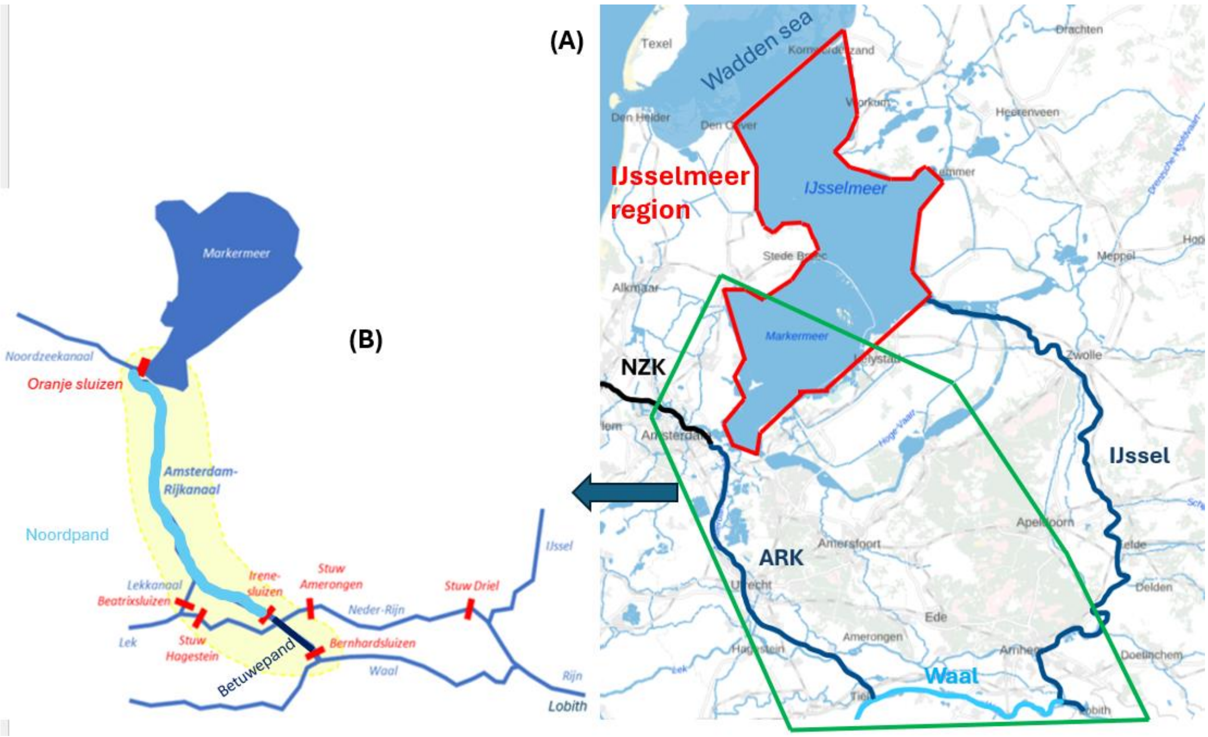

Figure1 Project Location, A shows the entire impacted systems addressed in this thesis, B illustrates the ARK system and its relevant connections.

(1) Safety (Flood Prevention): water must be stored in the IJsselmeer region to prevent flooding when conditions such as storm surges or high sea levels hinder discharge to the Wadden Sea (spuien), or when river inflow from the IJssel and surrounding regions is exceptionally high. To ensure safety, average water levels in the IJsselmeer region must be kept sufficiently low in winter to mitigate flood risk. In addition to average water levels, wind also influences the water level at the dikes. Therefore, water level, wave height, tilt (scheefstand), and the duration over which a certain water level persists are equally important for maintaining the safety function. These conditions are most critical during the winter months, from November to February. More information can be found in Appendix D (van Ginkel et al., 2022).

(2) Freshwater Supply: during periods of meteorological drought or when inflow from the IJssel temporarily falls short of demand, freshwater must be drawn from the buffer of the IJsselmeer region. This function is particularly critical in the summer months, from April to August. For effective freshwater supply, it is essential to maintain a higher summer water level to ensure adequate reserves when the IJssel's inflow is insufficient (van Ginkel et al., 2022).

During drought periods, the emergency limit of -0.40 m NAP is applied when the combined inflow to the IJsselmeer region from the IJssel and regional discharge is 200 m^3/s or less (van Ginkel et al., 2022). At the lower water level limit of -0.30 m NAP, a water use reduction (WUR) is imposed on certain economic water users according to the prioritization sequence. When the water level reaches -0.40 m NAP, a water extraction ban (WEB) is applied to all users to mitigate risks to dike stability. The current buffer capacity of 0.2 m corresponds to a buffer supply of 400 million m³ (van Ginkel et al., 2022), which supplements inflow from the IJssel. Under dry meteorological conditions, marked by a lack of rain and high evaporation, this buffer supply is typically exhausted within about two weeks, due partly to evaporation from the lake and partly to water deliveries to consumers (van Ginkel et al., 2022).

(3) Nature: the IJsselmeer region serves as a vital habitat for various flora and fauna. It functions as a foraging area for birds such as cormorants, a moulting area for resident birds like the great crested grebe, and a winter habitat for migratory birds such as smews (van Ginkel et al., 2022). Additionally, other animals, such as grass snakes, forage in the shoreline vegetation (Rijkswaterstaat, 2020). This region is also home to both freshwater fish and migratory fish. For this function, natural water level dynamics, with higher levels in winter and lower levels in summer, are beneficial (van Ginkel et al., 2022). More information can be found in Appendix E.

As shown in Figure 2, there is a conflict of interest between the water supply and safety with the nature function. The nature function requires a natural water level, which is low in summer and high in winter. In contrast, the safety function demands a low water level in winter, while the supply function necessitates a higher water level in summer.

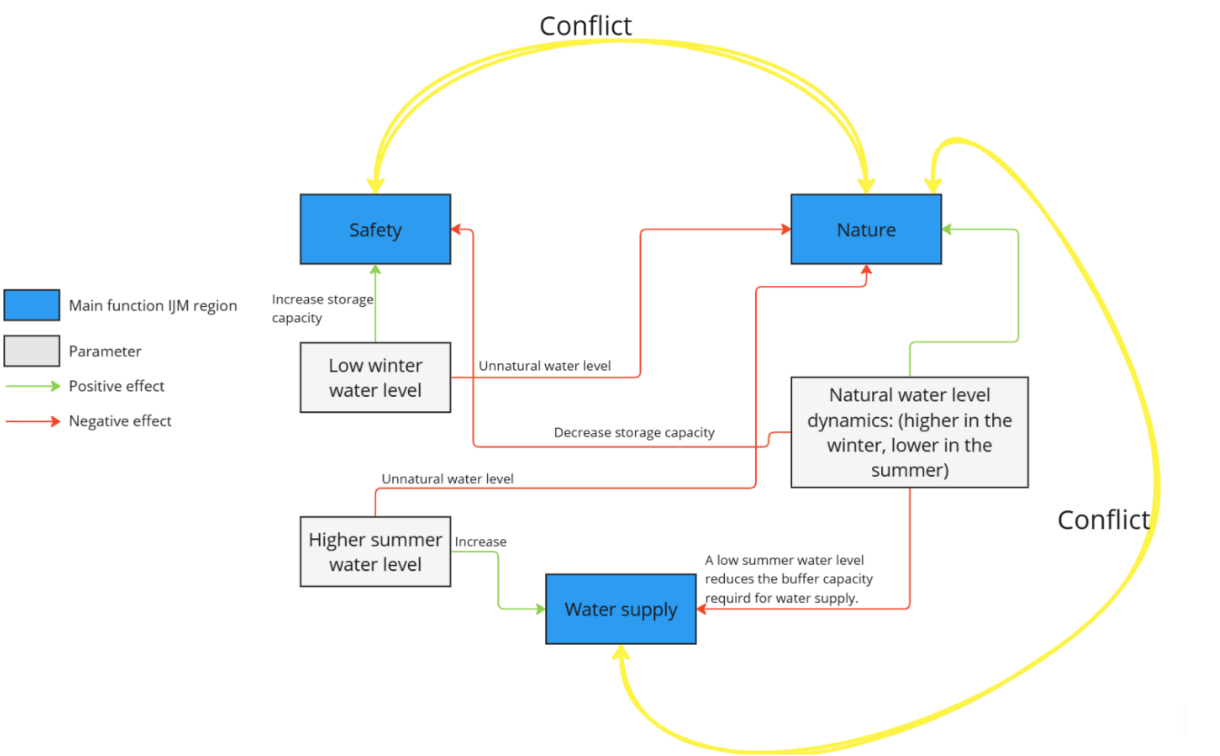

Figure 2 Impacts of water levels on the three main functions of the IJsselmeer region.

In addition to the three main functions, the IJsselmeer region supports other activities such as recreation, navigation, fisheries, sand extraction, recreation, energy generation (wind turbines and solar panels), and (large-scale) housing developments (Appendix F). Additionally, certain functions are closely related to the freshwater supply, such as drinking water production and agriculture.

Current regulations and impacts on the three main functions

In many successive water level regulations (Peilbesluiten), the first two functions, safety and freshwater supply, have consistently been prioritized (van Ginkel et al., 2022). This involves maintaining a low winter water level and a high summer water level, which is considered undesirable for nature (van Ginkel et al., 2022).

The summer target water level is set at -0.20 m NAP. During the "spring setup," water levels are raised from the winter level of -0.40 m NAP to -0.10 m NAP, then lowered in early April to reach the summer target level by mid-April. The upper limit of -0.10 m NAP is reached in the IJsselmeer by mid-March and in the Markermeer by the end of March, ensuring the safety function, as the critical water level in the Markermeer is lower than in the IJsselmeer (Rijkswaterstaat, 2018) (Figure D2). However, the spring setup can pose a risk to the safety function, as storms can occur in March, potentially causing floods. For this reason, the spring setup will be suspended if storms are expected. Furthermore, the spring setup can cause waterlogging in areas that drain into the IJsselmeer region and raise the groundwater level in areas outside the dikes (van Ginkel et al., 2022). The spring setup prevents birds from nesting in low areas that might later be flooded, positively contributing to the nature function (Table E1&E2) (Sweco, 2017).

The current water level regulation also introduced the so-called "summer setup," where, in anticipation of drought, the water level is raised from the summer target level of -0.20 m NAP to the upper limit of -0.10 m NAP. This setup is considered undesirable for nature, as it is highly unnatural and increases the risk of nest flooding (Sweco, 2017). To mitigate this, the summer setup is limited to a maximum of two weeks. The summer setup has, however, minimal impact on safety, as fewer storms are expected during dry summers (Rijkswaterstaat, 2018).

The nature function is also under pressure due to abrupt transitions between various environmental factors, such as deep to shallow waters, clear to turbid conditions, nutrient-poor to nutrient-rich waters, fresh to saltwater, stagnant to flowing water, and land to water interfaces (PAGW, 2017). These abrupt transitions prevent the formation of gradual ecological gradients, which are essential for connecting different ecosystems and habitats. To mitigate the impact of these abrupt transitions, shallow zones, islands, and foreshores near dikes have been constructed to create habitats for various plants and animals (van Ginkel et al., 2022).

Impacts of increasing the summer target water levels on the IJsselmeer region functions

Increasing the summer target water level of the IJsselmeer region enhances its buffer capacity, which benefits the freshwater supply function. However, this measure also impacts the other functions. The magnitude of these impacts depends on both the extent of the increase and its timing.

Safety

Raising the summer target water level is constrained by the current dike profiles, as the Delta Program has determined that no changes to these profiles will be made before 2050 (Delta Program, 2023). This restriction limits the extent to which the summer water level can be raised, as higher water levels increase wave height and, when combined with wind-induced tilt, elevate the risk of flooding (Figure D1) (Van Ginkel et al., 2022).

Raising the summer water level can also result in the submergence of islands and foreshores, which has both positive and negative effects on safety. The islands help reduce wave height, but the reduced water surface area can lead to higher flood levels (Van Ginkel et al., 2022; PAGW, 2020; Appendix E).

A positive impact of raising the summer water level is the reduced likelihood of a rapid drop in water levels, which could destabilize dikes and pose a safety risk (Rijkswaterstaat, 2020).

However, higher water levels can accelerate seepage under the dikes, increasing the risk of piping (Delta Programma IJsselmeergebied, 2014). A test conducted in 2020 revealed that several dikes in the IJsselmeer region do not meet the required standards for piping risk (Rijkswaterstaat, 2020), making this issue particularly critical.

Additionally, higher water levels make it more difficult to achieve free drainage into the IJsselmeer region, leading to waterlogging (Bos et al., 2012). This affects both low-lying and elevated areas that rely on free drainage, raising water levels in waterways and potentially causing regional flooding (Delta Programma IJsselmeergebied, 2014). Furthermore, higher water levels reduce the efficiency of water-lifting devices, such as screws and pumps used by water boards to discharge excess water into the IJsselmeer region, leading to increased energy consumption (Bos et al., 2012; Rijkswaterstaat, 2020).

All of these impacts are summarized in Figure 3.

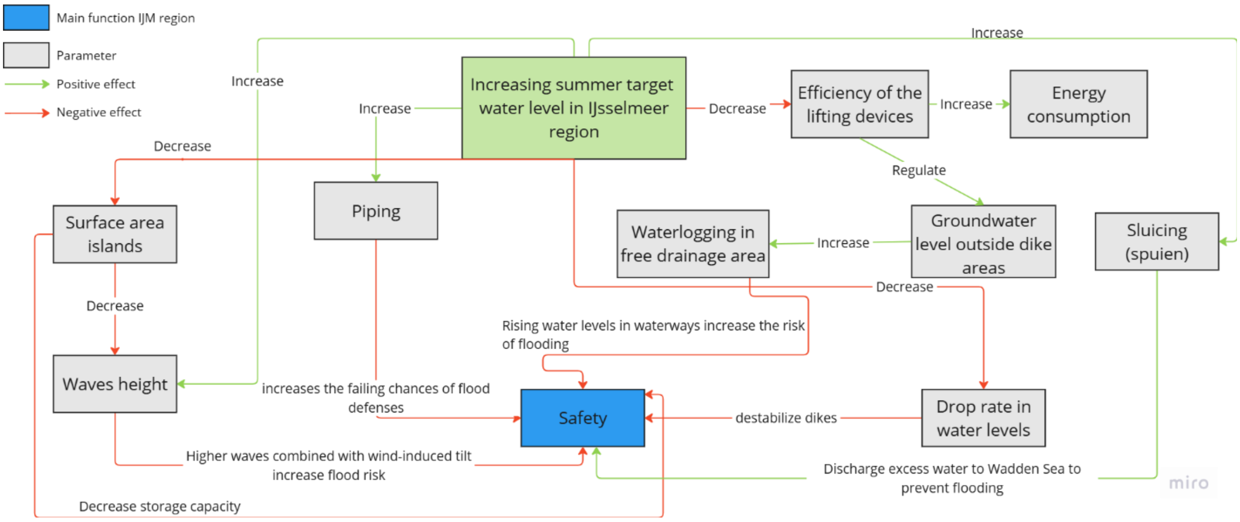

Figure 3 Impacts of increasing summer target water level on the safety function in the IJsselmeer region.

<u>Nature:</u>

Increasing the summer water level further intensifies the unnatural dynamics of water levels in the IJsselmeer region. Since the region is bordered by dikes, shallow zones cannot adjust to rising water levels. This results in the flooding and loss of certain habitats, such as transitions between deep and shallow waters or land and water interfaces (Sweco, 2017; PAGW, 2017). Submerged islands further reduce bird habitats, compounding the ecological impact (Sweco, 2017). The loss of shallow zones also negatively affects reed beds, as existing reed beds will be overtaken by forests. Increased areas with constant water levels lead to greater shoreline erosion, hindering the rejuvenation of pioneer communities. Over time, more shores become overgrown with rough vegetation and forests. Shoreline erosion also impacts species like the grass snake, whose breeding areas are located above water, while its foraging areas rely on shoreline vegetation (Sweco, 2017).

Additionally, raising the summer water level exacerbates abrupt transitions between salt and freshwater in the IJsselmeer, harming fish species unable to tolerate such shocks. This issue is further intensified by the need for sluicing (spuien) to return to the winter water level, which discharges freshwater fish into the Wadden Sea. Many of these fish die, negatively affecting bird species that depend on them as a food source (PAGW, 2017).

The increased water depth resulting from higher summer water levels reduces light penetration to the bottom, limiting the growth of aquatic plants. This, in turn, reduces food availability for non-diving water birds, further disrupting the ecosystem (Van Ginkel et al., 2022).

As shown in Tables E1 and E2, increasing the summer water level in early March can help prevent bird nesting sites from being flooded later in the season, offering a potential mitigation measure (Sweco, 2017).

All of these impacts are summarized in Figure 4 below:

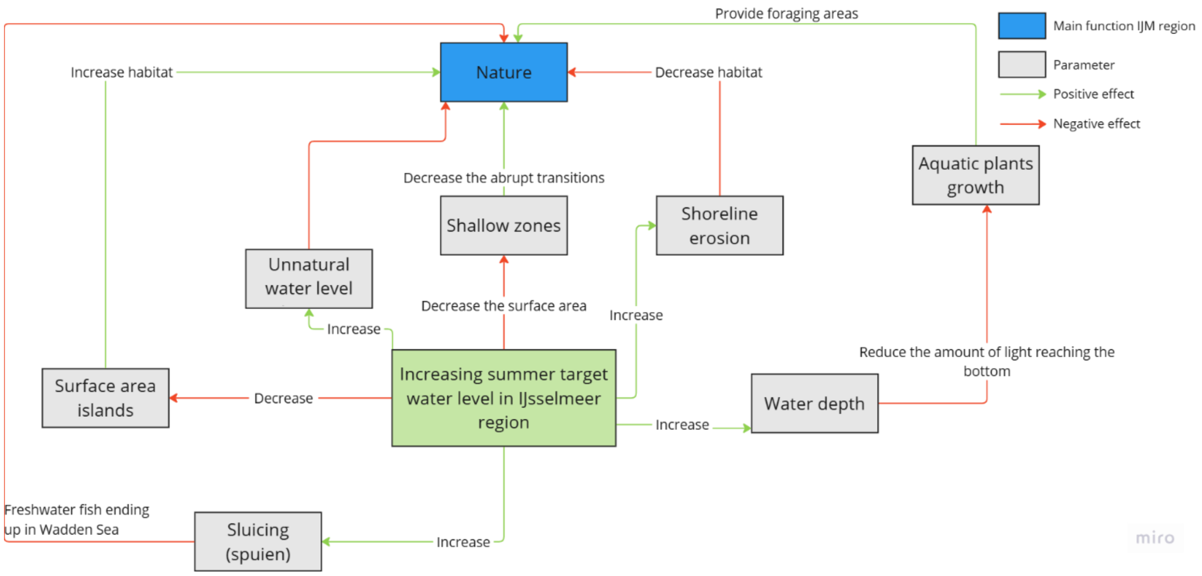

Figure 4 Impacts of increasing summer target water level on the nature function in the IJsselmeer region.

<u>Other functions:</u>

Urban area

Higher summer water levels increase groundwater levels in urban areas like Kampen and Zwolle (Kramer and van Meurs, 2011). Reports indicate that the average highest groundwater level (GHG) rise in central Zwolle is almost equivalent to the IJsselmeer water level rise, as Zwolle's city canals are directly connected to the IJsselmeer. This could lead to problems in basements and low-lying areas, with some overflows at risk of flooding (Klimaatrobuust Zwolle, Infram 2018; Rijkswaterstaat, 2020).

Recreation

The submerging of the islands negatively impacts recreation, as these islands hold significant recreational value. Furthermore, recreational sites such as vacation parks, campsites, recreational beaches, grassy areas (ligweiden), and sunbathing lawns outside the dikes may experience water nuisance (Tolk & van Staveren, 2012). Even with the current water level regulation, during the spring setup at -0.10 m NAP, concerns were raised to Rijkswaterstaat due to local flooding in recreational areas caused by strong easterly winds, resulting in tilts (Rijkswaterstaat, 2020). This effect is less severe in the IJsselmeer compared to the Markermeer.

Additionally, waiting times at the locks for recreational boating will increase due to the greater water level differences on the sides of the locks, potentially reducing the attractiveness of the recreational areas (Tolk & van Staveren, 2012).

Drinking water production

An increase in the water level leads to longer residence time of water in the IJsselmeer region, which can raise chloride levels and negatively impact drinking water production (Rijkswaterstaat, 2020). However, increasing the summer water level decreases the risk of water shortages. In times of water scarcity, maintaining a chloride content below 150 mg Cl-/L is crucial for drinking water production and preventing algal blooms. Therefore, higher summer water levels benefit drinking water production (Rijkswaterstaat, 2020).

Navigation

A higher water level reduces the clearance under fixed bridges, which can create challenges for ships, particularly those with tall masts (Rijkswaterstaat, 2020). However, increasing the summer water level also helps prevent water levels from becoming too low, which is beneficial for navigability. Low water levels can result in insufficient water depth in harbors and navigation channels, making some shallow areas of the IJsselmeer region unnavigable (Delta Program IJsselmeergebied, 2014).

Additionally, raising the summer water level increases waiting times for commercial navigation at locks, adding further inconvenience for waterway users (Rijkswaterstaat, 2020).

Agriculture
Increasing the summer water level leads to seepage in areas where arable farming is practiced, which is sensitive to such conditions. In the IJsselmeer region, this primarily affects well-drained fields in the Wieringermeer Polder, Flevoland, parts of Friesland, and scattered areas in the IJssel-Vecht Delta. Drainage pipes can manage excess groundwater and prevent crop damage, provided the seepage intensity remains lower than 0.5 mm/day (Boderie et al., 2012). If the seepage is saline, it also negatively impacts soil quality.

All of these impacts are summarized in Figure 5 below:

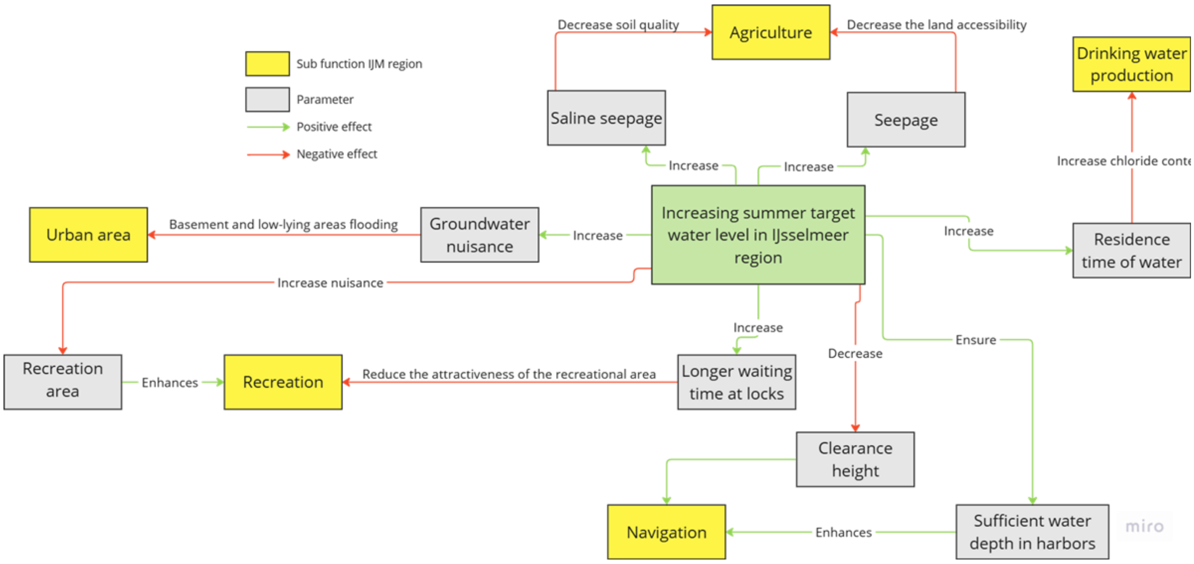

Figure 5 Impacts of increasing summer target water level on the other function of the IJsselmeer region.

