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Implementing and upscaling the "Improved Drainage System"

Modelling the effects of upscaling a flexible surface water level management to the agricultural areas of the Haarlemmermeerpolder, The Netherlands

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Abstract

This master thesis explores the implementation of the Improved Drainage System (VDS) in the agricultural area of the Haarlemmermeer polder, aiming to reduce freshwater demand and mitigate waterlogging risks while maintaining suitable water quality and salinity for agricultural functions. The study investigates the effect of VDS compared to traditional water management in response to climate change and autonomous salinisation.

The traditional approach in water management focuses on meeting societal demands for agriculture, involving rapid drainage of excess water, and flushing of brackish surface water resulting from the permanent saline seepage flux. VDS, on the other hand, applies a flexible surface water level within specific margins and reduces the need for inlet water by eliminating the flushing of the polder.

The STOWA model, created by “Stichting Toegepast Onderzoek Waterbeheer” in collaboration with Witteveen & Bos and Waternet, is a calculation tool in Excel that utilizes a box model of the Water Balance. The STOWA model was utilized for this study, this tool proved suitable for studying the effects of the implementation of VDS on the water system regarding the water level, water demand, and water saliniy. However, the STOWA model is inadequate for the modeling of the water quality, because the STOWA model is a point-based model and is incapable of employing the spatial and temporal variability. The large parameter variation and uncertainties make STOWA unsuitable for making robust decisions regarding VDS implementation.

The research findings indicate that VDS reduces freshwater demand when comparing to the traditional management without flushing, resulting in lower inlet water requirements. Additionally, the results showed that without irrigation, no inlet water is needed to maintain the minimum set levels in the water system. Furthermore, the traditional management approach in the polder demonstrated its capability to handle anticipated extreme rainstorm events, suggesting that adaptive measures are not required to mitigate waterlogging risks caused by climate change. In contrast, internal autonomous salinisation does require measures to prevent salinisation of the surface water.

Implementing VDS consistently leads to higher surface water salinity compared to traditional management, contradicting the hypothesis that rainwater capture in VDS management would have a freshening effect. The findings from upscaling VDS to the entire Haarlemmermeer polder indicate that VDS can be applied in specific areas of the polder while maintaining agricultural functionality, depending on the flux and salinity of the phreatic seepage and the presence of seepage boils. Consequently, determining the freshwater-saltwater interface is crucial for assessing the suitability of an area for the implementation of VDS.

Keywords: Flexible water level, STOWA Water Balance, Internal autonomous salinisation, Sustainability, Deep polder area, Haarlemmermeer

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List of terms and abbreviations

Abbreviation/Used noun	**Definition**
AD	Years after Christ.
BC	Years before Christ.
Boil discharge seepage *Wellen*	Intense preferential seepage via boils, which are small vents in the Holocene semi confining layer through which water discharges at high rates and lead to upconing of deeper and more saline groundwater with a constant temperature of 11,5°C.
BSL	below sea level.
Calculated inlet water *Berekend inlaatwater om het gezette peil te handhaven*	Calculated inlet water required to maintain the minimum set water level.
Diffuse seepage *Diffuse kwel*	Seepage of groundwater through the semi confining Holocene layer consisting of clay and peat.
Dutch hydrological Instrumentarium *Nederlands Hydrologisch Instrumentarium (NHI)*	The Dutch Hydrological Instrumentarium (NHI) is a collection of software and data used for developing groundwater and surface water models for the entire area of the Netherlands, at both national and regional scales (source: NHI).
Forced inlet water *Gestuurd inlaatwater ten behoeve van het doorspoelen*	The forced inlet water simulates the flushing in the STOWA model. The forced inlet water/flushing is 0.83 mm d^{-1} in summer from the first of April until the first of October. This value is obtained from field measurements by Delsman et al. (2013) (Deltares, 2015).
Hoogheemraadschap van Rijnland *Rijnland local water authority*	The local water authority of water management and flood control. Their jurisdiction region in the western part of the Netherlands. responsible for managing water systems, including rivers, canals,

	dikes, pumping stations, and water treatment facilities. They oversee flood protection, water quality, and water quantity management, ensuring the safety, availability, and sustainability of water resources in the region. They also play a crucial role in maintaining the balance between freshwater and saltwater in coastal areas.
Hydraulic head *Hydrologische drukhoogte*	A measure of the mechanical energy per unit weight of water (e.g., Freeze & Cherry, 1979). The hydraulic head is determined based on water-level measurements in wells and piezometers.
Internal autonomous salinisation *Interne autonome verzilting*	An increase in the salinity in the surface water and groundwater due to an increasing chloride input by seepage, either by an increasing flux and/or increasing chloride concentration of the seepage. Autonomous salinisation refers to the process by which the salinity of water bodies increases over time because the water system has not reached a state of dynamic equilibrium; the boundary conditions of the system are changing due to hydrogeological events including transgressions, subsidence, and land reclamation (Oude Essink et al., 2010). Autonomous salinisation has detrimental effects on agriculture, ecosystems, and water resources, as high salinity levels can impede plant growth, degrade soil fertility, and compromise the availability of freshwater for human consumption (Van Puijenbroek et al., 2004; James et al., 2013).
KWA, Climate-proof Water Supply Facility *Klimaatbestendige Water Aanvoervoorziening*	Alternative water supply routes used in times of extreme water shortage and low river discharge of the Rhine.
Local drainage catchment *Peilvak*	Area of homogenous service water levels. There are 63 local drainage catchments in the Haarlemmermeer polder.
Local water authority *Waterschap*	The 21 Local water authorities in The Netherlands one of the local water authorities tasked with several responsibilities, including