2.2 Amsterdam-Rhine Canal (ARK) system

The primary functions of the ARK are navigation and discharge of excess water from the surrounding regions, with an additional role in water supply. Furthermore, ARK water is used to direct water to the Noordzeekanaal (North sea canal) to counteract saltwater intrusion and support drinking water production (Naus et al., 2024). To enable water transfer from the ARK illustrated in yellow in Figure 1 (B) to the IJsselmeer region via the Markermeer, a physical connection, specifically a pumping station, is required, as the water level in the ARK is lower than the Markermeer target water level in spring and summer. The use of existing infrastructure, particularly the Bernhard and Irene locks, significantly influences the volume of water that can be transferred from the ARK to the Markermeer (Flipsen,2024). Currently, these locks regulate water primarily for navigation, though additional water supply functions are feasible. To supply water from the ARK to the Markermeer, extra discharge is required through the Bernhard and Irene locks.

Impacts of extracting water from the ARK to the IJsselmeer region on the functions of the ARK

<u>Fresh water supply</u>
Extracting water from the ARK to the IJsselmeer region reduces the water available for the functions of the ARK, including the Noordzeekanaal and drinking water production (Schuring, 2024).

Navigation

The extraction of water from the ARK necessitates additional water being discharged into the ARK, which increases the water level. This rise in water level may negatively impact the navigation function of the ARK, which is considered its most critical function (Naus et al., 2024). To maintain the navigation function, the following must be ensured:

ARK

The water level in the Noordpand must not exceed -0.20 m NAP to ensure clearance height for CEMT Class VIc vessels (9.10 m, RVW). Ships in classes Va, Vb, VIa, and VIb would face restrictions at this level when carrying four container layers, causing financial impacts on significant portions of ARK navigation (Flipsen,2024).

Irene locks

At least one lock of the two locks must remain available for navigation at the Irene locks (Flipsen,2024). Additionally, on the Nederrijn-Lek stretch and at the Irene locks (Figure1(B)), the water level must be at least 2.0 m NAP to maintain sufficient navigational depth (Flipsen,2024).

Bernhard Locks

To maintain navigation functionality at the Bernhard locks, flow speed should not exceed 0.5 m/s, as higher speeds hinder the movement of larger vessels (Bernhardsluizen measurements LCW, 2023).
Furthermore, when one lock of the two locks at the Bernhard complex is used for water supply and the other for navigation, the water level difference on both sides of the lock gate must be greater than the wave height (estimated at 0.5 m due to navigation activity) to prevent gate rattling. If the difference is less, technical adjustments are necessary (Flipsen,2024).

Waal

The Waal's water level must not fall below the Agreed Low River Level (OLR near Tiel = 2.55 m NAP, per Protocol 19 of the Central Commission for Navigation on the Rhine) more than 20 days per year to ensure navigational functionality.

Safety ARK

The water level in the Noordpand must not exceed the critical level of 0.00 m NAP to maintain the safety of adjacent flood defenses (Rijkswaterstaat,2023).

All of these impacts are summarized in Figure 6 below:

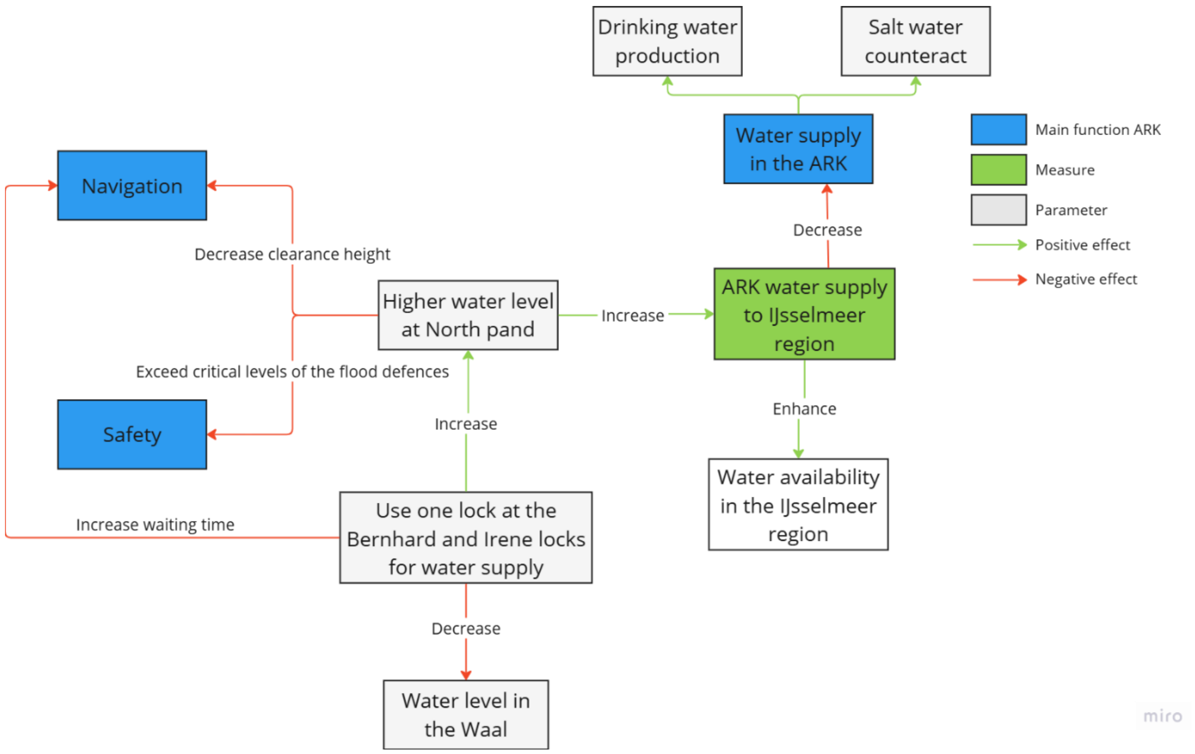

Figure 6 impacts of connecting the ARK to the IJsselmeer region on the functions of the ARK.

To ensure the navigation and safety functions of the ARK, the threshold values outlined in Table 1 were determined (Flipsen, 2024). The negative impacts correspond to the level of exceedance. Additionally, higher flow speeds in the locks, resulting from the added water supply function, may cause some erosion of the lock walls and bed (Flipsen, 2024).

Table1 Thresholds for connecting the ARK to the IJsselmeer region regarding the safety and navigation of the ARK (Flipsen,2024).

Navigation/ Safety	Threshold
Water level Waal	Max. 20 days with water level below OLR (2.55 m NAP near Tiel)
Rattling lock gates at Bernhard	Water level difference less than wave height for CEMT Class VI ships (0.5 m)
Navigation obstruction in both locks at Bernhard	Flow speed greater than 0.5 m/s
Navigation obstruction at Irene due to water discharge	Two locks in use for water discharge
Navigation obstruction at Irene due to water depth	Water level in the forebay of Irene locks less than 2.0 m NAP
Water level in Noordpand	Water height less than -0.20 m NAP (navigation hindered) or more than 0.00 m NAP (critical water level for flood defenses)

Based on Schuring's report (2024), there is no significant change in ARK and the Markermeer water quality, as all aspects: chloride, nutrients (nitrogen and phosphorus), water temperature, and suspended solids remained within the bandwidth of the standard (Schuring, 2024), which is expected as the water of the ARK and the IJsselmeer region originates from the Rhine. However, residence time in the Markermeer decreased by 30%, which also is anticipated due to the refreshing effect of additional ARK water (Schuring, 2024).

3.Materials and methods

3.1 Study area

The study area of this thesis is shown in Figure 1, focusing on the IJsselmeer region, which encompasses both the IJsselmeer and Markermeer. The majority of the water supplied to the IJsselmeer region originates from the IJssel River, accounting for an average of 70% of the annual inflow. The total surface area of the IJsselmeer region is approximately 2000 km² (Rijkswaterstaat, 2018). This thesis also investigated the possibility of connecting the Amsterdam-Rhine Canal (ARK) to the IJsselmeer region via the Markermeer. Details of the ARK system are provided in Figure 1(B), which highlights two main sections, or stretches between locks. The first section, the Betuwepand, lies between the Bernhard and Irene lock complexes, while the second section, the Noordpand, extends from the Irene lock complex to the Oranje lock complex (Naus et al., 2024). The Amsterdam-Rhine Canal connects the IJ in Amsterdam with the Waal near Tiel. It serves as a vital link between the Port of Amsterdam and Germany's Ruhr area. The canal is 72 km long, with a width ranging from 100 to 120 meters (Rijkswaterstaat).

3.2 Research tools

This research adopted a combination of quantitative and qualitative approaches. The quantitative part of the study involved data processing using Microsoft Excel and the application of the Quick Water Allocation Scan Tool (QWAST), a water distribution model designed for the large rivers, canals, and lakes of the Netherlands. QWAST was used to calculate the IJssel discharge based on the riverbed position of 1980. Additionally, a slightly modified version of the KZH comparison framework was employed to comprehensively evaluate the impacts of the two measures. The qualitative part of the research consisted of a literature review to assess the impacts of the measures, with primary reliance on the Rijkswaterstaat database. This focus was due to the thesis being conducted as part of an internship at Rijkswaterstaat.

3.3 Experiment design

Data on water demand and supply in the IJsselmeer region were gathered from baseline projections (Basisprognoses, Appendix G). These projections provide long-term calculations, spanning 100 years (1911 to 2011) using time intervals of ten days, resulting in 36 steps per year, for the entire Netherlands using the National Hydrological Model (LHM) (Appendix G). The data within these projections are available based on the Delta scenarios, which combine the KNMI 14 climate scenarios with the socio-economic scenarios from the "Welvaart en Leefomgeving" (Prosperity and the Living Environment, WLO) for the Netherlands. The Delta scenarios include four different future scenarios, along with one representing the current situation (Appendix B) (Prinsen et al., 2014). In this thesis, Delta scenarios Ref 2017 (current) and Steam 2050 (worst case) were considered. These scenarios consider Rhine riverbed position of 2018 as reference. The baseline projections provide data per district. It was then necessary to aggregate this data to represent the entire IJsselmeer region. This region is supplied by different water bodies, including the IJssel, Twente Canal and Overijsselse Vecht, as well as by regional discharges from Friesland, Flevoland, Overijssel, Noord-Holland (Rijkswaterstaat, 2017). Additionally, natural contributions come primarily from precipitation and the region's current buffer capacity.

Furthermore, the water from the IJsselmeer region is primarily demanded for flushing at the Afsluitdijk to manage salinity, which is set at 40 m^3/s to counteract rising saltwater intrusion through discharge sluices (spuisluizen) due to rising sea levels and decreasing river flow in the summer (Rijkswaterstaat, 2021; Pouwels et al., 2021). Additionally, the water is demanded to maintain water levels, particularly in the IJsselmeer and Markermeer, to account for losses (including lockage and leakage), and to provide water to the regions of Friesland, Flevoland, and Noord-Holland for irrigation, industry, and drinking water production (Rijkswaterstaat, 2021). Natural losses, primarily due to evaporation, were also considered to provide a comprehensive picture of the total water balance of the IJsselmeer region.

3.4 Step by step analysis

The general setup is illustrated in Figure 7, where each step corresponds to a sub-question outlined in section 1.3. The final step (Step 6) addressed the two main research questions together.

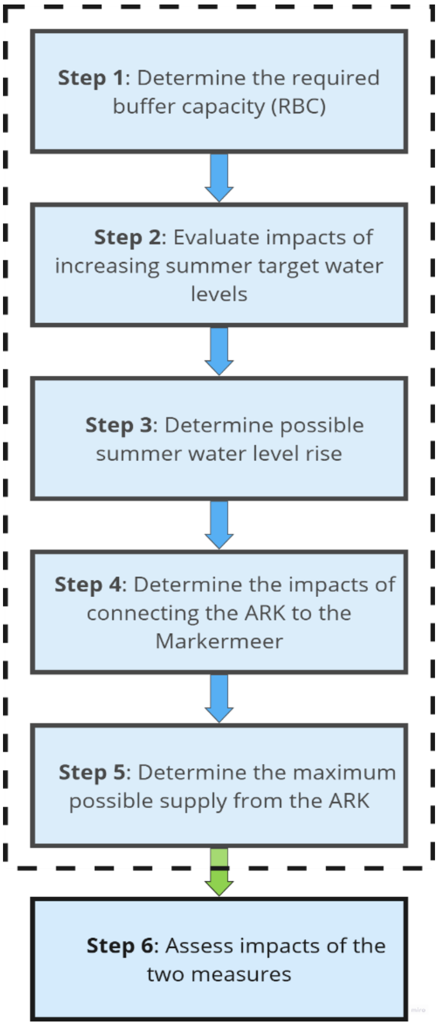

Figure 7 Schematic illustration of the general set up

In the first step, using water balance equation (supply minus demand), the water shortage years were determined. In this thesis, a water shortage year was defined as a year in which demand exceeds supply. The Delta Program's freshwater ambition is to allow no more than one shortage year in every twenty years, equating to a 1:20 frequency. Thus, over a 100-year time series, up to five shortage years are considered acceptable (Delta program freshwater) (Beleidstafel Droogte, 2019). Based on this ambition the required buffer capacities were determined. Using QWAST, the IJssel discharge corresponding to the riverbed position of 1980 was determined based on distribution ratio at the Waal/Pannerdensch Canal and IJssel/Nederrijn of the year 1980. The impact of the two different riverbed positions (2018 and 1980) on the IJssel discharge, and consequently on the required buffer capacities, was analyzed separately. The final result of this step were four different required buffer capacities to achieve five water shortage years per 100-year series, as per the Delta Program Freshwater's target:

- Scenario Ref 2017 with riverbed position 2018;
- Scenario Ref 2017 with riverbed position 1980;
- Scenario Steam 2050 with riverbed position 2018;
- Scenario Steam 2050 with riverbed position 1980.

In the second step, the possibility of increasing the summer target water level was examined to enhance the current buffer, and the impacts of raising the summer target water level on the two main functions, safety and nature, were analyzed. This thesis focused on the duration of the target summer water level, which spans from mid-April to mid-August. The lower limit of -0.30 m NAP remained unchanged, and the winter water level is kept constant to ensure safety. Moreover, raising the summer target water level was limited by the current dike profiles, as the Delta Program has determined that no changes to these profiles will be made before 2050 (Delta Program, 2023). This limits how much the summer target water level can be raised, particularly in the Markermeer, where the critical water levels used for designing the dikes are lower compared to the IJsselmeer (Figure D2). Raising the water level beyond certain limits would increase the risk of flooding, particularly from overtopping, and the risk of piping (Rijkswaterstaat, 2020). Because increasing water levels in March raises the risk of flooding and doing so after March significantly harms nature, this thesis was limited to the following options for raising the summer target water level:

- Increasing the summer water level in the IJsselmeer and Markermeer to +0.10 m NAP, starting in March;

- Increasing the summer water level in the IJsselmeer and Markermeer to +0.10 m NAP, starting in April;
- Increasing the summer water level in the IJsselmeer and Markermeer to -0.05 m NAP, starting in March;
- Increasing the summer water level in the IJsselmeer to -0.05 m NAP, starting in April;
- Increasing the summer water level in the IJsselmeer to -0.05 m NAP, starting in March.

In the third step, the impacts of increasing the summer target water level to -0.05 m NAP or +0.10 m NAP on the buffer capacities, as determined in Step 1, were evaluated. However, the timing of the increase, whether in April or March, did not affect the required buffer capacity and was therefore not considered in this step.

In the fourth step, to ensure the safety and navigation functions of the ARK when connecting it to the IJsselmeer region, the threshold values outlined in Table 1 must not be exceeded. Additionally, the water demand of the ARK must be fully met before any additional water is directed to the Markermeer, ensuring the water supply function of the ARK. It is valuable to mention that the needed placement of the pumping station impacts water quality and flow rate at that location, with potential for increased salinity and higher flow speeds (Odink, 2024). However, the location of the pumping station is outside the scope of this thesis.

To assess the ARK's supply capacity, two drought scenarios, "Very dry" and "Dry," were considered in Flipsen's report (2024) based on the riverbed position of the year 2018. These scenarios are based on the Lobith discharge levels: 800 m^3/s for the "Very dry" scenario and 1200 m^3/s for the "Dry" scenario (Flipsen,2024). This was translated into the Delta scenario Steam 2050 with the 2018 riverbed position (considered the worst-case in this thesis) by comparing the average Lobith discharge during the defined water shortage years of Steam 2050 with the two drought scenarios used by Flipsen (2024).

In the fifth step, the maximum possible supply from the ARK to the IJsselmeer region through the Markermeer was determined based on the thresholds outlined in Table 1 and the specified drought scenarios (dry/very dry). The impact of this measure on mitigating water shortages in the IJsselmeer region was evaluated. This evaluation was conducted in conjunction with the current buffer capacity in the IJsselmeer region under the two scenarios for both riverbed positions, as determined in Step 1, and in combination with increasing the summer target water level in the IJsselmeer region.

For the sixth step, the benefits and drawbacks of the two measures and the combination of implementing the two measures were assed comprehensively using a modified version of the KZH comparison framework (The original version, Appendix H). This framework aims to:

1. Gain an overview of the goal achievement and side effects (both positive and negative) of the measures;
2. Have criteria by which the measures can be filtered;
3. Serve as a checklist in the development of the measures.

The framework organizes and filters the available options of measures for policymakers, enabling them to make informed choices. This framework can thus be utilized at different stages of projects, applicable with both detailed (1) and limited information (2 and 3). In this thesis, the first aim was implemented, since it was employed at the final stage of this study.

The modification of the original tool included adding a safety criterion (included as Criterion 2) due to its relevance to this thesis. Criterion 3 was limited to only the impact on functions without considering Dutch welfare, as this is beyond the scope of this thesis. Additionally, the criteria Sustainability, Integration, and Feasibility were removed, as assessing these would require a broader context beyond this thesis's scope.

The goal of implementing the two measures was to mitigate water shortages in the IJsselmeer region, to align with the Delta Program's ambition. Furthermore, the definitions of the criteria for assessing the impact of the measures on the functions of the IJsselmeer region and/or the ARK, as well as costs and flexibility, are outlined in Table 2.

Table 2 Modified version of KZH comparison framework, assessment criteria of the measures (HASKONINGDHV, 2024)

Criterion	Definition
1. Goal achievement freshwater availability	Mitigating water shortages in the IJsselmeer region aims to meet the Delta Program's freshwater goal of limiting water shortage frequency to five occurrences per 100 years
2. Safety	Effect of the measure on the flood prevention
3. Effects on freshwater use functions	Effects on nature (including water quality),navigation and other functions like recreation, urban area and agriculture
4. Costs	Investment costs + costs for management and maintenance (possibly mitigation costs can be included).
5. Flexibility	A measure is flexible if it can easily be accelerated/delayed and/or scaled up/down as new insights justify it. Flexible variants reduce the chance of regret (better safe than sorry) because implementation can be postponed until there is more clarity about future developments. Moreover, flexible measure with short lead times score high on this criterion.

The evaluation of the measures against the criteria shown in Table 2 was conducted using a Likert scale, as detailed in Table 3 below:

Table 3 Evaluation criteria scores (HASKONINGDHV, 2024)

++	= Expected strong positive effect
+	= Expected positive effect
0	= Neutral (no effect)
-	= Expected negative effect
--	= Expected strong negative effect
+-	= Both negative and positive effect
?	= No rating possible and/not applicable/or unknown

The final result of this step was the identification of the most desirable measure or combinations of measures. Based on the criteria outlined in Table 2, two scenarios, Ref 2017 and Steam 2050, were considered. A distinction was made between implementing the 2018 riverbed position and the 1980 riverbed position. This distinction was necessary because IRM manages the implementation of the 1980 riverbed position.

4. Results

This chapter presents the research results. In 4.1, the years of water shortage were first calculated using the current buffer capacity. Subsequently, the required buffer capacities for two Delta Scenarios, Ref 2017 and Steam 2050, were determined, each analyzed in combination with the Rhine riverbed positions from 2018 and 1980, corresponding to step 1 in the methods. In 4.2, corresponding to steps 2 and 3 of the methods, the impacts of increasing the summer target water level on the buffer capacity of the IJsselmeer region were examined. In 4.3, the impact of the maximum additional water supply from the ARK on the current buffer capacity of the IJsselmeer region was tested in combination with the increased summer target water level identified in 4.2, corresponding to steps 4 and 5 of the methods. Finally, 4.4 corresponds to step 6 of the methods, outlining the impacts of the two examined measures across various criteria detailed in Table 2. The best measures were then identified based on the two riverbed positions, 2018 and 1980.

4.1 Required buffer capacity IJsselmeer region

To determine the required buffer capacity, the current buffer capacity was first tested. The results showed that the current buffer capacity was sufficient for the Ref 2017 scenario with the 2018 riverbed position, resulting in 5 shortage years over a 100-year period. The average water level decrease was 0.26 m (as indicated by the number above the bar), meaning that the water level in the IJsselmeer region would drop to –0.36 m NAP on average (compared the upper limit in the IJsselmeer region of -0.10 m NAP). This reflects the severity of water shortage years, as a decrease of 0.2 m results in a water level of -0.30 m NAP, which is the threshold for applying Water Use Reduction (WUS) to economic water users according to the prioritization sequence. A decrease of 0.3 m results in a water level of -0.40 m NAP, where a total Water Extraction Ban (WEB) applies.

When the decrease results in water use restrictions, it is indicated in orange with the abbreviation WUS above the bar, and when it triggers a total ban, it is shown in red with the abbreviation WEB. This notation applies to all figures in this chapter.

For the Ref 2017 scenario with the 1980 riverbed position, only 2 water shortage years occurred, with an average water level decrease of 0.11 m, resulting in a water level of –0.21 m NAP in the IJsselmeer region. In the Steam 2050 scenario with the 2018 riverbed position, 11 water shortage years were observed. The average water level decrease was 0.35 m, bringing the IJsselmeer water level to –0.45 m NAP. For the Steam 2050 scenario with the 1980 riverbed position, 7 water shortage years occurred, with an average water level decrease of 0.15 m, resulting in a water level of –0.25 m NAP in the IJsselmeer region. This analysis considered the summer half-year from April to October, as all shortages were observed during this period (Figure 8).

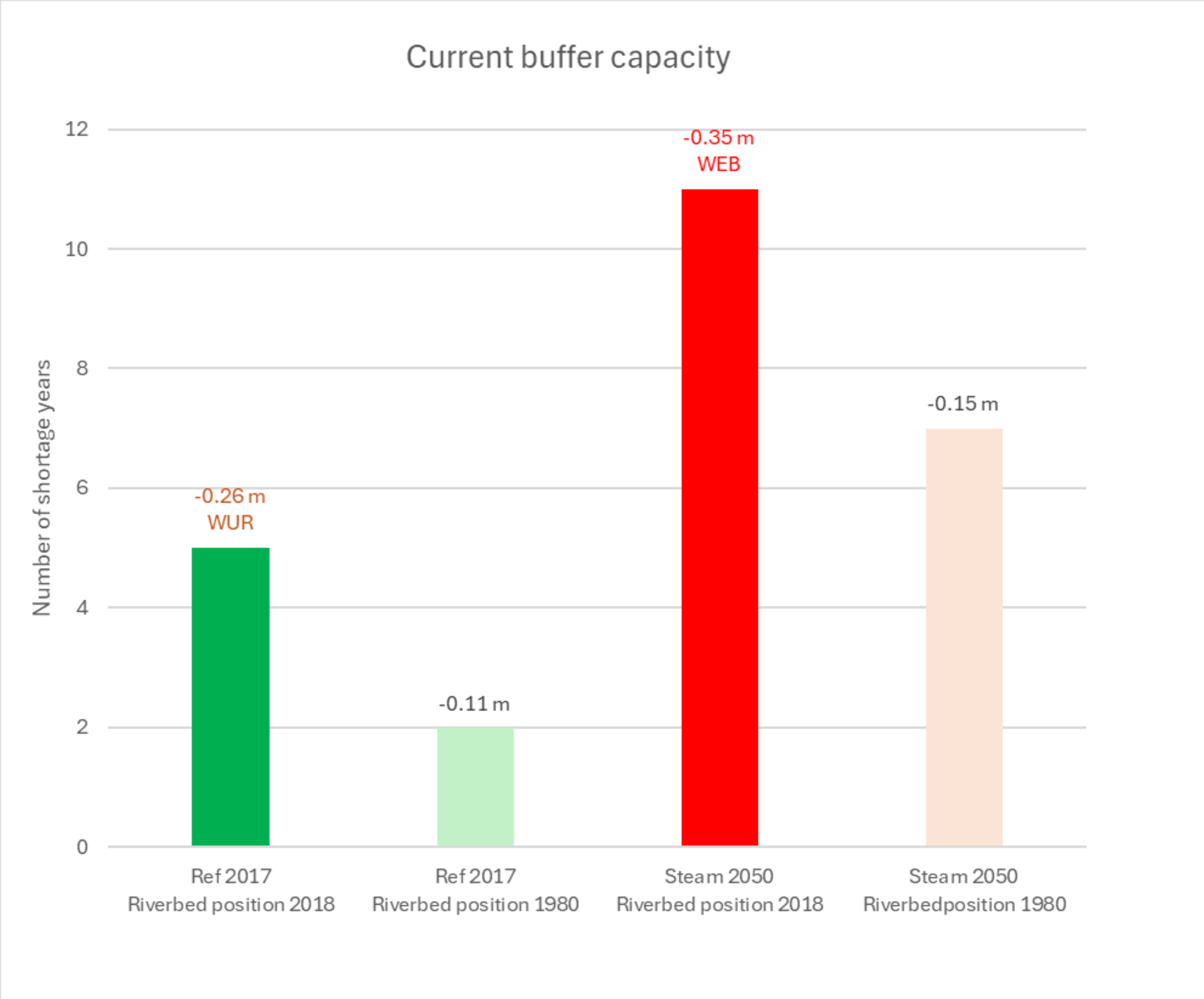

Figure 8 Current Buffer Capacity: The y-axis shows the number of water shortage years per 100 years, while the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

The decrease in both the frequency and severity of water shortages in both scenarios when using the 1980 riverbed position is attributed to an increased discharge from the IJssel. This increase in IJssel discharge is a direct result of the 1980 riverbed position. As shown in Table 4, the IJssel discharge increased from 345 m^3/s to 381 m^3/s in the Ref 2017 scenario and from 330 m^3/s to 371 m^3/s in the Steam 2050 scenario when comparing the 1980 riverbed position to that of 2018.

Table 4 Average IJssel discharge in m^3/s for scenario Ref 2017 and Steam 2050 with riverbed position 2018 and 1980.

	Ref 2017	Steam 2050
Riverbed position 2018	345	330
Riverbed position 1980	381	371

To achieve the goal of five water shortage years over a 100-year period, the required buffer capacity for each scenario, combined with the two riverbed positions, was calculated and is presented in Figure 9 and Table 5. The current buffer capacity was sufficient for the Ref 2017 scenario with both riverbed positions, requiring a buffer capacity of 0.191 m for the 2018 riverbed position and 0.062 m for the 1980 riverbed position. In contrast, for the Steam 2050 scenario with the 2018 riverbed position, the required buffer capacity was 0.42 m, which is 0.22 m higher than the current buffer capacity. This corresponds to a required supply increase of 440 million m^3. For the Steam 2050 scenario with the 1980 riverbed position, the required buffer capacity was 0.23 m, which is only 0.03 m higher than the current capacity. This corresponds to a required supply increase of 60 million m^3.

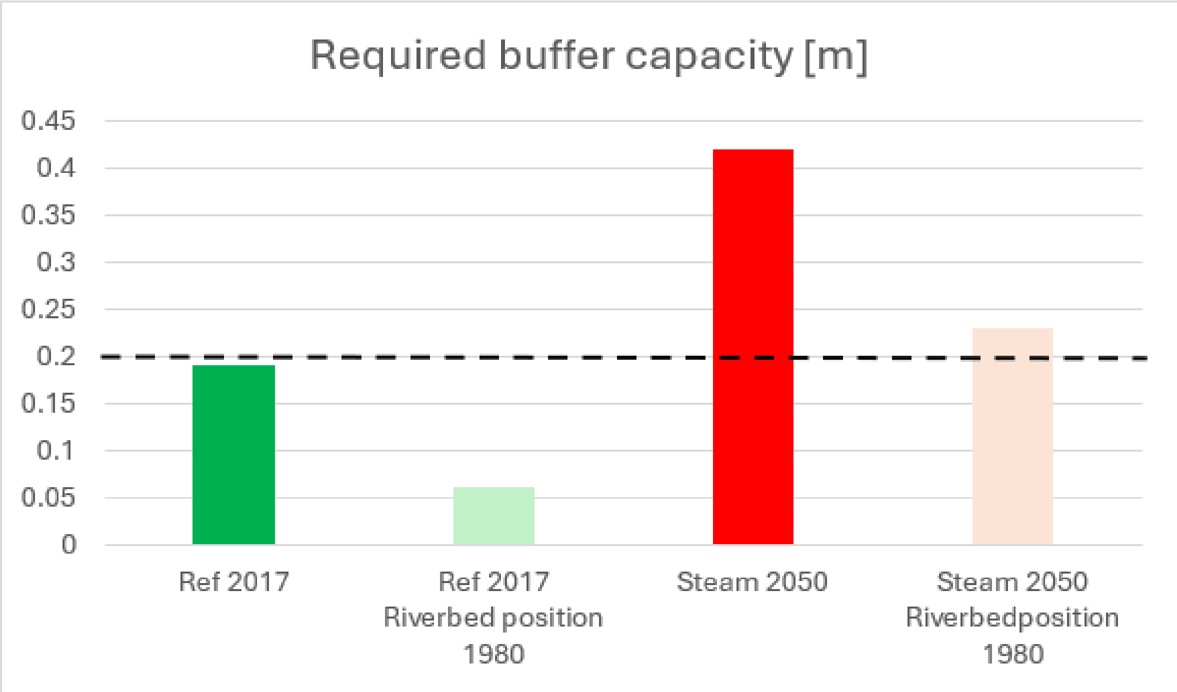

Figure 9 Required buffer capacity in meters (y-axis) for each scenario (Ref 2017 and Steam 2050), shown with two different riverbed positions (2018 and 1980). The dashed line represents the current buffer capacity of 0.2 meters.

Table 5 Required buffer capacity, corresponding required increase summer water level, and required increase in supply. For the Ref 2017 scenario with both riverbed positions, the current buffer capacity is sufficient, as indicated by the required capacities being less than 0.2 meters.

Scenario	Required buffer capacity [m]	Required summer water level in m NAP	Required increase supply in Mm^3
Ref 2017 Riverbed position 2018	0.191	-	-
Ref 2017 Riverbed position 1980	0.062	-	-
Steam 2050 Riverbed position 2018	0.42	+ 0.02	440
Steam 2050 Riverbed position 1980	0.23	-0.17	60

4.2 Impacts of increasing the summer water level on the freshwater supply

This paragraph evaluated the impact of increasing the summer target water level exclusively in the IJsselmeer, as well as in both the IJsselmeer and Markermeer. The options for water level increases to -0.05 m NAP and +0.10 m NAP were explored.

By increasing the summer target water level to -0.05 m NAP in the IJsselmeer, the water shortage goals for the Steam 2050 scenario with the 1980 riverbed position were achieved, reducing the number of water shortage years to 4, compared to 7 years under the current buffer capacity (Figure 8). For the Ref 2017 scenario with the 2018 riverbed position, the frequency of water shortage years decreased to 3, compared to 5 years in the current situation. The water shortage years remained at 2 for the Ref 2017 scenario with the 1980 riverbed position. However, additional measures were still required for the Steam 2050 scenario with the 2018 riverbed position, which resulted in 9 water shortage years (Figure 10).

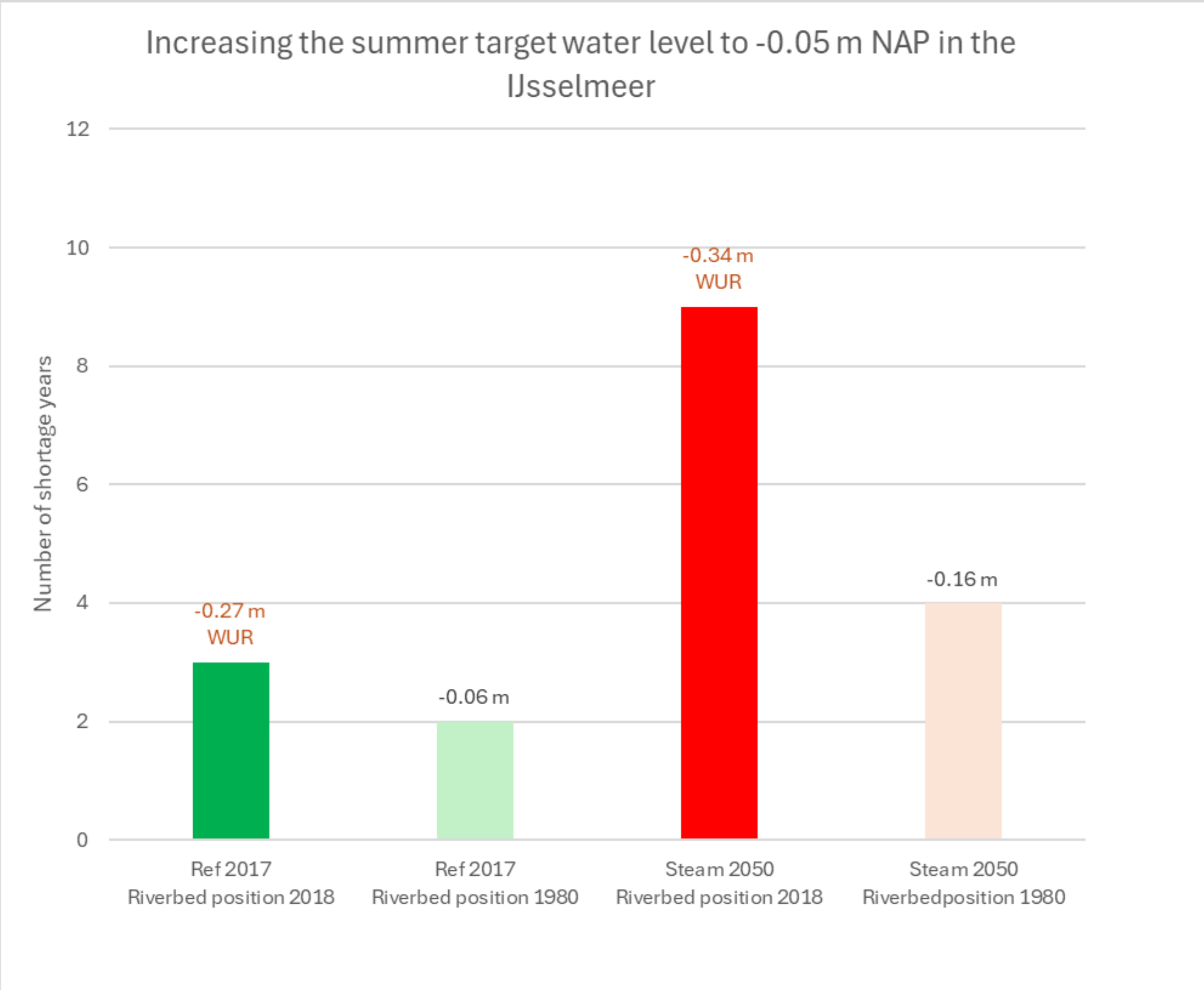

Figure 10 Buffer capacity of 0.25 m in the IJsselmeer and 0.2 in the Markermeer: The y-axis shows the number of water shortage years per 100 years, and the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

Increasing the summer water level to -0.05 m NAP in the IJsselmeer region, including the Markermeer, reduced the number of water shortage years under the Steam 2050 scenario with the 1980 riverbed position by one year, decreasing from 4 to 3 compared to the previous option (Figure 10). Additionally, it slightly reduced the severity of water shortages relative to the previous option. However, the target number of water shortage years for the Steam 2050 scenario with the 2018 riverbed position was still not achieved, remaining at 9 years (Figure 11).

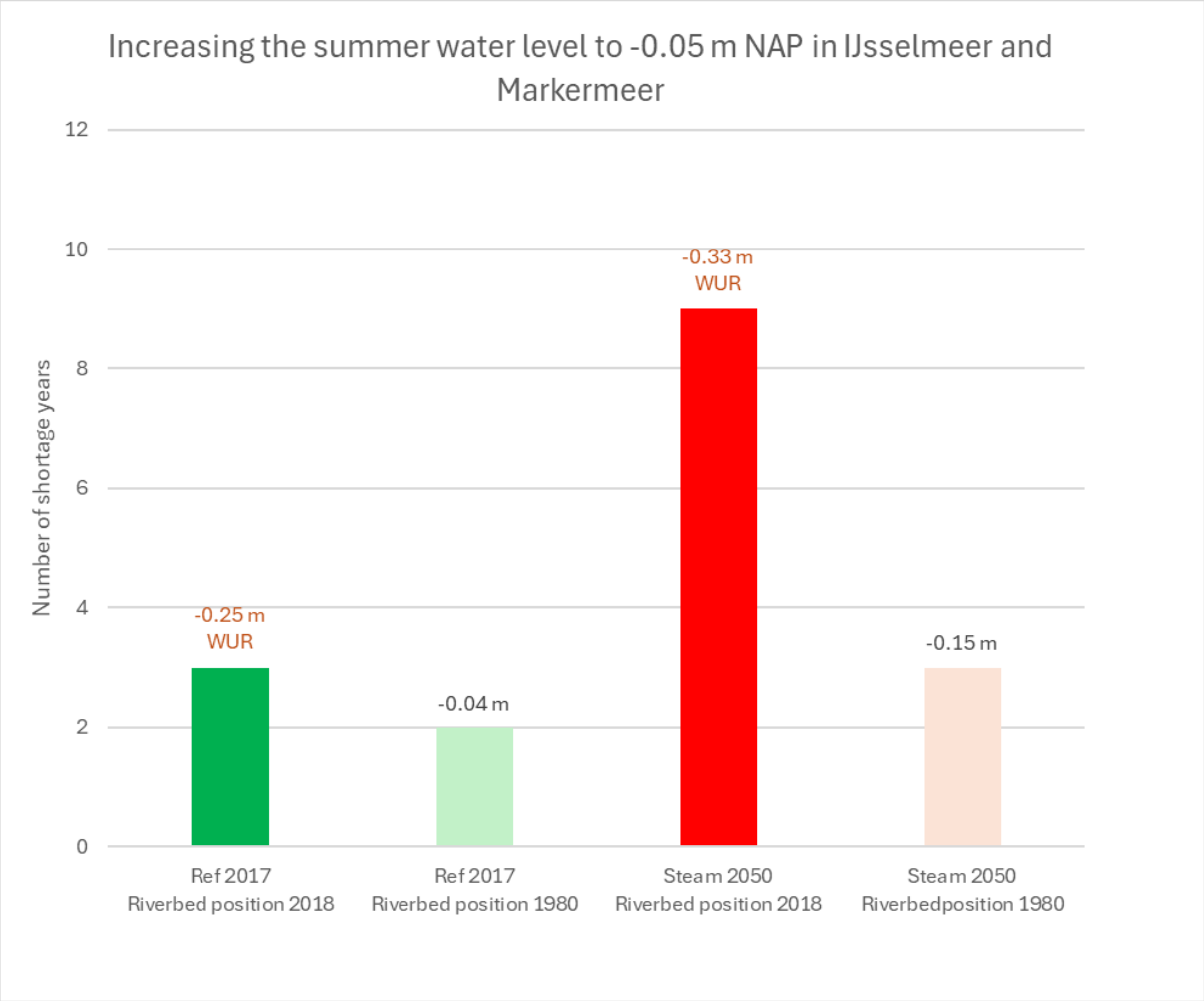

Figure 11 Buffer capacity of 0.25 m in the IJsselmeer and Markermeer: The y-axis shows the number of water shortage years per 100 years, and the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

Increasing the summer water level to +0.10 m NAP in the IJsselmeer region (including the Markermeer), achieved the target for the Steam 2050 scenario with the 2018 riverbed position, reducing the number of water shortage years to 3 (Figure 12), compared to 11 years in the current situation (Figure 8) and 9 years in the previous two options (Figures 10 and 11).

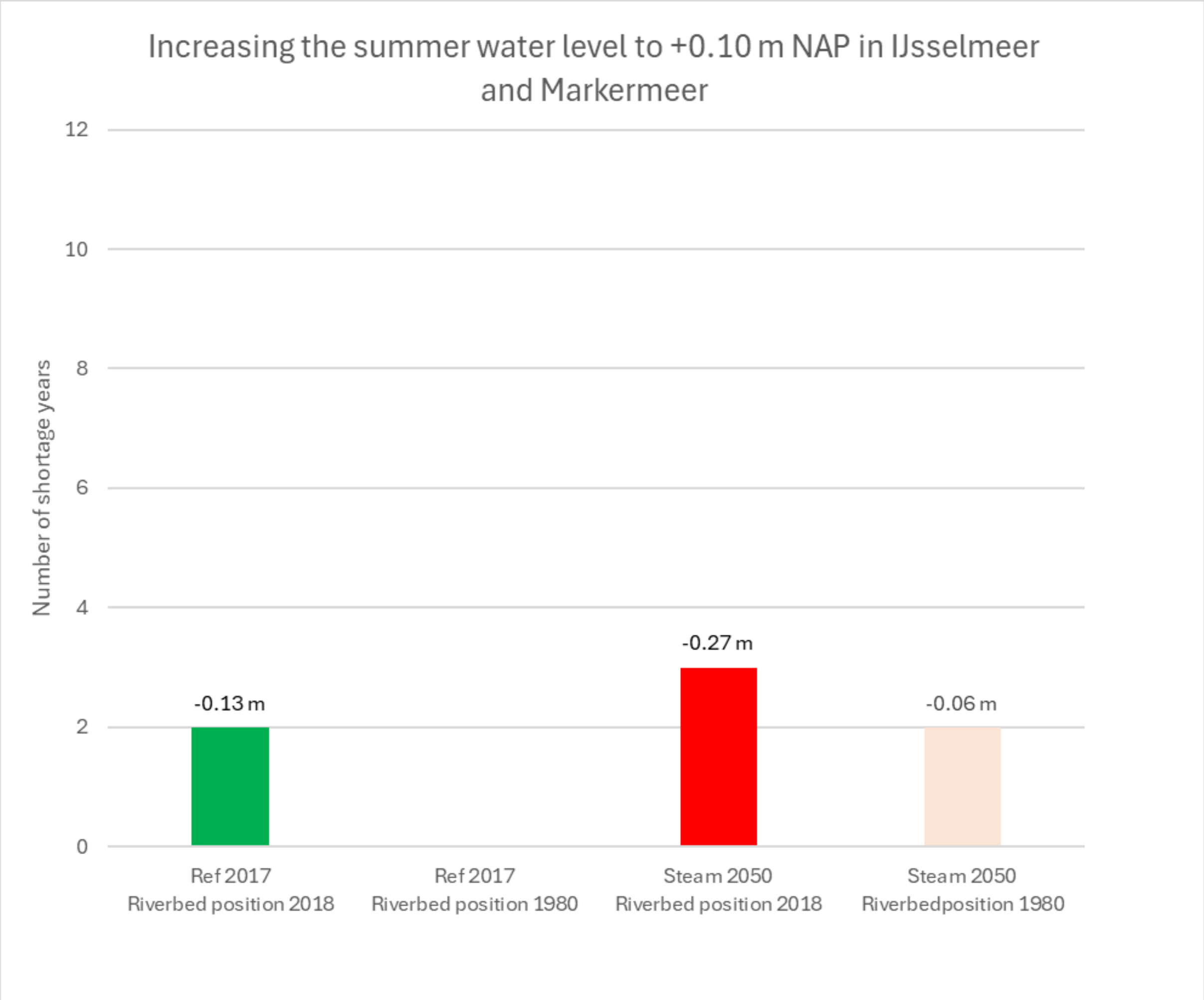

Figure 12 Buffer capacity of 0.5 m in the IJsselmeer and Markermeer: The y-axis shows the number of water shortage years per 100 years, and the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

4.3 Impact of the maximum possible supply from the ARK

The maximum possible supply from the ARK to the IJsselmeer region was determined to be 51 m³/s, based on the "dry" scenario considered in Flipsen's report (2024). This determination was made because the average discharge at Lobith during the water shortage years of the Steam 2050 scenario with the 2018 riverbed position was 1259 m³/s, which is close to the 1200 m³/s discharge level at Lobith of the "dry" scenario in Flipsen's report (2024).

The 51 m³/s supply was achieved by utilizing both locks at the Bernhard complex for water supply and navigation, while at the Irene complex, one lock was designated for navigation and the other for water supply. This configuration is referred to by Flipsen (2024) as “Bernhard2-Irene1-L (Limited)” and is one of six options studied. However, only this configuration met the threshold values specified in Table 1 (Figure I2 and Table I1). The other five configurations are detailed in Appendix I.

Based on the maximum possible supply from the ARK of 51 m³/s, the impact on the buffer capacity of the IJsselmeer region, combined with the increased summer target water level identified in section 4.2, was evaluated.

Supplying 51 m³/s from the ARK to the IJsselmeer region, while considering the current buffer capacity, demonstrated a reduction in both the frequency and severity of water shortage years across both scenarios and riverbed positions (Figure 13) compared to the current buffer capacity (Figure 8). For the Ref 2017 scenario with the 2018 riverbed position, the number of water shortage years decreased to 2, compared to 5 years in the current situation. With the 1980 riverbed position, there were no water shortage years, compared to 2 years with the current buffer capacity. For the Steam 2050 scenario with the 1980 riverbed position, the number of water shortage years decreased from 7 in the current buffer capacity to just 2. However, in the Steam 2050 scenario with the 2018 riverbed position, the goal of limiting water shortage years to five was still not met, with eight shortage years remaining, which is three fewer than in the current buffer capacity.

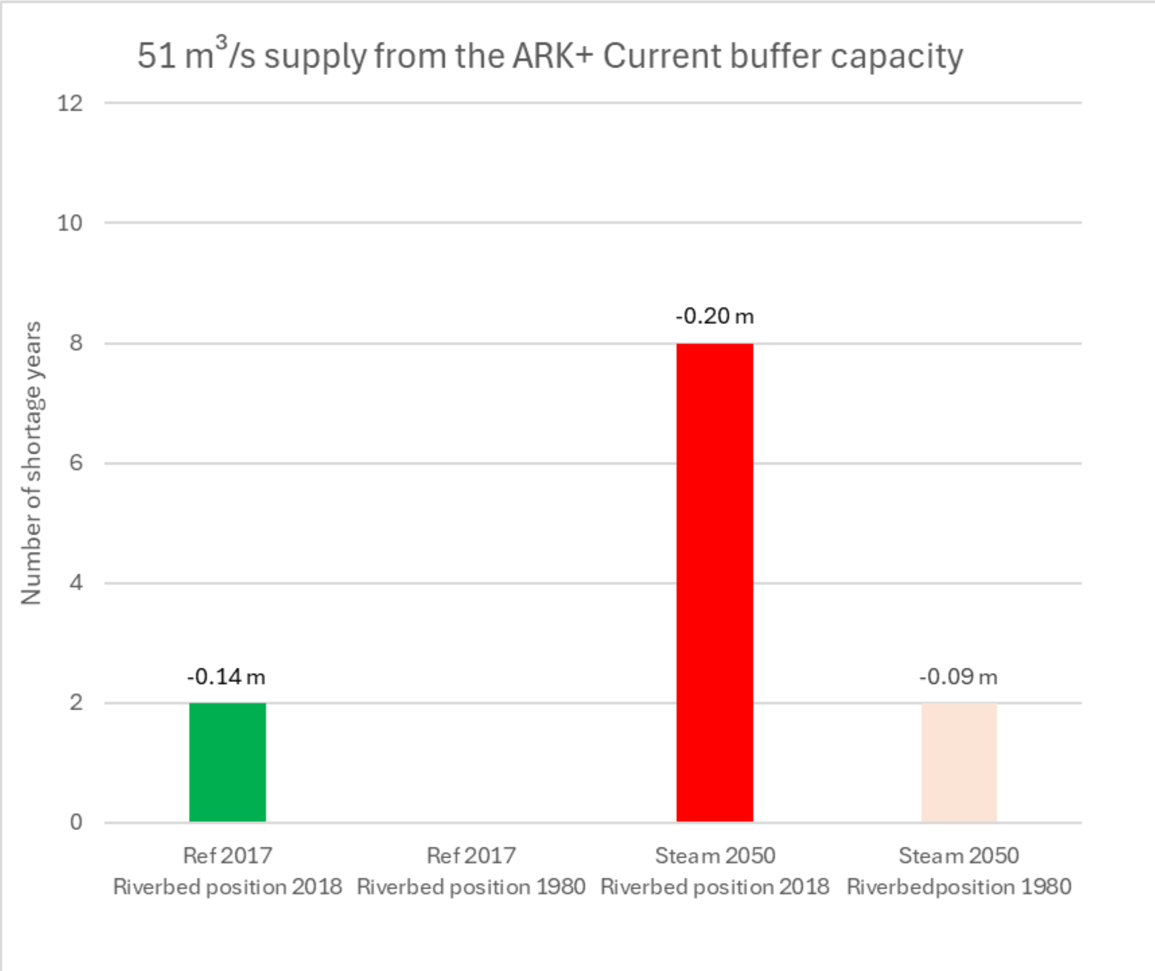

Figure 13 ARK supply of 51 m³/s in combination with the current buffer capacity of 0.2 m in the IJsselmeer region: The y-axis shows the number of water shortage years per 100 years, and the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

Supplying 51 m³/s from the ARK to the IJsselmeer region, combined with increasing the summer water level to -0.05 m NAP in the IJsselmeer, demonstrated a reduction in both the frequency and severity of water shortage years across both scenarios and riverbed positions compared to the current situation (Figure 8) and the previous option (Figure 13). In this case, all scenarios with the different riverbed positions achieved the target for the number of water shortage years. Notably, the Steam 2050 scenario with the 2018 riverbed position met the target with exactly 5 water shortage years (Figure 14), compared to 8 years in the previous option and 11 years under the current buffer capacity.

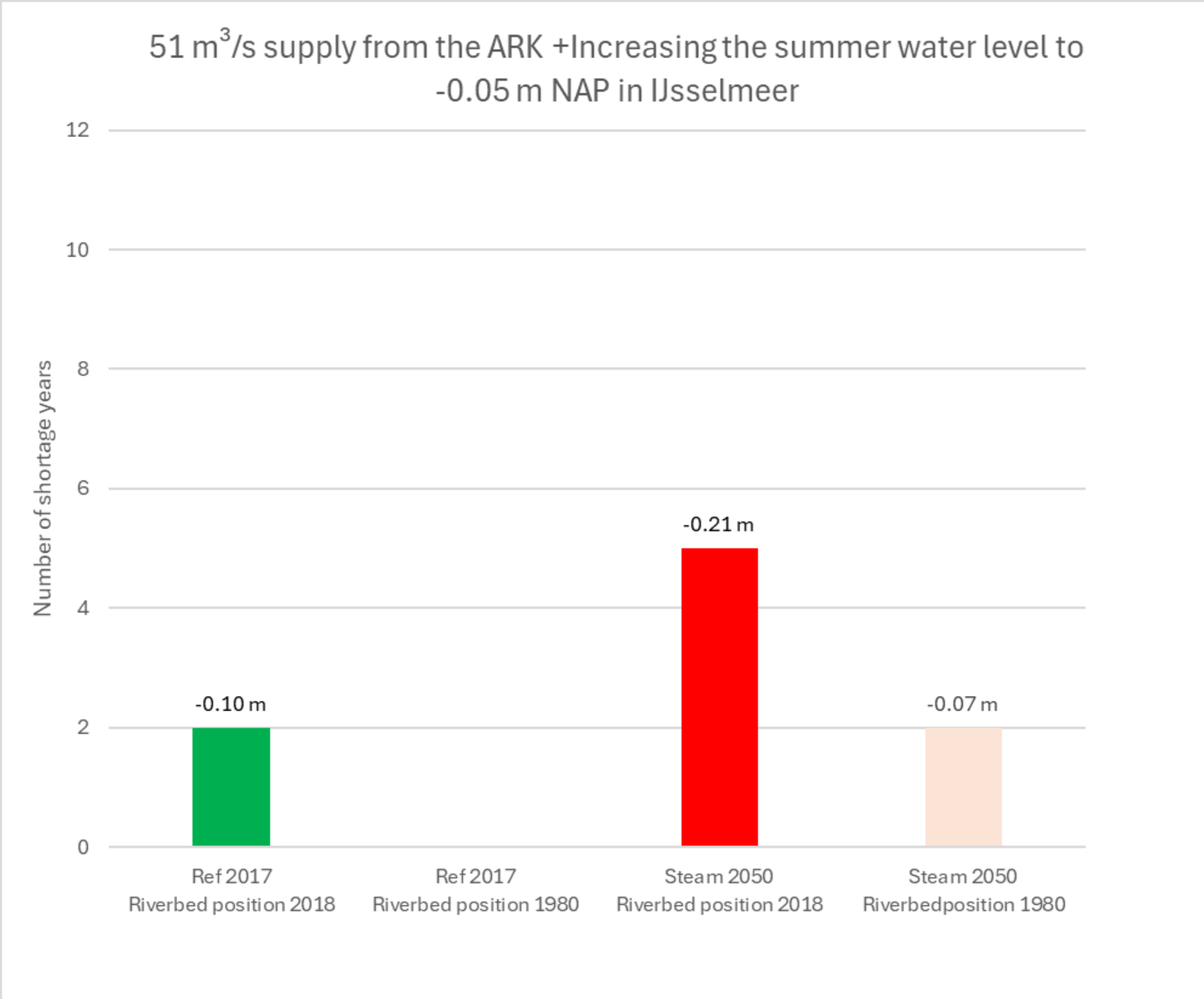

Figure 14 ARK supply of 51 m³/s in combination with the increasing the summer water level in the IJsselmeer to -0.05 m NAP: The y-axis shows the number of water shortage years per 100 years, and the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

Supplying 51 m³/s from the ARK to the IJsselmeer region, combined with increasing the summer water level to -0.05 m NAP in the IJsselmeer region (including the Markermeer), as expected, ensured that all scenarios achieved the target. This approach further reduced both the frequency and severity of water shortages compared to the previous option (Figure 15).

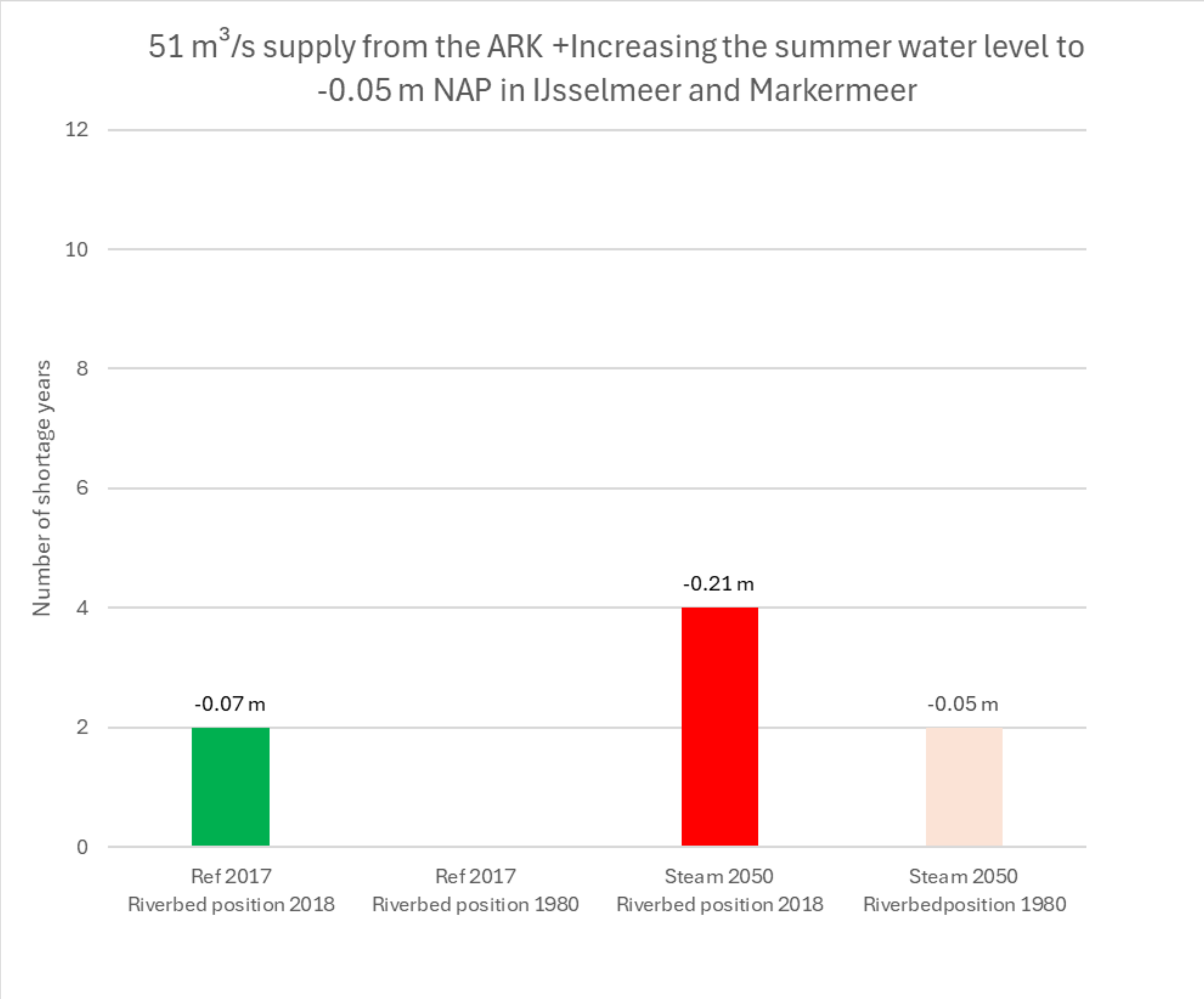

Figure 15 ARK supply of 51 m³/s in combination with the increasing the summer water level in the IJsselmeer and Markermeer to -0.10 m NAP: The y-axis shows the number of water shortage years per 100 years, and the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

In Appendix J Figures J1 till J4 , the exact required supply capacity of the ARK was determined for Steam 2050 in combination with the 1980 and 2018 riverbed positions for the current buffer capacity. Additionally, the exact required supply for Steam 2050 was determined when the water level in the IJsselmeer and in both the IJsselmeer and Markermeer is increased to -0.05 m NAP.

4.4 KZH comparison framework

Table 6 shows the impacts of the measures in combination with the 2018 riverbed position (A). Measure A7, involving a supply capacity of 51 m^3/s from the ARK to the Markermeer and an increase in the summer water level to -0.05 m NAP in the IJsselmeer starting in March, was considered the most desirable option. This measure achieved the project goals of mitigating water shortages and ensures the safety function while avoiding significant harm to nature. The impacts on other functions were minor and deemed irrelevant.

Table 7 shows the impacts of the measures in combination with the 1980 riverbed position (B). Among these, measure B1, which involves increasing the summer water level in the IJsselmeer to -0.05 m NAP starting in March, was identified as the most desirable. This measure achieved the project goals, ensures the safety function, and guarantees the protection of other functions while avoiding significant harm to nature.

Primary effects were summarized in the tables, while Appendix K provides additional details about the scores.

Table 6 Modified version of KZH comparison framework assessing the studied measures with riverbed position 2018.

Measure in combination with riverbed position 2018	Goal	Safety	Nature, navigation and other functions	Costs	Flexibility	Primary effects
A.1 Increasing summer water level in the IJsselmeer to -0.05 m NAP begin March	+	0	+-	?	+	Additional measures were still required for Steam 2050 to meet the target. This measure prevents nests from being flooded but reinforces unnatural water level dynamics.
A.2 Increasing summer water level in the IJsselmeer to -0.05 m NAP begin April	+	+	--	?	+	No added value for goal achievement compare to A.1, but safer due to fewer storms in April; bird nests will be flooded.
A.3 Increasing summer water level in the IJsselmeer and Markermeer to -0.05 m NAP begin March	+	-	+-	?	+	Slight reduction in severity of water shortage years; recreational sites around Markermeer will be flooded.
A.4 Increasing summer water level in the IJsselmeer and Markermeer to -0.05 m NAP begin April	+	-	--	?	+	No added value for goal achievement compared to A.3; more bird nests and recreational sites around Markermeer will be flooded.
A.5 Increasing summer water level in the IJsselmeer and Markermeer to +0.10 m NAP begin March/April	++	--	--	?	+	Goal achieved; significant risks to nearly all functions in the IJsselmeer region.
A.6 Supply capacity of 51 m^3/s from the ARK to the Markermeer with the current buffer capacity	+	0	0	-	+-	Additional measures needed for Steam 2050 to meet the target; investment required for the pumping station. Station is inflexible, but operation remains flexible.
A.7 Supply capacity of 51 m^3/s from the ARK to the Markermeer with increasing the summer water level to -0.05 m NAP in the IJsselmeer being March	++	0	+-	-	+-	Goal achieved; similar impacts on safety, nature and other functions as A.1. Costs and flexibility remain consistent with those in Measure A.6.
A.8 Supply capacity of 51 m^3/s from the ARK to the Markermeer with Increasing the summer water level to -0.05 m NAP in the IJsselmeer and Markermeer being March	++	-	+-	-	+-	Goal achieved with one fewer water shortage year than A.7; recreational areas around Markermeer will flood. Impacts on nature and other functions are similar to A.1. Costs and flexibility remain the same as A.6 and A.7.

Table 7 Modified version of KZH comparison framework assessing the studied measures with riverbed position 1980.

Measure in combination with riverbed position 1980	Goal	Safety	Nature, navigation and other functions	Costs	Flexibility	Primary effects
B.1 Increasing summer water level in the IJsselmeer to -0.05 m NAP begin March	++	0	+-	?	+	Goal achieved with 4 shortage years for Steam 2050; other scores similar to A.1
B.2 Increasing summer water level in the IJsselmeer to -0.05 m NAP begin April	++	+	--	?	+	Goal achievement similar to B.1; other scores similar to A.2
B.3 Increasing summer water level in the IJsselmeer and Markermeer to -0.05 m NAP begin March	++	-	+-	?	+	Goal achieved with 3 water shortage years for Steam 2050 and further reduction in severity; other scores similar to A.3.
B.4 Increasing summer water level in the IJsselmeer and Markermeer to -0.05 m NAP begin April	++	-	--	?	+	Goal achievement similar to B.3; other scores similar to A.4.
B.5 Increasing summer water level in the IJsselmeer and Markermeer to +0.10 m NAP being March/April	++	--	--	?	+	Goal achieved; with no water shortage years in Ref 2017 and just two with negligible severity for Steam 2050; other scores similar to A.5.
B.6 Supply capacity of 51 m^3/s from the ARK to the Markermeer with the current buffer capacity	++	0	0	-	+-	Goal achieved; with no water shortage years in Ref 2017 and just two with negligible severity for Steam 2050; other scores similar to A.6.
B.7 Supply capacity of 51 m^3/s from the ARK to the Markermeer with increasing the summer water level to -0.05 m NAP in the IJsselmeer being March	++	0	+-	-	+-	Negligible effect on the goal compare to B.6 achievement; other scores similar to A.7.
B.8 Supply capacity of 51 m^3/s from the ARK to the Markermeer with Increasing the summer water level to -0.05 m NAP in the IJsselmeer and Markermeer being March	++	-	+-	-	+-	Negligible effect on the goal compare to B.6 and B.7 achievement; other scores similar to A.8.

5. Discussion

In this section the results for each sub-question(s) were discussed, as well as the reliability of the results. The reliability was determined by assessing the uncertainties and limitations with regard to the used methods, data and assumptions.

Research question 1.1: What is the required buffer capacity in the IJsselmeer region to mitigate water shortages under the Delta Scenarios (Ref 2017 and Steam 2050), considering each scenario in combination with both the 2018 (current) and 1980 riverbed positions?

The current buffer capacity of 0.2 m, equivalent to 400 Mm^3, was sufficient for the Ref 2017 scenario, in combination with both riverbed positions, to achieve the target water shortage frequency of 1 in 20 years. This corresponds to five or fewer water shortage years in the 100-year calculation, aligning with the objective of the Delta Program Freshwater. However, for Steam 2050, additional measures were required to meet this target. When combined with the 2018 riverbed position, 11 water shortage years were observed, whereas 7 were recorded with the 1980 riverbed position. To achieve the target frequency, buffer capacities of 0.42 m and 0.23 m were required for the 2018 and 1980 riverbed positions, respectively. These results did not align with the findings of a previous study conducted by Hydrologic (Hydrologic, 2024), which reported 15 water shortage years for Steam 2050 with the 2018 riverbed position.

The discrepancy was attributed to differences in the surface area of the IJsselmeer region used in the calculations. This thesis employed a surface area of 2,000 km^2, while Hydrologic used 1,700 km^2. The difference likely stems from this thesis treating the Veluwerandmeren as part of the IJsselmeer, whereas Hydrologic considered it a separate water body. Despite this, the surface area of the IJsselmeer region used in this thesis and the corresponding buffer capacity of 400 Mm^3 align with the literature (van Ginkel et al., 2022). If the Veluwerandmeren's surface area were excluded, the buffer capacity decreases to 360 Mm^3. Furthermore, the results of this thesis align with those of the freshwater test conducted for the IJsselmeer (excluding the Markermeer) (Kort et al, 2020) (Appendix C).

When the 1,700 km^2 surface area was tested, similar results to Hydrologic study were obtained. It is important to note, that the definition of a "water shortage year" in this thesis differed from that used in the Hydrologic study. In this thesis, a water shortage year is defined as a year in which demand exceeds supply at one or more time steps. In contrast, the Hydrologic study defined a water shortage year as one where demand exceeds supply by more than 3%, following the Delta Program Freshwater's definition. Applying this threshold had a minor impact on the classification of water shortage years. Additionally, while there is no universally defined method for calculating the severity of water shortage years, this thesis aligns with Hydrologic in its approach to assessing severity.

Moreover, both this thesis and Hydrologic study adopted an updated approach to increasing flushing rate at the Afsluitdijk to 40 m^3/s, compared to the previously used 10 m^3/s. This update was recommended by the Sea Level Rise Knowledge Program (Het Kennisprogramma Zeespiegelstijging) (van Ginkel et al., 2022).

The water supply and demand data used in this thesis were based on baseline projections from the Ref 2017 and Steam 2050 Delta scenarios, assuming the Rhine riverbed position as of 2018. However, in reality, the current riverbed position differs. The IJssel's water supply is lower due to ongoing erosion in the Waal, which diverts more water to the Waal at the expense of the IJssel. This redistribution of water contributes to an increased frequency of water shortage years. If this erosion trend persists, the IJssel's discharge is projected to decrease significantly by 2050, potentially exacerbating water shortages in the IJsselmeer region unless appropriate mitigation measures are implemented.

The implications of adopting the 1980 riverbed position were not analyzed in this thesis. Achieving this riverbed position would require extensive sediment transport to raise the Rhine branches, potentially leading to lower water levels in the Waal. This could reduce water availability for the western Netherlands and affect navigation on the Waal. While studies have explored the effects of adopting the 2000 riverbed position (Asselman et al., 2022), no research has investigated the implications of the 1980 position yet. The IRM is currently exploring alternatives to achieve the 1980 water distribution through infrastructure adjustments rather than riverbed modifications, which are costly and require continuous maintenance.

Additionally, the National Climate Agreement (2019) commits to reducing greenhouse gas emissions from peat meadow oxidation by 1 megaton CO_2 equivalent by 2030. Achieving this goal requires keeping peat meadow areas wet, necessitating 200 Mm³ of water under the Ref 2017 scenario and potentially increasing to 400 Mm³ by 2050 under the Steam 2050 scenario. This additional water demand, equivalent to a buffer increase of 10–20 cm in the IJsselmeer, was not included in this thesis. Incorporating this demand will increase the number of water shortage years significantly.

Finally, regarding the current water level regulation, the buffer capacity of 0.2 m is defined as the difference between the upper limit of -0.10 m NAP and the lower limit of -0.30 m NAP, with the summer target water level set at -0.20 m NAP (Rijkswaterstaat, 2018). However, achieving the upper limit of -0.10 m NAP to prepare for droughts is not feasible due to the models' limited forecast horizon. Instead, the achievable level is -0.15 m NAP, effectively reducing the buffer capacity by 25% compared to initial calculations. This reduction suggests that water shortage years may occur more frequently than previously estimated (van Ginkel et al., 2022).

Research question 1.2: What are the impacts of increasing the summer target water level on safety, nature, and other functions of the IJsselmeer region?

To enhance the current buffer capacity and, consequently, the water supply function, increasing the summer target water level in the IJsselmeer region was evaluated. The impacts of this adjustment on safety, nature and other functions of the IJsselmeer region are closely tied to the timing and magnitude of the increase. The nature function of the IJsselmeer region depends on water levels that mimic natural conditions (Rijkswaterstaat, 2018), making an increase in the summer water level undesirable for this function. However, water levels in the IJsselmeer region have been regulated for decades, with higher levels maintained in the summer and lower levels in the winter. This long-term regulation may have caused the local ecosystem to adapt to these conditions, though there is no comparable reference elsewhere in the world to conclusively substantiate such adaptation.

From the nature function perspective, increasing the summer target water level starting in March ensures that birds do not nest in low-lying areas, which might otherwise be flooded if the increase occurs later in the season (Sweco, 2017). Conversely, from the safety perspective, it is preferable to delay raising the summer target water level until the risk of storms has passed. Increasing the water level after April is considered acceptable to reduce the risk of storm-related impacts (Rijkswaterstaat, 2018).

Furthermore, increasing the summer target water level beyond the critical water levels for which the dikes in the IJsselmeer region were designed could result in flooding, compromising the safety function. Comparatively, the safety and nature functions impose greater constraints on increasing the summer target water level than other functions. Ensuring safety and minimizing negative impacts on nature significantly limits the potential for raising the summer target water level to a degree that have negligible effects on other functions.

Research question 1.3: What is the maximum possible rise in summer target water level in the IJsselmeer, considering safety, nature and the other functions?

To address the conflict between the safety and nature functions, it was determined that the summer target water level increase should begin in March, but only if no storms are forecasted during this period, aligning with current water level regulations (Rijkswaterstaat, 2018). Additionally, maintaining the current dike profiles has limited the ability to increase the summer target water level in the Markermeer. This limitation arises because the critical water levels used in the design of the Markermeer dikes are lower than those in the IJsselmeer. In contrast, a slight increase in the summer target water level to -0.05 m NAP, compared to the current upper limit of -0.10 m NAP, is feasible in the IJsselmeer (van Ginkel et al., 2022). However, this increase enhances the buffer capacity by only 0.05 m. To overcome this limitation, reinforcing the dikes could provide greater flexibility in managing water levels, enabling more effective measures to enhance buffer capacity while maintaining safety and minimizing ecological impacts, but doing this is very costly.

Given the limited potential for increasing the summer water level, another method to enhance buffer capacity involves allowing water levels to drop below the current emergency lower limit of -0.40 m NAP. A key advantage of lowering water levels, compared to raising them, is that storm predictions in existing models are not always reliable. Lowering water levels decreases the flood risk associated with higher water levels and benefits nature, as lower summer water levels are considered ecologically advantageous.

However, a potential drawback of lowering water levels is the impact on dike stability. Current practice enforces a complete water extraction ban when levels fall below -0.40 m NAP to preserve dike stability. Despite this, ongoing discussions among experts suggest that the dikes surrounding the IJsselmeer region, primarily constructed from clay rather than peat, may be less vulnerable to air exposure and less prone to oxidation. This distinction could allow for a reassessment of the current water extraction policy (Luijn,2024).

Although accepting lower water levels was not analyzed in this thesis due to time constraints, it represents a promising area for future research. Further exploration of this approach could provide valuable insights into enhancing buffer capacity while addressing safety and ecological considerations.

Research question 2.1: What are the impacts of connecting the Amsterdam-Rhine Canal to the IJsselmeer region on water quality in both the canal and the IJsselmeer region, and on navigation and safety in the canal?

Due to the limitations of increasing the summer target water level to mitigate water shortages in the IJsselmeer region, additional measures were required. Connecting the Amsterdam-Rhine Canal (ARK) to the IJsselmeer region via the Markermeer provided significant benefits for the water supply function in the IJsselmeer region. This connection had no major impacts on water quality in either the ARK or the IJsselmeer region, as both systems consist of Rhine water (schuring,2024). However, the required pumping station to connect the ARK to the IJsselmeer region would increase salinity at that location within the ARK, which is detrimental to drinking water production (Odink, 2024).

Considering the navigation and safety functions of the ARK, the volume of water that could be supplied to the IJsselmeer region was limited. Furthermore, this connection must be evaluated in combination with the 1980 riverbed position if the IRM decides to implement either the 1980 riverbed position or the 1980 water distribution using infrastructure. Adopting this configuration would divert less water to the Waal, resulting in reduced flow to the ARK and, consequently, less water available for extraction into the IJsselmeer region.

If the 1980 riverbed position is implemented, only 7 m³/s would be required from the ARK to achieve the target of five water shortage years in the IJsselmeer region under the Steam 2050 scenario. This is significantly lower than the 65 m³/s required under the 2018 riverbed position, even while maintaining the current buffer capacity of 0.2 m, without increasing the summer target water level.

Research question 2.2: What is the maximum possible additional inflow from the Amsterdam-Rhine Canal to the IJsselmeer region, considering the impacts under the Delta Scenarios (Ref 2017 and Steam 2050), and taking into account each scenario in combination with both the 2018 and 1980 riverbed positions?

Based on the identified impacts of connecting the Amsterdam-Rhine Canal (ARK) to the IJsselmeer region on the safety and navigation functions of the ARK, threshold values for these impacts, as established in Flipsen's report (2024), were applied. It was determined that the maximum additional supply from the ARK to the IJsselmeer region is 51 m³/s when the discharge levels at Lobith are 1,200 m³/s. However, when the discharge at Lobith decreases to 800 m³/s, only 5 m³/s can be extracted from the ARK for the IJsselmeer region.

To enable greater water extraction from the ARK to the IJsselmeer region at a discharge level of 800 m³/s at Lobith, alternative operational strategies for the existing infrastructure are necessary. These strategies primarily focus on optimizing the operations of the Bernhard and Irene lock complexes to ensure that additional water extraction does not compromise navigation or safety functions (Flipsen,2024).

An advised configuration, referred to as "Bernhard1-Irene1" in Flipsen's report (2024), involves using one of the two Bernhard locks exclusively for water supply while reserving the other for navigation. Additionally, the chambers of one lock at the Irene lock complex would remain partially open. Under this configuration, 35 m³/s can be extracted from the ARK for the IJsselmeer region when the discharge at Lobith is 800 m³/s, and 53 m³/s can be extracted when the discharge at Lobith is 1,200 m³/s.

However, this configuration has not yet been implemented in practice, and its use is associated with uncertainties. Implementing this option may require modifications to the locks to ensure that one lock at the Bernhard complex remains navigable.

6. Conclusions

This thesis focused on enhancing freshwater availability in the IJsselmeer region, the largest freshwater basin in the Netherlands, by mitigating water shortages caused by drought. To achieve this, two measures were formulated and translated into two main research questions:

Main research question 1: What are the impacts of increasing the summer target water levels in the IJsselmeer region to mitigate water shortages, under both the current climate and socioeconomic conditions (Ref2017), and the worst-case climate and socioeconomic scenario projected for the year 2050 (Steam 2050)?

The impacts of raising the summer target water level are closely linked to the timing, duration, and volume of the increase. Increasing the summer water level in the Markermeer is not feasible due to flood risks, while raising it in the IJsselmeer is constrained by the limitations of surrounding dikes and the presence of bird nests. This thesis concludes that increasing the summer target water level in the IJsselmeer to -0.05 m NAP, by early March is possible only if no storms are expected. In scenario Steam 2050 this measure is sufficient combined with the 1980 riverbed position. However, with the 2018 riverbed position, additional measures are needed. For scenario Ref 2017 combined with both riverbed positions, no water shortage mitigation measures are needed.

Main research question 2: What are the impacts of connecting the Amsterdam-Rhine Canal to mitigate water shortages in the IJsselmeer region, under both the current climate and socioeconomic conditions (Ref2017), and the worst-case climate and socioeconomic scenario projected for the year 2050 (Steam 2050)?

Extracting 51 m^3/s from the Amsterdam-Rhine Canal to the Markermeer mitigates water shortages in the IJsselmeer region under the Steam 2050 scenario with the 1980 riverbed position, without significant impacts on the canal's functions. However, additional measures are required when scenario Steam 2050 is combined with the 2018 riverbed position.

In conclusion, the extraction of 51 m^3/s from the Amsterdam-Rhine Canal, combined with raising the summer target water level in the IJsselmeer to -0.05 m NAP, mitigates water shortages in the IJsselmeer region across both scenarios and both riverbed positions, including the Steam 2050 scenario with the 2018 riverbed position. Furthermore, implementing this measure eliminates the need to apply any form of water use reductions.

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Appendix A: Prioritization sequence

In the event of a water shortage, water managers apply the regional prioritization sequence when weighing water distribution during times of national or regional shortages. These efforts aim to distribute the available water effectively to minimize damage. This distribution is based on land use, as demonstrated in the Table A1 below. The categories are ranked, with category 1 considered the most important due to irreversible damage and category 4 considered the least important due to primarily economic damage (Kort et al., 2020). Additionally, categories 1 and 2 are determined nationally, while categories 3 and 4 can be differentiated regionally (Beleidstafel Droogte, 2019).

Table A1 Numbers (1, 2, 3, etc.) indicate higher priority within the same category, Bullet points (•) indicate equal priority within the same category. The prioritization sequence. Within categories 3 and 4, regions can set their own priorities. Categories 1 and 2 are national.(Kort et al, 2020)

Category 1 **Safety and Prevention of Irreparable Damage**	**Category 2** **Public Utilities**	**Category 3** **Small-scale High-value Use**	**Category 4** **Other Interests (Economic Considerations, including for Nature)**
1. Stability of water defenses **2. Shrinkage and settlement (peat and high peat areas)** **3. Nature (dependent on soil moisture**	1. Drinking water supply 2. Energy supply	• Temporary irrigation of capital-intensive crops • Process water	• Navigation • Agriculture • Nature (as long as irreparable damage is prevented) • Industry • Water recreation • Inland fisheries

Appendix B: Delta scenarios

The Delta scenarios, which amalgamate the KNMI climate scenarios with the socio-economic scenarios from the "Welvaart en Leefomgeving" (Prosperity and the Living Environment, WLO) for the Netherlands, are represented in four different future scenarios (Figure B1) over two different years: 2050 and 2100. The four scenarios are:

- Rest: moderate climate change and limited socioeconomic growth;
- Pressure: moderate climate change and strong socioeconomic growth;
- Warm: Strong climate change and limited socioeconomic growth;
- Steam: Strong climate change and Strong socioeconomic growth. (Stow, 2021)

Furthermore, the reference scenario of 2017 (Ref2017) assumes that the climate and socio-economic conditions of 2017, which are considered current in this thesis, will remain unchanged (Prinsen et al., 2014).

Figure B1 Delta scenarios, (Stowa , 2021)

In April 2024, a new set of Delta scenarios is launched, as it is done every six years, based on the latest KNMI climate scenarios and socio-economic scenarios from the "Welvaart en Leefomgeving." However, it was decided to use the scenarios from the year 2018 in this thesis.

Appendix C: Fresh water test IJsselmeer

In Delta scenarios with minimal climate change (Busy & Rest) by 2050, it is projected that the frequency of shortages in the IJsselmeer could rise from once every 50 years to once every 15 to 20 years. In Delta scenarios with rapid climate change (Steam & Warm), this frequency might increase from once every 15 to 20 years to once every 5 years (Table C1), primarily due to decreased water inflow via the IJssel (Rijkswaterstaat, 2021).

The IJsselmeer buffer, established by the Peilbesluit IJsselmeer 2018 of 0.2 m, may prove insufficient during dry years, potentially falling short once every 15 to 20 years under the Steam delta scenario (where a water shortage once every 20 years is considered to be the minimum according to the Delta Program). In the current climate, including the Rest and Busy scenarios, this buffer is generally deemed adequate.

Table C1 Frequency of water shortages with the current IJsselmeer buffer under different scenarios in 2017 and 2050.

Year	Scenario	Water shortage frequency (once per x year)	Acceptable (minimum 1/20)
Current (2017)	Busy &Rest	1/50	Yes
Current (2017)	Steam	1/15 to 1/20	No
2050	Busy &Rest	1/15 to 1/20	No
2050	Steam&Warm	1/5	No

Appendix D: Safety function IJsselmeer region

Safety:

To ensure the safety function the flood defenses (dikes, dames and other water-retaining infrastructure) must comply with standards for the probability of failure of those defenses ('flood risk' according to the Water Act 2017) being 1:10000 which means that floods are acceptable to happen once in ten thousand years as a result of breach (kans op bers). To meet this standard two aspects are considered in designing the defenses:

1. the height and strength of the defense;
2. the hydraulic load on that defense

For height of the defenses: short-term peaks are important.
For strength of the defenses: longer-lasting water levels (a few weeks), which are usually lower than those peaks, are crucial, But during such a long, wet period, the dike becomes saturated, which can eventually cause it to become unstable (macro-instability) (Remmelzwaal et al., 2015)
The hydraulic load is a function of the water level, wave height, tilt (scheefstand) and period (Figure D1). Where the period is influenced by wind speed and the geometry of the area (Remmelzwaal et al., 2015). The wave height is very related the wind as it is represented in two important processes:

1. **Wind setup (opwaaing)**: This occurs due to strong winds, which cause the water to pile up on one side of the lake, making it higher than on the other side. **This is called tilt (scheefstand)**.
2. **Wave run-up** : During storms, high waves can develop, which can crash against the dikes and cause damage.

Both factors, wind setup and waves, are crucial for protecting the hinterland from flooding and can be influenced by how the IJsselmeer is managed.

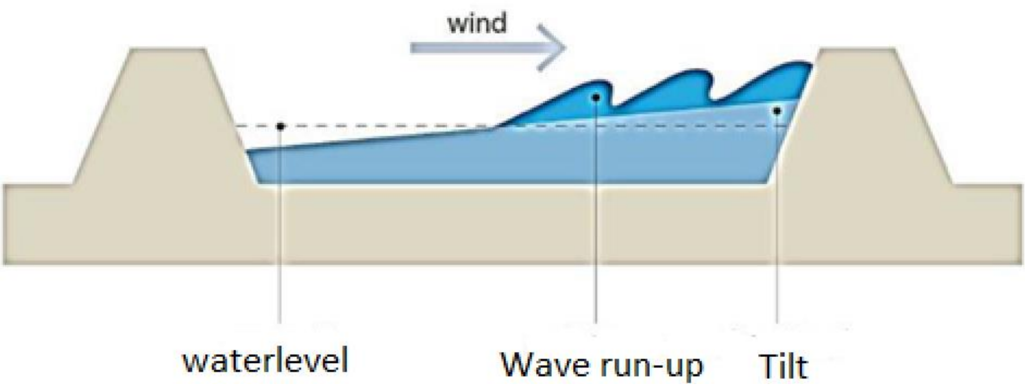

Figure D1 Wind impact on the wave development in the IJsselmeer region, modified from (Remmelzwaal et al., 2015)

Furthermore, since 2015 standardization methodology has changed, the critical water level is no longer used but with probability distributions per dike section. And that is quite complicated, partly because it can vary per failure mechanism such as overtopping, piping and macro-instability". Additionally, the hydraulic load levels around the lakes vary from place to place (Figure D2), because wind speeds are not equally strong from all directions, the fetch (strijklengte) (the distance over which waves can develop) is not the same everywhere, and water depth, which can limit wave height varies greatly. The factors combined determine the critical water level (maatgevend hoogwaterstand), however, the water level is the most decisive factor for the hydraulic load in most of the IJsselmeer region with the tilt being for important in some places both factors determine the critical water level.

On top of that, there are waves, whose run-up against the dike is again dependent on the dike profile: the slope angle, the presence of any berms (riprap or rubble), and the roughness of the slope. The critical water level is lowest in the Markermeer coast being between 0 and 0.8 as it is shown in the Figure D2 below, which makes then the hinterland of the Markermeer very vulnerable to floods in case of increased water levels in combination with wind speed and duration (van Ginkel et al, 2022).

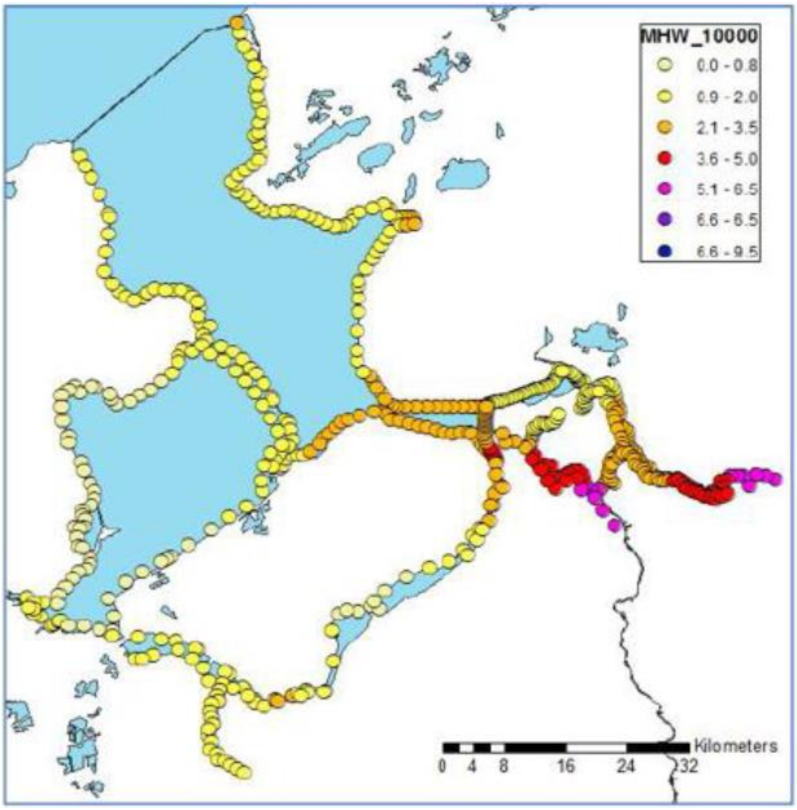

Figure D2 Water levels which can occur 1 in 10,000 , (Remmelzwaal et al., 2015)

Due to the impacts of climate change, water levels on the Wadden Sea side are rising, making it more difficult to discharge water into the Wadden Sea by gravity. As a result, more water needs to be stored in the IJsselmeer region, pumped, or managed through a combination of both. Additionally, climate change has caused increased discharge from the IJssel River and regional waters during the winter due to increased precipitation. This, along with increased seepage in the polders, leads to a higher salt load in the IJsselmeer, which raises the flushing demand for the water supply. These factors add further pressure on the safety functions. To mitigate these impacts and enhance safety, pumps with a total capacity of 275 m³/s were installed in May 2024. This is done based on the study of Remmelzwaal et al. (2015), where it was found that it is much cheaper to increase the pumping and sluicing (spuien) capacity than to reinforce the dikes (The Sea Level Rise Knowledge Program, Defacto Stedenbouw 2021, Detares,2019).

Appendix E: Nature function IJsselmeer region

Ecosystem

A robust ecosystem requires the presence of a large diversity of species at all trophic levels (from algae, through filter feeders to top predators, such as pike and sea eagles). This means that there must be sufficiently large habitats for all characteristic species, and that the environment in those habitats must be of good quality. In other words, the diversity of environments and the (water) quality of those environments must meet certain quality standards.

The IJsselmeer region, however, is characterized by predominantly abrupt transitions, between deep-shallow, clear-muddy, nutrient-poor-nutrient-rich, fresh-salt, stagnant-flowing, and land-water; instead of gradual gradients with intermediate environments. The main ecological problems in the IJsselmeer region therefore stem from the absence of habitats (sub-habitats for, for example, spawning, growing, foraging, etc.) for various species. As a result, important plant and animal species are missing from the ecosystem, and there is no robust and diverse food web (PAGW, 2017A, 2017B). The abrupt transitions also mean that the different ecosystems and habitats in the IJsselmeer region are not well connected to each other (PAGW, 2017A, 2017B).

Furthermore, due to the lack of "natural dynamics," habitats for certain species, such as the Great Reed Warbler and Bittern, are under pressure. Natural dynamics refer to natural water flow and fluctuations in water levels. While there are some fluctuations due to tilting from wind-driven water movement, the unnatural water level change from a low winter level to a high summer level hinders the establishment and growth of reeds. In locations with a constant water level, shoreline erosion occurs, and the lack of water level fluctuation prevents the rejuvenation of pioneer communities, causing the shores to overgrow with rough vegetation and forests (PAGW, 2017A, 2017B) .According to an expert interview mention in the report of (van Ginkel et al, 2022), in order to enhance the natural function of the IJsselmeer more natural water level fluctuations should take place.

Water quality

Additionally, according to the most recent assessment (Water Framework Directive, 2021), the ecological water quality of the Markermeer is still ‘insufficient,’ and that of the other waters in the IJsselmeer region is ‘moderate’. The bad water quality in the Markermeer is because of a strong phosphorus limitation , leading to a more significant reduction in primary production (especially algae), and this effect extends to higher trophic levels: fewer fish and, consequently, less food for birds (see Noordhuis et al., 2022). Although the chemical water quality has improved, there are still too many pharmaceutical residues and pesticides present in the water of the IJssel and Makermeer. To what extent these affect the functioning of the ecosystem is unknown.

Animals

Fish

The species composition of resident fish communities (species that remain in the area) lags behind what might be expected in the corresponding environment (too few species), and the age structure of populations of many species is imbalanced (many young fish, but too few adult specimens) (De Leeuw & Van Donk, 2020). This is partly due to a lack of shallow zones with aquatic plants. It is also caused by commercial fishing, which removes many individuals from certain age classes of some fish species.

Additionally, large numbers of freshwater fish are discharged into the Wadden Sea during sluicing (spuien), where they cannot survive.
For migratory fish, even after the construction of the fish migration river and other fish passages, there are still many barriers on the way to or from the sea, to or from the upstream Rhine basin, the drainage waters, and polders (PAGW, 2017A, 2017B).

Birds
The breeding success of birds is under pressure due to insufficient protection of breeding areas from disturbances caused by humans, predators, storms, and the overgrowth of breeding sites. For fish-eating birds, the declining fish population also means food shortages.
For marsh birds, there are too few habitats with extensive reed beds. For reed lands, there are insufficient suitable locations with shallow water (which dries up in the spring), and the unnatural water level dynamics prevent the establishment of new reed beds. Existing reed beds are also being overtaken by forests (PAGW, 2017A, 2017B).

Table E1 Breeding period of marshland birds in the IJsselmeer region, all birds nest after begin of March.

Species	Breeding season	Breeding habitat
Bittern	March to June	Old reed vegetation
Marsh harrier	April to June	Drier reed vegetation
Purple heron	April to June	Drier reed vegetation
Spotted crake	April to July	Marsh vegetation of reed, rushes, sedges, bulrush
Savi's warbler	Late April to July	Dense vegetation of water reed
Great reed warbler	Mid-May to August	Wet reed vegetation
Sedge warbler	Late April to July	Transition from old reed to reedbeds

Table E2 Breeding period of ground-nesting birds in the IJsselmeer region, all birds nest after begin of March.

Species	Breeding season	Breeding habitat
Cormorant	Mid-February to July	Bare ground, short vegetation, low shrubs, trees
Spoonbill	January to July	Ground, stones, low shrubs
Ringed plover	Early April to July	Bare ground
Common tern	Late April to August	Bare ground
Ruff	Late April to August	Moist poor grassland

Plants
Lastly, mowing of aquatic plants in the Gooimeer and Eemmeer, as these plants hinder navigation. Although aquatic plants are inconvenient for boating activities, their presence is of great value to the ecosystem. (PAGW, 2017a)

Important developments impacting the nature function:

- To improve the nature function, some measures have already been implemented such as adding the missing habitats by constructing islands, shallow water, foreshores and giving more space for gradual transitions between areas with different characteristics in the IJsselmeer region.
- Due to rising sea levels, increased saltwater intrusion is expected at the Afsluitdijk, which can be interpreted both positively and negatively from an ecological perspective. This is related to

the estuarine past of the IJsselmeer region. Besides salt leakage through the Afsluitdijk, there is also salt input from polders where saline seepage occur.

- The current aquatic communities are not very sensitive to higher salt concentrations, in contrast to some terrestrial communities that have adapted over the past 90 years to the water level management of a freshwater system, particularly in the areas outside the dikes. The sharp transition from salt to fresh water at the Afsluitdijk limits opportunities for estuarine species and, consequently, the biodiversity in the area. Migratory fish and estuarine fish (Herring, Sprat, Smelt, Flounder, etc.) that manage to enter experience a salt shock (and may be flushed out again during the next discharge). A gradual transition would facilitate migratory and estuarine fish (cf. fish migration river), especially if estuarine prey (larger zooplankton, mysid shrimp, and sand shrimp, etc.) could also move in and out. However, such a gradual transition would need to be spatially stable or follow a natural rhythm. (van Ginkel et al, 2022)
- Constructing the Island, has a positive impact on nature as it provide new habitats and safe breeding areas close to food sources. Additionally, these island has a positive impact on recreation although recreation can disturb nature, particularly during the molting period of some waterfowl or breeding season. The construction of new islands is not favorable for the freshwater supply, as it reduces the surface area of the lakes and, therefore, the volume of the water reserve. Even islands with limited height reduce the volume of the buffer reserve.
- Constructed the shallow areas has a positive effect on nature due to the provision of smother transition between shallow and deep water. As long as shallow water zones do not dry up when the lake level drops (for example to -50 cm NAP), the freshwater supply is not effectively reduced. For the storage capacity of the basin, shallow areas have no effect

Appendix F: Other functions of the IJsselmeer region

The IJsselmeer region is used by many sectors that are dependent on or benefit from the good condition of the area, such as fisheries or recreation. A good condition, in turn, depends on the proper functioning of the system (the three main functions). In this case, it usually involves users who have adapted to the existing situation.

Secondly, there are sectors seeking space in the IJsselmeer region, such as for energy production and urban development. However, such sectors can put pressure on the spatial quality or the proper functioning of the system. This can come at the expense of the three previously discussed main public functions of the system, or it can make the area less attractive for existing users. (van Ginkel et al, 2022)

Fisheries

Until the late 1980s, there were rich fishing grounds in the IJsselmeer, Markermeer, and IJmeer. Since the 1990s, populations of commercially attractive fish species have sharply declined. The fisheries have a great interest in the good ecological functioning of the system and the fish stocks dependent on it, but sometimes have different priorities than nature conservation.

Commercial navigation

Passenger and freight transport are important forms of commercial navigation in the IJsselmeer region. These require a certain water depth in the waterways, harbors, and infrastructure, which is partly maintained through 'nautical dredging.' There are also requirements for bridge heights, bridge operation, and lock operation. Significant adjustments or fluctuations in water levels can make it difficult to meet some of these requirements, and limiting saltwater intrusion by restricting sluice operations can also conflict with the need for 'unhindered navigation.'

Sand extraction

In 2012, 15-20% of the sand needed for the construction sector in the Netherlands was supplied by sand extraction from the IJsselmeer region (Bos et al., 2012). Sand is becoming increasingly scarce in the Netherlands. Sand extraction can conflict with the goals of ecological functioning, but there are also potential synergies, such as reducing water quality problems due to high silt content—similar to those seen in the Markermeer—by creating deep pits that act as silt traps (Klijn et al., 2006). However, caution is needed in this regard.

Water-based recreation: a major user of water and coastlines

The IJsselmeer region is an important area for water sports. There is also much beach recreation, for which sufficient water quality is required. There is a lot of boating, both with larger ships (sailing charters and sport fishing) and smaller private (sailing) yachts, and sport fishing is very popular (Rijkswaterstaat, 2018). There is a slow but steady growth in the number of vessels in the area (Rijkswaterstaat, 2018). Large-scale marinas have been created for water recreation, some of which are not equipped to handle large water level fluctuations (fixed piers instead of floating ones).

Accommodation-based recreation: also in areas outside the dikes

After the closure of the IJsselmeer, several locations in the areas outside the dikes were developed with 'permanent' holiday homes. These are not designed for larger water level fluctuations in the lakes than currently occur with the existing water level management system and tilting due to wind setup.

Wind farms

As part of the energy transition, the IJsselmeer region is increasingly being considered as a potential location for generating energy from wind or solar power. A large wind farm with 89 turbines has already been built near the Afsluitdijk. The spatial impact of wind farms does not align well with other uses of the water and detracts from qualities like the expansive horizon, tranquility, and darkness.

Solar energy

There are various ideas for floating solar fields, solar fields on islands in the IJsselmeer region, and solar parks on or behind the dikes. The effects of this on the three main functions depend heavily on the location, method of implementation, and design.

Housing: small-scale outside the dikes to large-scale on (peninsula) islands

With the growing population, substantial housing developments have already been built on the outskirts of Amsterdam in recent decades (Rijkswaterstaat, 2018), where parts of the IJsselmeer region (peninsula islands) have been created at the expense of the water surface, such as with the construction of IJburg. Large-scale urban development's outside the dikes have also been proposed for the near future in the Markermeer, as illustrated in Koolhaas et al. (2006). In the Amsterdam Bay Area program (Almere 2.0, 2022), recently submitted to the House of Representatives, there is mention of 100,000 new homes in this area. In the BARRO, reservations have been made for the IJsselmeer region for urban development's outside the dikes in Amsterdam, Almere, and Lelystad. This would reduce the water surface area of the Markermeer by approximately 1.5%. However, this would negatively affect all three main functions of the IJsselmeer region.

Appendix G: National Hydrological Model (LHM) and Baseline Projections

The Baseline Projections (Basisprognoses) provide long-term calculations of water demand and supply for the entire Netherlands using the National Hydrological Model (LHM), which is part of the National Water Model. The LHM calculates the regional groundwater flow pattern of the Netherlands for the current and for future climate scenarios. The toolset is focused on the simulation of average and dry conditions. With this toolset, groundwater levels, piezometric heads in deeper aquifers, seepage and drainage fluxes, and the exchange between groundwater and surface water can be calculated. Additionally, the distribution of surface water over the national water distribution network and across various regional surface waters in the Netherlands is calculated, enabling the visualization of surface water availability at regional and national levels. The model output can be used as input for other models like QWAST. (Delares, 2017)

The LHM is composed of four linked models (Figure G1):

• MODFLOW for the saturated zone (groundwater);

• MetaSWAP for the unsaturated zone;

• MOZART for the regional surface water;

• Distribution Model (DM) for the national water distribution network. (Delares, 2017).

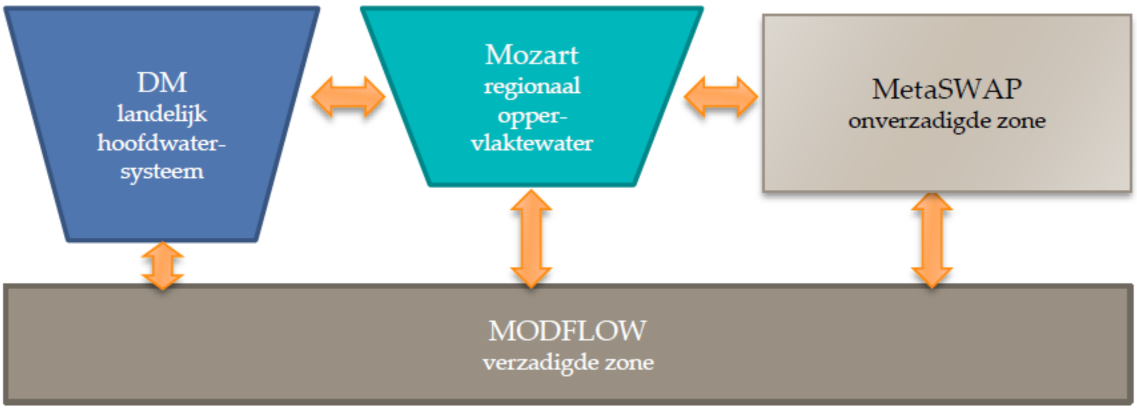

Figure G1 Correlation of LHM models, (Delares, 2017)

In the LHM, the Netherlands is schematized into cells of 250 x 250 meters, and vertically into 8 model layers (Figure G2&3) for the subsoil and soil compartments in MetaSWAP. For the surface water, approximately 8500 drainage units are distinguished in MOZART, which are connected to about 250 larger regional units (districts) that are linked to the national water distribution network in DM.

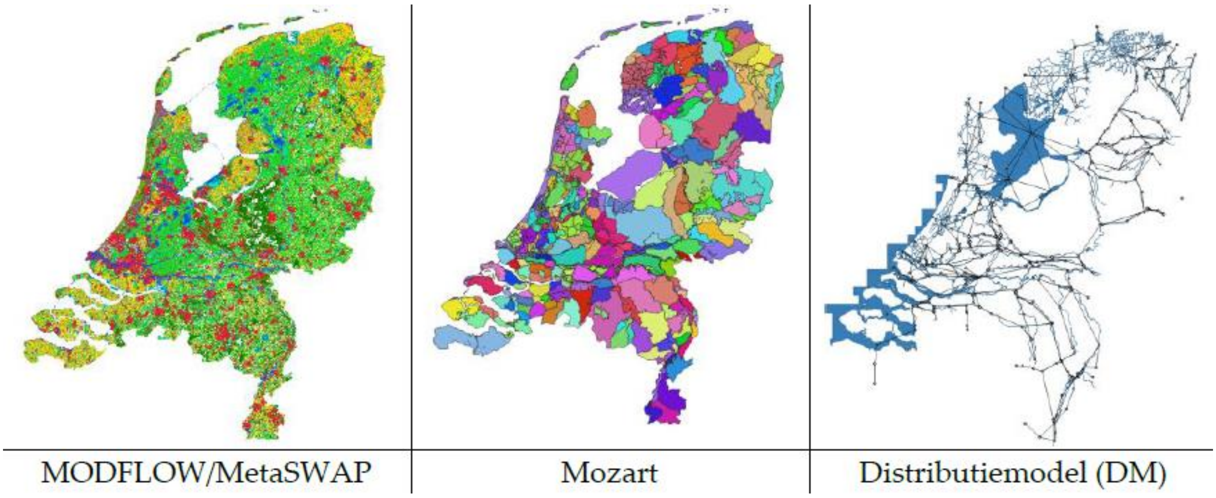

Figure G2 Inputs sub-models LHM, (Delares, 2017)

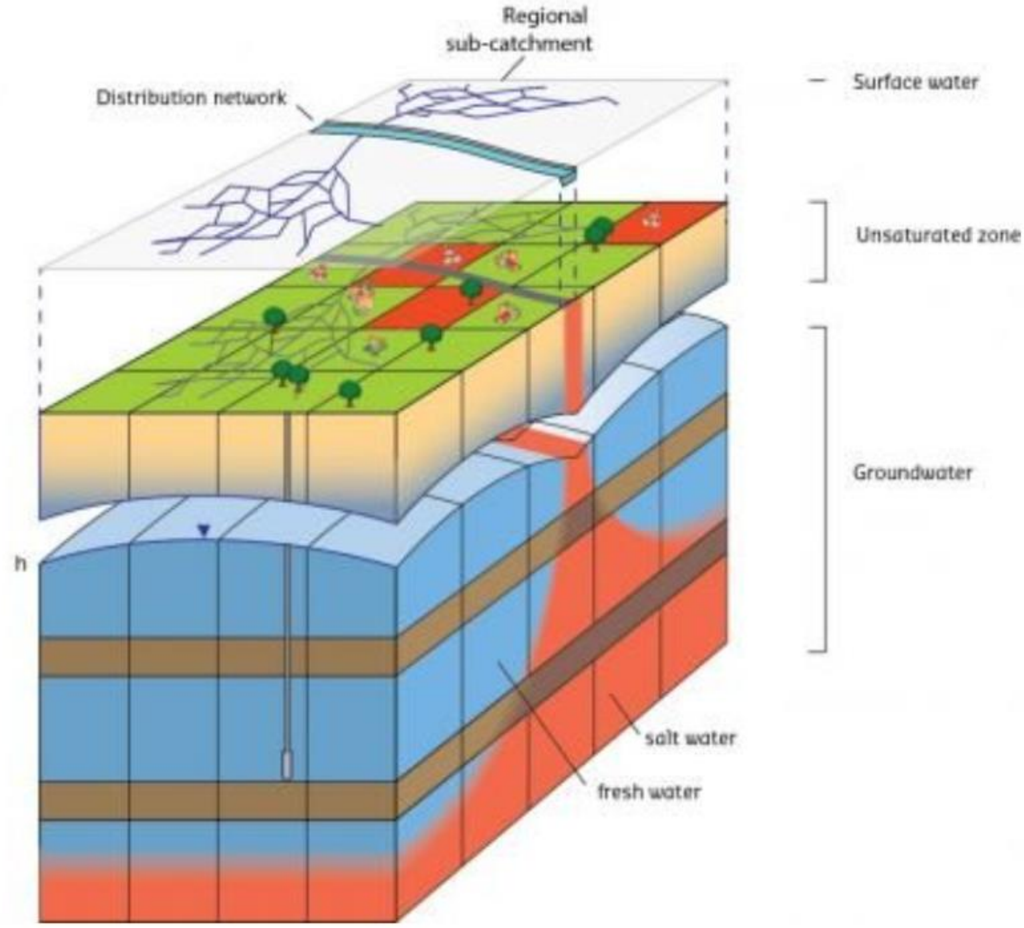

Figure G3 Sub-models LHM, layers, (Delares, 2017)

The LHM is employed for various purposes such as the Baseline Projections (Basisprognoses).Using the LHM, a long-term calculation of water demand and availability for the entire Netherlands has been carried out for analysis within the Delta Program Freshwater. The results of the calculations are available as 'Baseline Projections 2018' for (further) analysis.

The Baseline Projections utilize historical data from 1911 to 2011 to predict future conditions by identifying and modeling patterns and trends observed in the past. Historical data on precipitation, evaporation, and river discharges are collected and analyzed. These data serve as the foundation for modeling future scenarios. Models like the HBV model use historical climate data as input to simulate the water discharges of rivers such as the Rhine and Meuse. These simulated discharges are then corrected by comparing them with actual measurements to ensure the model's reliability.

Various climate scenarios, such as the KNMI’14 scenarios, are employed to predict future changes in water discharge, precipitation, and evaporation. These scenarios illustrate how discharges will increase in winter and spring and decrease in summer and autumn, while the average annual discharge will rise. The simulated discharges for both current and future climates are adjusted to maintain consistency. This involves applying a correction factor to align the simulated data with historical measurements.

Delta scenarios are used to describe potential future scenarios that encompass both physical and socio-economic changes. These scenarios are based on historical trends and are utilized to model how future climate changes and economic developments will affect water availability and distribution.

By employing these methods, the Baseline Projections provide a reliable indication of how future conditions might appear based on trends observed in historical data. This approach aids policymakers and water managers in preparing for potential future changes in water availability and management (Edwin Snippen, 2016).

Appendix H: Comparison System for KZH

The KZH team at Rijkswaterstaat (RWS) is evaluating various measures to comprehensively assess their benefits and drawbacks. This evaluation is expected to result in a definitive course of action by 2026, determining which measures will be implemented or abandoned, along with their respective implementation strategies (Rijkswaterstaat, 2018). To ensure this process proceeds successfully, the program requires a tool that contributes to this process. For this purpose, this comparison system is designed as a comprehensive assessment tool. The assessment tool for the KZH program and its partners aims to:

1. Gain an overview of goal achievement and side effects (positive and negative) of the KZH variants
2. Have criteria by which variants can be filtered
3. Serve as a checklist in the development of the variants.

<u>Note:</u> It is important that this assessment tool (Table H1) is well aligned with other instruments of the Delta Program. However, since the other tools of the Delta Program are still in development, this tool is considered a draft.

This assessment tool is modified from the assessment tool of the Interpretation Framework (Duidingskader) of the Sea Level Rise program (Table H2). The difference between this tool and the original one is that the KZH team chose to omit the Water Safety and Sandy Coast criteria and add Freshwater Availability to meet the objectives of the KZH. Furthermore, the impacts are aligned with the instrument being developed within the framework of the DPZW. Consequently, criteria (E) through (G) of the Interpretation Framework have been removed and replaced by criteria from the DPZW assessment tool.

The assessment tool

The desired outcome of the application of the tool are:

1. The result is an organized overview of the effects on goal achievement, side effects, costs, benefits, and risks per variant. The effects can be valued both qualitatively (on a Likert scale) and quantitatively (in money, hectares of nature, discharge etc.). The valuation is explained through arguments/reasoning lines/sources (the substantiation). The tool then provides insight into the effects for individual regions as well as on a national scale.
2. In the early stages of the process, the valuation of effects will primarily be qualitative; later in the process (when more data is available), the valuation will be more quantitative in nature. In both forms of valuation, the substantiation is of great importance.
3. The tool does not provide for an explicit weighting between criteria.
4. The result of the tool forms input for advice to policymakers, (KZH in the case of this study)
5. For the valuation of possible mitigating measures, a separate column can be provided. In this way, the value of both the variants and the possible mitigating measures can be assessed independently of each other.

The draft assessment tool for KZH consists of 1 goal achievement criterion and 6 criteria related to side effects. The criteria can be assessed both qualitatively and quantitatively.

Table H1 Assessment tool KZA

Main Criterion	Definition
1. Goal achievement freshwater availability	Contribution to achieving the objective based on the latest delta scenarios and the concretized DPZW goals. By 2050, the Netherlands will be resilient to freshwater shortages. This means that the KZH should contribute as much as possible to the goal of the DPZW: 1) The Netherlands has a robust and balanced (fresh) water system in which water supply and demand for all social functions are balanced, and dry periods occur less than once every 20 years. This goal is made explicit by determining the effects of operational flexibility (through variable control) on goal achievement for all functions and areas. This objective is still under further development in the DPZW. It must also be clarified whether this concerns a 1/20 situation in the general sense or a 1/20 situation for a specific function.
2. Costs	Investment costs + costs for management and maintenance (possibly mitigation costs can be included in the assessment, in which case it is important to label these costs as mitigation).
3. Effects on freshwater use functions and Dutch welfare	Effects on all freshwater use functions, side effects, and social effects such as the quality of the living environment. This includes the three elements, people (social), planet (ecological), and prosperity (economic). Note: By determining the effects on all freshwater use functions, side effects, and social effects, the effects of operational flexibility (through variable control) are made explicit.
4. Sustainability	A KZH variant is sustainable if it also effectively withstands further climate change. The variant is part of a strategy that is also sustainable in the (longer) term and prevents shifting the burden to future generations.
5. Flexibility	A KZH variant is flexible if it can easily be accelerated/delayed and/or scaled up/down as new insights justify it. Flexible variants reduce the chance of regret (better safe than sorry) because implementation can be postponed until there is more clarity about future developments. Moreover, flexible variants with short lead times score high on this criterion.
6. Integration	An integrated approach means addressing different water (dependent) tasks in conjunction. A variant scores high on this criterion if it not only contributes to the freshwater task but also to, for example, reducing greenhouse gas emissions by preventing groundwater desiccation in low-lying areas. This may involve a coupling task with other policy sectors. A variant scores low on this criterion if it shifts the burden to another water (dependent) task.
7. Feasibility	What technical, administrative, and institutional risks and opportunities does the KZH variant bring with it?

The effects of the KZH variants are visualized through a brief description and a summary rating, expressed as a score on a five-point Likert scale. For each freshwater region, a brief description of the effect is provided. The summary rating of the effects of the variants is also expressed through a score on a five-point Likert scale. These scores can be based on expert judgment or quantitative information. If suitable quantitative information is available (such as "damage in euros"), it can be used instead of the score on the five-point scale.

In addition to the five scores, an 'X' is added to indicate a showstopper, and a '?' is used for situations where no rating can be given.

++	= Expected strong positive effect
+	= Expected positive effect
0	= Neutral
-	= Expected negative effect
--	= Expected strong negative effect
X	= Showstopper*
?	= No rating possible and/or not applicable

Showstoppers are effects that are so negative that the variant cannot be implemented. For example, if one of the KZH variants has technical or financial risks that are too great, the variant cannot be implemented. This is then a showstopper for the variant in question, and the assessment will not be further elaborated.

Criteria assessment

1. Goal Achievement: Freshwater Availability: In assessing this criterion, freshwater use functions are reviewed to determine whether the water demand and supply for all societal functions are balanced during dry periods that occur more frequently than once every 20 years. This goal achievement criterion is assessed solely from a hydrological perspective. Other effects on the freshwater use functions are assessed and described under criterion 3. This criterion can be assessed based on both qualitative and quantitative information.
   Note: During the process of developing this tool, it was noted that operational flexibility can have a positive effect on goal achievement. An example of operational flexibility mentioned was the measure to configure the Amsterdam-Rhine Canal in such a way that the discharge direction can be changed when the situation demands it. It is important to consider such opportunities when assessing variants.

2. Assessment of Side Effects: The assessment of side effects relates to criteria (2) through (7). These are non-hydrological effects that occur as side effects of the KZH variant. These include unintended effects that can be both positive and negative.
   2.1. *Costs:* In assessing this criterion, investment costs and costs for management and maintenance are taken into account. The methodology also lends itself to displaying mitigation costs in a separate column. It is important to agree beforehand whether mitigation/mitigating costs will play a role in the assessment and in what manner. When mitigating costs are also considered during the assessment, it may happen that the investment costs + M&M (Management and Maintenance) score neutrally, while the costs

for mitigation are very high, resulting in a negative score. This criterion can be assessed based on both qualitative and quantitative information.

2.2. *Effects on freshwater use functions and Dutch welfare*: Under this criterion, the (hydrological) effects of the KZH variant are monetized (expressed in euros) if possible. This can be based on quantitative information or expert judgment. When it is not possible to monetize the effects, the criterion can be scored qualitatively.

2.3. *Sustainability:* Under this criterion, it is assessed whether the KZH variant is sustainable under further climate change. This is evaluated in terms of sustainability and adaptability. This criterion is assessed qualitatively. It originates from the DPZW assessment tool, and the definitions will be aligned with the definitions of the Delta Program throughout the process.

2.4. *Flexibility:* Operational flexibility can add value to the goal achievement of a variant. This is reflected in the scoring of 'goal achievement'.

2.5. *Integration:* This criterion is scored qualitatively (Likert scale)

2.6. *Feasibility:* Under this criterion, the technical and institutional risks and opportunities of the KZH variant are identified. Institutional risks and opportunities may relate to:

- Legal risks and opportunities
- Organizational risks and opportunities
- Political-administrative risks and opportunities
- Financial risks and opportunities
- Support from stakeholders (particularly citizens and sectors)

2.7 *Safety:* Effect of the variant on the flood prevention (mitigation)

Interpretation Framework (duidingskader) Sea Level Rise program.

Table H2 Assessment tool Sea Level Rise program

Main Criteria	Criteria
Water Safety (A)	1. Water safety in inland areas 2. Water safety in outer dike areas
Sustainable Maintenance of Sandy Coast (B)	3. Dynamically maintaining the coastline with coastal supplements 4. Keeping the coastal foundation in balance (with additional coastal foundation supplements)
Freshwater Supply (C) (for water use functions)	5. Resilience to freshwater shortage
Effects and Opportunities for Economic Functions and Values (D)	6. Agriculture 7. Raw material extraction, construction, and industry 8. Transport and transshipment 9. Recreation and tourism 10. Drinking water 11. Energy
Effects and Opportunities for Non-Economic Functions and Values (E)	12. Nature 13. Physical living environment 14. Sustainability
Risks and Opportunities for Feasibility (F)	15. Technical content-related risks and opportunities 16. Institutional risks and opportunities
Costs (G)	17.Realization costs 18. Costs for management, maintenance, organization, and demolition

Appendix I: ARK supply capacity options

A total of six options were calculated in the report of Flipsen (2024). The naming convention for these options was consistent: the name of each option consists of "Bernhard" and "Irene," followed by a number. The number indicates how many locks at each complex are used to supply water. In addition, the terms "L" or "F" are sometimes added. These letters stand for "Limited" and "Full," indicating whether water is restricted due to an impact or whether as much water as possible is being supplied. In this thesis only the results of the used dry scenario is considered.

The options are tested against each impact to identify limiting factors. Additionally, an assessment is conducted using different colors to provide a clear overview. The assessment is as follows:

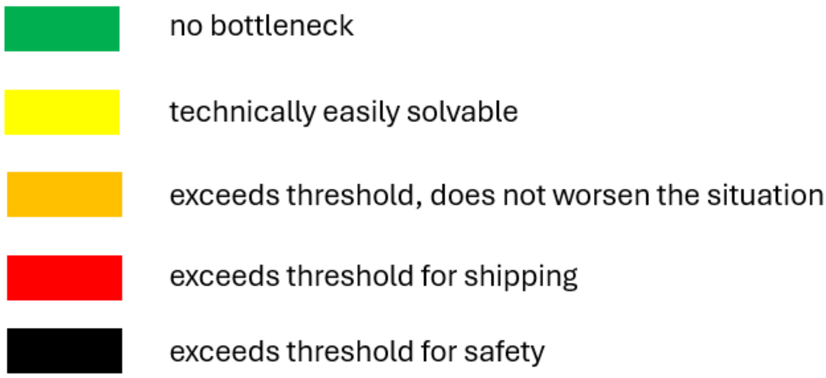

Figure I1 The method for assessing the bottlenecks (Flipsen,2024)

Bernhard2-Irene1-L, (which is the selected option)

In this configuration, both locks at the Bernhard complex are used for both water supply and navigation, while one lock at the Irene complex is designated for navigation and the other for water supply. The chambers in the old lock at the Irene complex, which is used for water supply, are partially opened to limit water inflow and prevent a gradient in the Noordpand, hence the term “Limited” is applied (Flipsen,2024).

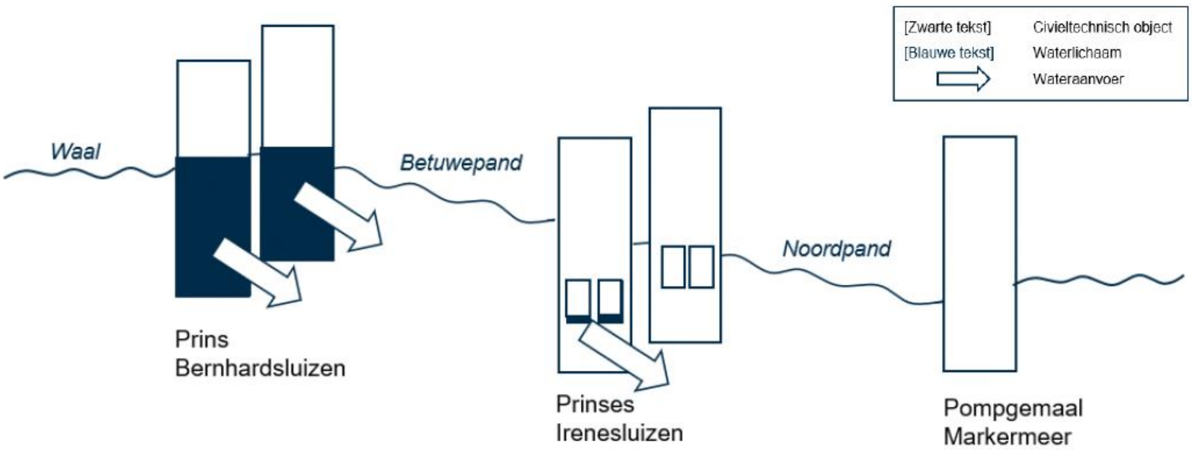

Figure I2 The use of the infrastructure in b Bernhard2-Irene1-L: At the Bernhard locks, both locks are open for water supply and navigation. At the Irene locks, the chambers in one lock are partially opened. [Black text] Civil engineering structure, [Blue text] Body of water, Arrow Water supply (Flipsen,2024)

In this configuration, **51 m³/s** can be supplied to the Markermeer. Additionally, the impact of "Rattling lock gates at Bernhard" has not been evaluated here, as this problem only arises when a lock is used for navigation (schutten), whereas in this case, both locks are used for water supply (Flipsen,2024).

Table I1 impacts of Bernhard2-Irene1-L (Flipsen,2024)

Bottleneck	Threshold	Observed Value	Assessment
Water level Waal	Max. 20 days water level < OLR (2.55 m NAP at Tiel)	2.83 m NAP	
Rattling lock doors Bernhard	Difference < wave height CEMT-VI vessels (0.5 m)	-	-
Navigation obstruction in both locks Bernhard	Flow velocity > 0.5 m/s	0.4 m/s	
Navigation obstruction at Irene due to discharge	2 locks in use for discharge	No	
Navigation obstruction at Irene due to water depth	Water level Forebay Irene lock < 2.0 m NAP	2.81 m NAP	
Water level North pand	Water height > -0.20 m NAP (navigation obstruction) or > 0.00 m NAP (water barrier)	-0.20 m NAP	

Bernhard2-Irene1-F (Full)

In this situation, both locks of the Bernhard locks are open, and the maximum amount of water is supplied through one lock at the Irene locks by fully opening the chambers. This may require structural adjustments.

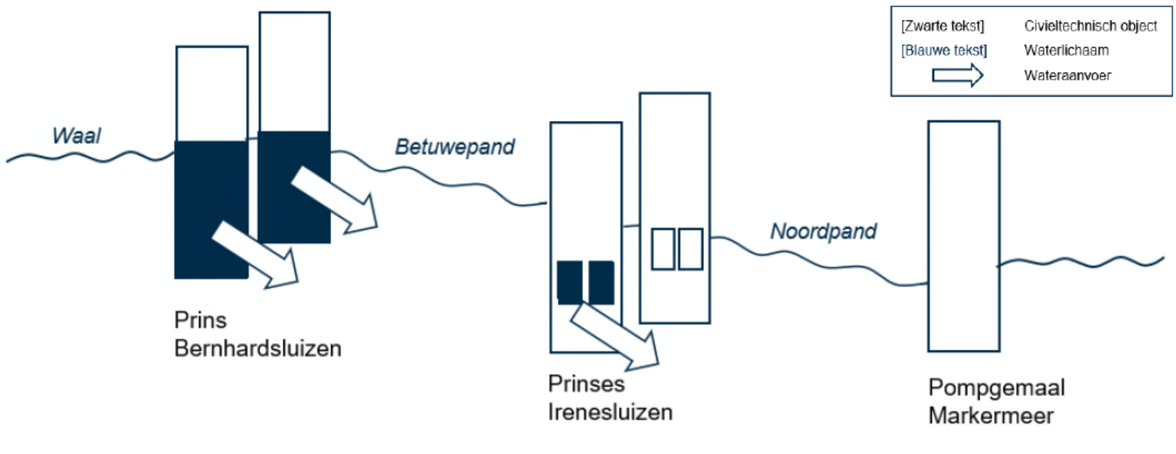

Figure I3 Bernhard2-Irene1-F (Full), [Black text] Civil engineering structure, [Blue text] Body of water, Arrow Water supply (Flipsen,2024)

In this option the maximum supply from the ARK to the IJsselmeer region is 108 m^3/s. However, This option already exceeds several threshold values. The water level on the Waal falls below the threshold value, flow rates in the Bernhard locks are excessive, and the water level in the Noordpand exceeds the calculated value for the water defenses, compromising the safety of these defenses.

Table I2 impacts of Bernhard2-Irene1-F (full) (Flipsen,2024)

Bottleneck	Threshold	Observed Value	Assessment
Water level Waal	Max. 20 days water level < OLR (2.55 m NAP at Tiel)	2,67m NAP	
Rattling lock doors Bernhard	Difference < wave height CEMT-VI vessels (0.5 m)	-	-
Navigation obstruction in both locks Bernhard	Flow velocity > 0.5 m/s	0.7 m/s	
Navigation obstruction at Irene due to discharge	2 locks in use for discharge	No	
Navigation obstruction at Irene due to water depth	Water level Forebay Irene lock < 2.0 m NAP	2.57 m NAP	
Water level Noordpand	Water height > -0.20 m NAP (navigation obstruction) or > 0.00 m NAP (water barrier)	0.09 m NAP	

Bernhard1-Irene1

In this situation, one lock is open at the Bernhard locks, and the chambers in one lock at the Irene locks are partially open.

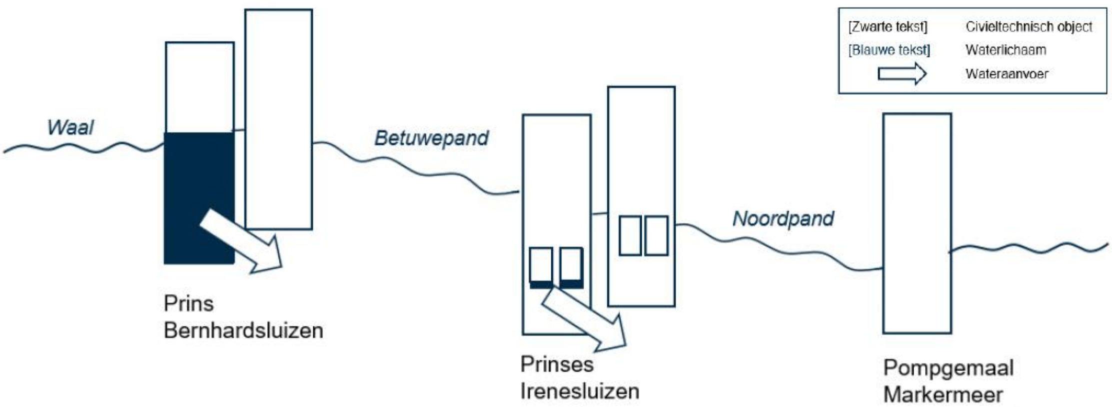

Figure I4 Bernhard1-Irene1-F, [Black text] Civil engineering structure, [Blue text] Body of water, Arrow Water supply (Flipsen,2024)

In this option the maximum supply from the ARK to the IJsselmeer region is 53 m^3/s.

A configuration like this, where water is supplied through one lock while the other lock is used for navigation, has not yet been implemented in practice. Therefore, the use of this option is accompanied by uncertainties. Implementing this option may require certain modifications to the locks to keep one lock at the Bernhard locks navigable. For instance, a flow-guiding screen might need to be installed to divert flow from the adjacent lock away from the other lock. Additionally, a gate may need adjustments to prevent rattling. Modifications will also be necessary in the lock used for water supply, as it will need to be made resistant to erosion. The mechanism for moving the gate may also need adjustment to ensure safety. There is a risk that, if water flows through the lock at a significant speed and the gate is lowered to stop water inflow, the gate may encounter increased resistance and become jammed due to the high flow velocity. In this scenario, stopping the water inflow at the Bernhard locks may not be possible, though the chambers at the Irene locks could still be closed to regulate water flow.

Table I3 impacts of Bernhard1-Irene1 (Flipsen,2024)

Bottleneck	Threshold	Observed Value	Assessment
Water level Waal	Max. 20 days water level < OLR (2.55 m NAP at Tiel)	2,83m NAP	
Rattling lock doors Bernhard	Difference < wave height CEMT-VI vessels (0.5 m)	0.01 m	
Navigation obstruction in both locks Bernhard	Flow velocity > 0.5 m/s	-	-
Navigation obstruction at Irene due to discharge	2 locks in use for discharge	No	
Navigation obstruction at Irene due to water depth	Water level Forebay Irene lock < 2.0 m NAP	2.8 m NAP	
Water level Noordpand	Water height > -0.20 m NAP (navigation obstruction) or > 0.00 m NAP (water barrier)	-0.2 m NAP	

Bernard2-Irene2-L

In this situation, both locks at the Bernhard locks are open, and the chambers at the Irene locks are adjusted to ensure that the water level in the Noordpand does not exceed 0.00 m NAP, thereby avoiding the impact on the safety of the water defenses in the Noordpand.

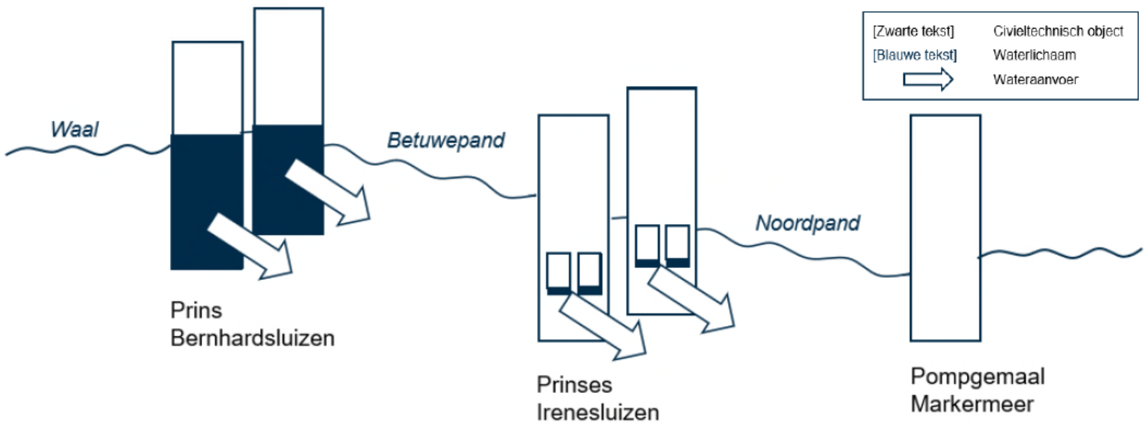

Figure I5 Bernhard2-Irene2-L, [Black text] Civil engineering structure, [Blue text] Body of water, Arrow Water supply (Flipsen,2024)

In this option the maximum supply from the ARK to the IJsselmeer region is 90 m^3/s. The impact analysis also shows that multiple impacts create hindrances for navigation: flow rates in the Bernhard locks are too high, both locks at the Irene locks are used for water discharge, and the required clearance height of 9.10 m in the Noordpand is not achieved.

Table I4 impacts of Bernhard2-Irene2-L (Flipsen,2024)

Bottleneck	Threshold	Observed Value	Assessment
Water level Waal	Max. 20 days water level < OLR (2.55 m NAP at Tiel)	2,21m NAP	
Rattling lock doors Bernhard	Difference < wave height CEMT-VI vessels (0.5 m)	-	-
Navigation obstruction in both locks Bernhard	Flow velocity > 0.5 m/s	0.6 m/s	
Navigation obstruction at Irene due to discharge	2 locks in use for discharge	Yes	
Navigation obstruction at Irene due to water depth	Water level Forebay Irene lock < 2.0 m NAP	2.65 m NAP	
Water level Noordpand	Water height > -0.20 m NAP (navigation obstruction) or > 0.00 m NAP (water barrier)	0m NAP	

Bernhard2-Irene2-F

In this situation, both locks at the Bernhard locks are open, and the chambers of both locks at the Irene locks are fully open.

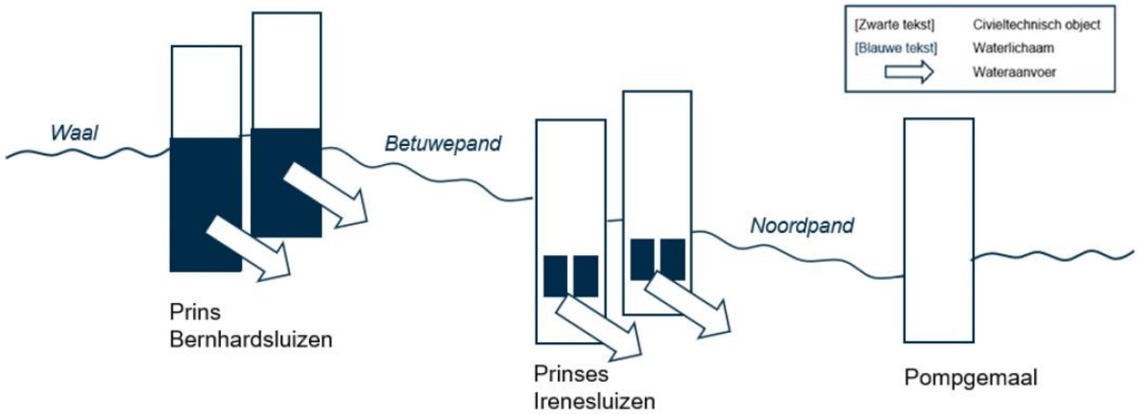

Figure I6 Bernhard2-Irene2-F, [Black text] Civil engineering structure, [Blue text] Body of water, Arrow Water supply (Flipsen,2024)

In this option the maximum supply from the ARK to the IJsselmeer region is 199 m^3/s**.** This option illustrates the hypothetical amount of water that could be supplied through the Amsterdam-Rhine Canal during these drought scenarios. These water volumes result in nearly all threshold values for impacts being exceeded (Table I4). This not only causes complete navigation hindrances at both lock complexes and partial hindrances in the Noordpand, but also leads to water levels exceeding the design water level for the water defenses in the Noordpand.

Table I5 impacts of Bernhard2-Irene2-F (Flipsen,2024)

Bottleneck	Threshold	Observed Value	Assessment
Water level Waal	Max. 20 days water level < OLR (2.55 m NAP at Tiel)	2,40 m NAP	
Rattling lock doors Bernhard	Difference < wave height CEMT-VI vessels (0.5 m)	-	-
Navigation obstruction in both locks Bernhard	Flow velocity > 0.5 m/s	1.2 m/s	
Navigation obstruction at Irene due to discharge	2 locks in use for discharge	Yes	
Navigation obstruction at Irene due to water depth	Water level Forebay Irene lock < 2.0 m NAP	2.05 m NAP	
Water level Noordpand	Water height > -0.20 m NAP (navigation obstruction) or > 0.00 m NAP (water barrier)	0.69 m NAP	

Bernhard1-Irene-BP

In this final option, the effect of a possible bypass at the Irene locks is examined. If the Irene locks were a limiting factor for water supply to the Markermeer, a bypass could increase the supply capacity. At the Bernhard locks, one lock remains open to minimize disruption to navigation, while a new bypass with a similar wetted area to the West lock (Irene) is implemented at the Irene locks.

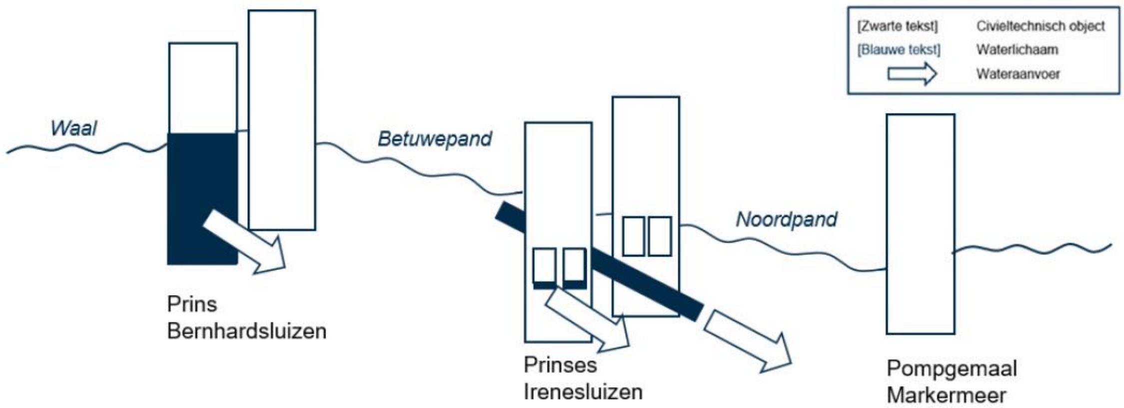

Figure I7 Bernhard1-Irene-BP, [Black text] Civil engineering structure, [Blue text] Body of water, Arrow Water supply (Flipsen,2024)

In this option the maximum supply from the ARK to the IJsselmeer region is 175 m^3/s. The impact analysis in Table I5, shows that even with a bypass, navigation on the Noordpand will still be hindered, as was anticipated from the results of the Bernhard2-Irene1-L option. In that option, the chambers already had to be partially closed to prevent the water level in the Noordpand from exceeding the threshold value. A bypass does not change the limiting factor—the water level in the Noordpand—and therefore adds little value.

Table I6 impacts of Bernhard1-Irene-BP (Flipsen,2024)

Bottleneck	Threshold	Observed Value	Assessment
Water level Waal	Max. 20 days water level < OLR (2.55 m NAP at Tiel)	2,55 m NAP	
Rattling lock doors Bernhard	Difference < wave height CEMT-VI vessels (0.5 m)	0.37m	
Navigation obstruction in both locks Bernhard	Flow velocity > 0.5 m/s	-	
Navigation obstruction at Irene due to discharge	2 locks in use for discharge	No	
Navigation obstruction at Irene due to water depth	Water level Forebay Irene lock < 2.0 m NAP	1.61 m NAP	
Water level Noordpand	Water height > -0.20 m NAP (navigation obstruction) or > 0.00 m NAP (water barrier)	0.52 m NAP	

Appendix J: Required supply capacity of the ARK

This Appendix determines the exact supply capacity required for the ARK under the Steam 2050 scenario, in combination with the 1980 and 2018 riverbed positions, based on the current buffer capacity. Additionally, it calculates the exact required supply for Steam 2050 when water levels in the IJsselmeer, as well as in both the IJsselmeer and Markermeer, are increased to -0.05 m NAP.

The required supply from the ARK for Steam 2050 Steam with riverbed position 1980 is 7m³/s.

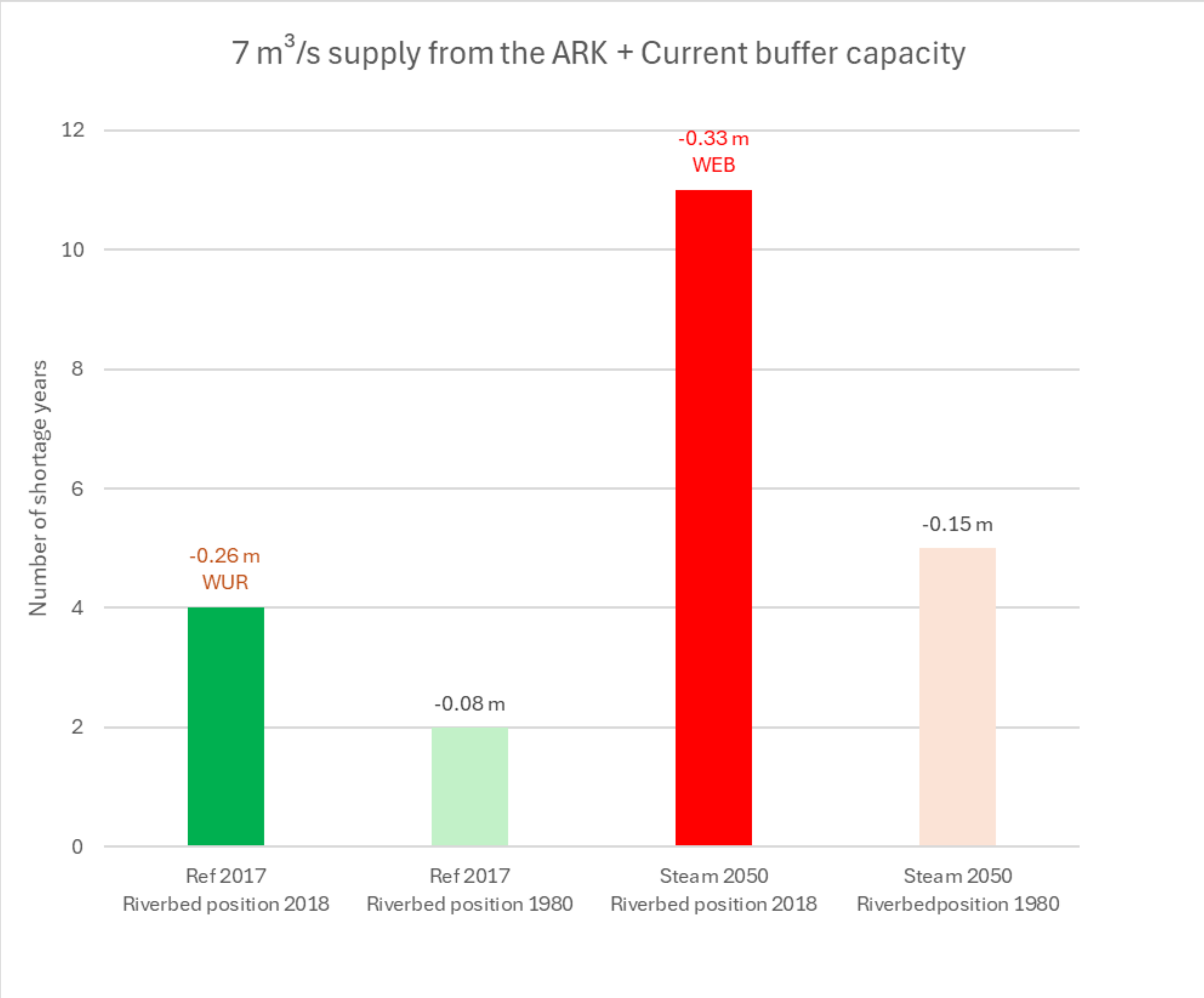

Figure J1 The required water supply from the ARK for the Steam 2050 scenario with the 1980 riverbed position, to meet the target number of water shortage years in the IJsselmeer region, taking into account the current buffer capacity. The y-axis shows the number of water shortage years per 100 years, and the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

The required supply capacity from the ARK is 65 m³/s for Steam 2050 with the 2018 riverbed position.

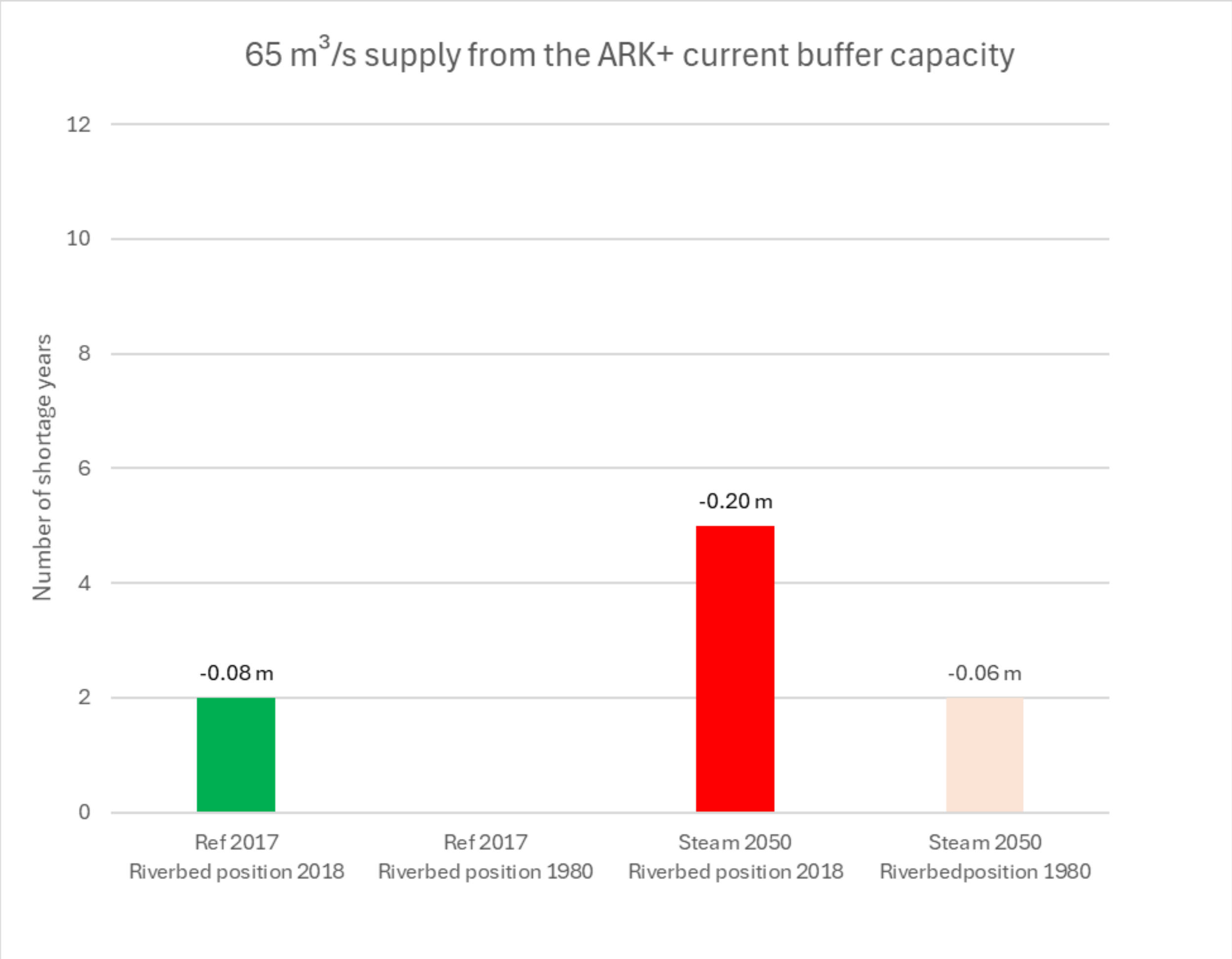

Figure J2 The required water supply from the ARK for the Steam 2050 scenario, with the 2018 riverbed position, to meet the target number of water shortage years in the IJsselmeer region, taking into account the current buffer capacity. The y-axis shows the number of water shortage years per 100 years, and the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

The required supply capacity from the ARK is 47 m³/s when the summer water level in the IJsselmeer is increased to -0.05 m NAP, which is 18 m³/s lower than with the current buffer capacity.

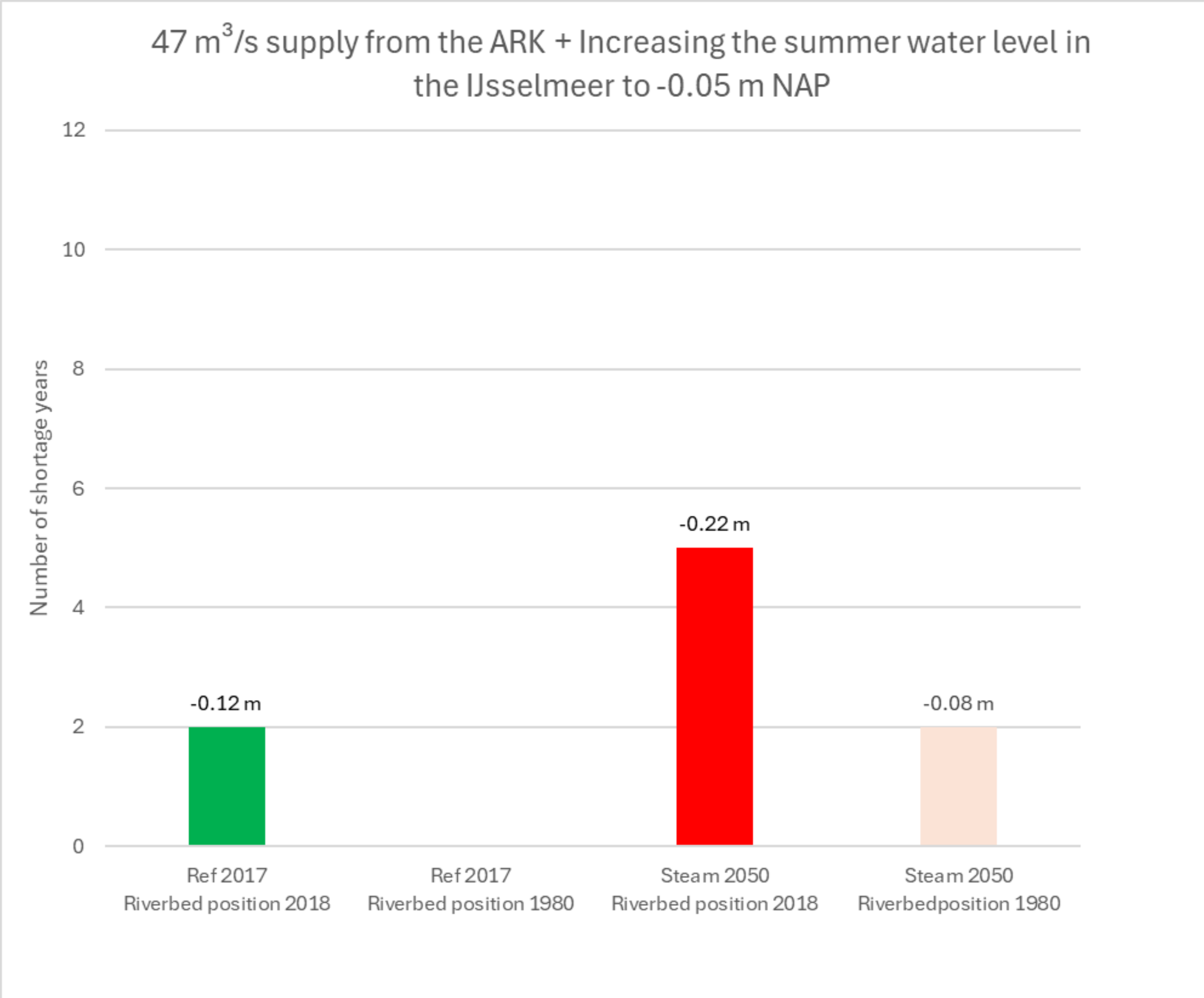

Figure J3 The required water supply from the ARK for the Steam 2050 scenario, with the 2018 riverbed position, to meet the target number of water shortage years in the IJsselmeer region, taking into account rising the summer water level to -0.05 m NAP in the IJsselmeer. The y-axis shows the number of water shortage years per 100 years, and the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

The required supply capacity from the ARK is 40 m³/s when the summer water level in the IJsselmeer region is increased to -0.05 m NAP. This is 25 m³/s lower than with the current buffer capacity and 7 m³/s lower than when only the summer water level in the IJsselmeer is increased to -0.05 m NAP.

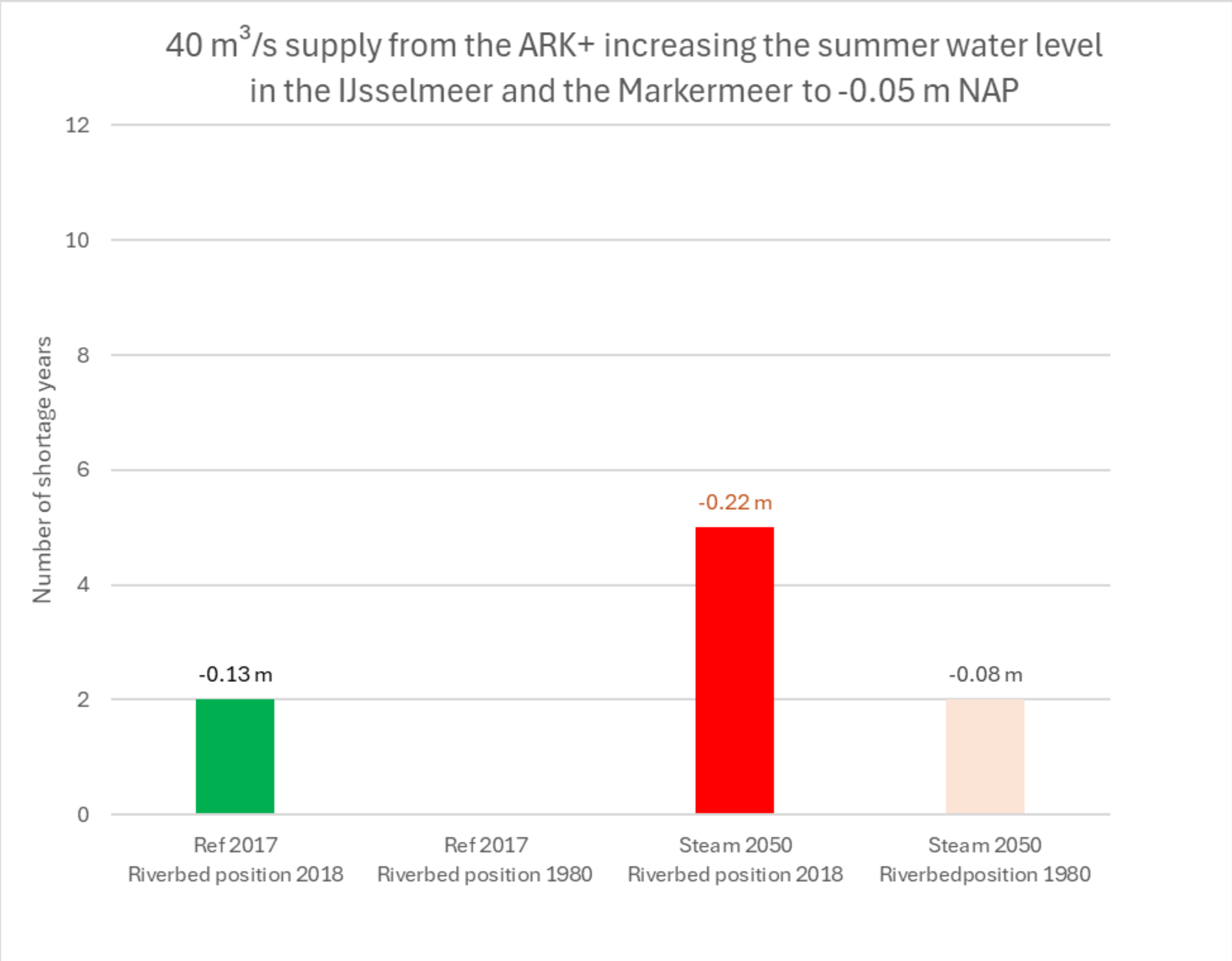

Figure J4 The required water supply from the ARK for the Steam 2050 scenario, with the 2018 riverbed position, to meet the target number of water shortage years in the IJsselmeer region, taking into account rising the summer water level to -0.05 m NAP in the IJsselmeer and Markermeer. The y-axis shows the number of water shortage years per 100 years, and the x-axis represents the scenario combined with the riverbed position. The number above each bar indicates the average water level change in meters.

Appendix K: Detailed explanation scores KZH comparison framework

As outlined in Chapter 5, this Appendix provides additional information on the scores within the KZH comparison framework for the measures, distinguishing between riverbed position A (2018) and riverbed position B (1980).

Description of the scores (A indicate riverbed position 2018)

A.1 Increasing summer water level in the IJsselmeer to -0.05 m NAP begin March:

Implementing this measure reduces both the severity and frequency of water shortage years in the Ref 2017 and Steam 2050 scenarios compared to the current situation. However, additional measures are still needed under the Steam 2050 scenario to meet the target of five water shortage years per 100 years, as this scenario projects nine water shortage years. The safety function is rated as neutral, as this measure will not be implemented if storms are expected, aligning it with the current safety standards. Regarding nature, this measure prevents nests from being flooded but reinforces unnatural water level dynamics, and slightly reduces the area of shallow zones, dikes foreshores, and islands, and consequently less available habitats. Additionally, slight increases in shoreline erosion and reduction in light penetration to the lakebed, negatively impacting aquatic plants. This measure involves no known associated costs and remains flexible, as it can be reversed at any time.

A.2 Increasing summer water level in the IJsselmeer to -0.05 m NAP begin April:

This measure does not improve goal achievement compared to the previous measure, as the frequency and severity of water shortages remain unchanged. This measure is considered safer, as fewer storms are expected in April. However, in addition to the negative impacts mentioned in the previous measure on nature, this timing also results in the flooding of bird nests, which is regarded as a very negative impact. The costs and flexibility scores are the same as those of the previous measure.

A.3 Increasing summer water level in the IJsselmeer and Markermeer to -0.05 m NAP begin March:

This measure slightly reduces the severity of water shortage years in the Ref 2017 and Steam 2050 scenarios compared to the previous measures. However, the target for Steam 2050 is still unmet, with nine shortage years projected. In terms of safety, more areas in the Markermeer will be flooded, primarily recreational sites such as vacation parks, campsites, recreational beaches, and grassy areas, due to the lower critical water levels of the dikes around the Markermeer compared to those around the IJsselmeer. For nature, costs, and flexibility, the situation remains the same as in the two measure above.

A.4 Increasing summer water level in the IJsselmeer and Markermeer to -0.05 m NAP begin April:

This measure does not further contribute to achieving the target compared to measure A.3, as the frequency and severity of water shortages remain unchanged. This measure is considered safer compared to measures 1 and 3, as fewer storms are expected in April; however, recreational sites around the Markermeer will still experience flooding. Regarding nature, similar to measure 2, bird nests will be flooded along with other negative impacts noted in measure 1. The costs and flexibility scores remain the same as in the previous measures.

A.5 Increasing summer water level in the IJsselmeer and Markermeer to +0.10 m NAP:

Implementing this measure ensures that the target for the number of water shortage years is met under the Steam 2050 scenario, with only three shortage years, and the severity of shortages in these years remains acceptable . However, this measure poses significant risks to nearly all functions in the IJsselmeer region, particularly in terms of safety. Higher water levels resulting from tilting will lead to overtopping. Piping will occur as well causing flooding or even dike failures around the IJsselmeer and

Markermeer. Additionally, all shallow zones, dike foreshores, and islands would disappear, and shoreline erosion would increase significantly, leading to substantial habitat loss for various species. Considerably longer waiting times are expected at the locks as water levels difference rise on both sides. Nuisance issues would also arise in urban areas such as Zwolle, with basements and low-lying areas at risk of flooding. Recreational sites, especially around the Markermeer, would disappear permanently, and accessibility to farmland would decline significantly due to rising groundwater levels from seepage, which would negatively impact agriculture. . The costs and flexibility scores remain the same as in the previous measures.

A.6 Supply capacity of 51 m^3/s from the ARK to the Markermeer with the current buffer capacity:
Implementing this measure will reduce the severity and frequency of water shortages in the IJsselmeer region compare to the current situation. However, the target will not be achieved for the Steam 2050 scenario, as eight water shortage years are still expected (one year less than A.1 with reduction in severity). There are minimal or negligible impacts on various functions of the Amsterdam-Rhine Canal (ARK) and IJsselmeer region, as thresholds were applied to mitigate impacts. However, these effects may vary depending on the location of the necessary pumping station to connect the ARK to the Markermeer, as flow rate and salinity could increase near the station. It should be noted that the location of the pumping station was not considered in this thesis. Investment costs will be required for the pumping station. This measure is both flexible and inflexible: while using the pumping station to supply water from the ARK to the Markermeer is flexible, the installation of the pumping station itself is irreversible.

A.7 Supply capacity of 51 m^3/s from the ARK to the Markermeer with increasing the summer water level to -0.05 m NAP in the IJsselmeer begin March:
Implementing this measure achieves the target for the number of water shortage years in the Steam 2050 scenario being five years, with almost an acceptable severity in those years. The impacts on safety, nature, and other functions are the same as in Measure A.1, as these impacts occur within the IJsselmeer. Costs and flexibility remain consistent with those in Measure A.6.

A.8 Supply capacity of 51 m^3/s from the ARK to the Markermeer with Increasing the summer water level to -0.05 m NAP in the IJsselmeer and Markermeer begin March:
This measure also achieves the target for the number of water shortage years and further reduces the frequency and severity of water shortages compared to measure A.7 (with one fewer shortage year). However, regarding safety, recreational areas around the Markermeer will experience flooding. The impacts on nature and other functions are the same as in Measure A.1. The costs and flexibility remain the same as in Measures A.6 and A.7.

Description of the scores (B indicate riverbed position 1980):

B.1 Increasing summer water level in the IJsselmeer to -0.05 m NAP begin March:
Implementing this measure ensures the water shortage target for the Steam 2050 scenario, reducing the occurrence to four years with acceptable severity, compared to seven years under the current buffer capacity. The scores for the other criteria are the same as those for Measure A.1. However, this thesis does not consider the costs and other impacts associated with achieving the 1980 riverbed position.

B.2 Increasing summer water level in the IJsselmeer to -0.05 m NAP begin April:
This measure does not further improve goal achievement compared to the previous measure, as the frequency and severity of water shortages remain unchanged. The scores for the other criteria are the same as those for Measure A.2.

B.3 Increasing summer water level in the IJsselmeer and Markermeer to -0.05 m NAP begin March:
This measure further reduces the severity of water shortage years in the Ref 2017. For Steam 2050 3 water shortage years occur (one less than B.2). The scores for the other criteria are the same as those for Measure A.3.

B.4 Increasing summer water level in the IJsselmeer and Markermeer to -0.05 m NAP begin April:
This measure does not further contribute to achieving the target compared to measure B.3, as the frequency and severity of water shortages remain unchanged. The scores for the other criteria are the same as those for Measure A.4.

B.5 Increasing summer water level in the IJsselmeer and Markermeer to +0.10 m NAP:
Implementing this measure results in having no water shortage years at all for Ref 2017 and just two water shortage years for Steam 2050 with negligible severity. The scores for the other criteria are the same as those for Measure A.5.

B.6 Supply capacity of 51 m^3/s from the ARK to the Markermeer with the current buffer capacity:
Implementing this measure results in having no water shortage years at all for Ref 2017 and just two water shortage years for Steam 2050 with negligible severity. The scores for the other criteria are the same as those for Measure A.6.

B.7 Supply capacity of 51 m^3/s from the ARK to the Markermeer with increasing the summer water level to -0.05 m NAP in the IJsselmeer begin March:
Implementing this measure further reduces the severity of water shortage years, though two years of water shortage still occur. The scores for the other criteria remain the same as those for measure A.7.

B.8 Supply capacity of 51 m^3/s from the ARK to the Markermeer with Increasing the summer water level to -0.05 m NAP in the IJsselmeer and Markermeer begin March:
Implementing this measure has little additional impact on reducing the severity of the two occurring water shortage years. The scores for the other criteria remain the same as those for measure A.8.