	water quality and water quantity, water defense, and nature and environment conservation.
NAP *Normaal Amsterdams Peil*	Reference water level relative to average sea level.
National Hydrological Model *Landelijk Hydrologisch Model (LHM)*	An integrated nationwide groundwater and surface water model of the Netherlands that combines several coupled models to simulate different aspects of the hydrological system to provide a comprehensive representation of the hydrological processes occurring across the entire country, allowing for a better understanding of water movement, interactions between groundwater and surface water, and the overall water management in the Netherlands. (*LHM - Nationaal Water Model - Deltares Public Wiki*, n.d.)
Phreatic seepage *Freatische kwel*	This study utilizes the term “phreatic seepage” for the combination of the diffuse seepage and preferential seepage, because of the large heterogeneity in the area.
Preferent seepage *Preferente kwel*	Seepage of groundwater through local permeable sandy paleochannel belts that exist in the Holocene layer.
Pumping station *Gemaal*	Pumping stations maintain the water level. When the water level in a polder exceeds the set level, the excess water is pumped from the polders to the boezem (basin of canal). When the water level goes below the minimum set level, the pumping station admits water to replenish water shortages in the local drainage catchment
Salinisation *Verzilting*	Increasing chloride concentrations. This becomes problematic when the water salinity becomes too high for the intended use such as crop growing or drinking water abstraction.
Seepage *Kwel*	A saline and nutrient-rich upward flow of groundwater polluting the surface water.

STOWA model *STOWA model*	The STOWA model is a calculation tool in Excel that utilizes a box model of the Water Balance. The model is created by "Stichting Toegepast Onderzoek Waterbeheer", a Dutch knowledge center of water boards and provinces, in collaboration with Witteveen & Bos and Waternet (Tanis, Schep, & van Dijk, 2018).
Sub-regional storage system *Polderboezem*	Major water storage system: in the Netherlands usually consisting of (a) higher lying canal(s). The boezem discharges the combined polder water surplus to the main rivers or directly to the sea or admits water from the main rivers to replenish water shortages in the polder ditches (Delsman, 2015). In this thesis, the Dutch terminology will be used.
VDS, Improved Drainage System *Verbeterd Droogmakerij Systeem*	A flexible surface water level between margins for which the upper margin is the boezem level, making pumping stations and flushing redundant. A "natural, free fluctuation within a bandwidth", which means that a flexible water level (20-30 cm) is maintained between the current summer water level in the drainage catchment and the water level in the polder basin. The upper margin of the VDS water level corresponds with the water level of the polderboezem (winter NAP -6,02m, summer NAP -5,87m).
Water Framework Directive *Kaderrichtlijn Water, KRW*	KRW (Kaderrichtlijn Water, Water Framework Directive) threshold for chloride is set at 700 milligrams per liter
Water Level Decisions Note *Nota Peilbesluiten*	The policy framework for water level management and the specific water level decisions (peilbesluiten) that the local water authority is responsible for. (source: https://lokaleregelgeving.overheid.nl/CVDR661462)
WH2085 scenario *WH2085 scenario*	The climate change scenario WH2085 is adopted from the KNMI'14 signaal, and represents the most extreme projections for the year 2085, characterized by the highest frequency and intensity of extreme weather events.

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1. Introduction

Changes of the earth's climate are inherently changes in the polder hydrology. As the water quality and salinity of the water in polders are mainly controlled by seepage, a saline and nutrient-rich upward groundwater flow contaminating the surface waters, the polder relies on the processes of pumping contaminated water out of the polder and freshwater admission to the polder. This is managed by strict surface water levels in summer and winter. Climate change is fundamentally affecting the precipitation and evaporation and thereby the water discharge out of- and into the polder, posing possible risks on the water quality, salinity, and water logging in the deep polders.

Deep polders are characterized by a continuous seepage flux. The supply of irrigation water depends on the flushing of the ditches during the growing season in summer (Apr.–Sep.). Flushing of the ditches refers to a controlled and planned process of admitting a specific amount of water into the waterways, intentionally exceeding the maximum water level, and thus subsequently pumping out the excess water. This approach is adopted to enhance water quality and reduce water salinity, thereby making the surface waters more suitable for irrigation. The practice aims to dilute pollutants, remove excess nutrients, and improve water flow from the area. Consequently, flushing plays a crucial role in maintaining the overall water management system and ensuring the suitability of surface waters for agricultural purposes. Outside the growing season in winter (Oct.–Mar.), the water levels are lower to accommodate the heavy machinery to cultivate the land. The continuous subtraction of surface water results in seepage originating from greater depth, which is more saline. This process is referred to as internal autonomous salinisation (hereafter "autonomous salinisation") (Oude Essink, 2008).

The traditional water management in polders dates from a time of water abundance. Here, the focus lies on the societal demands for agriculture that request lowering the water level by rapid drainage of redundant water and flushing the brackish surface water, continuously managed by costly and energy-consuming pumping stations. The IPCC report on climate change indicates the prospect of increasing air temperatures and changing precipitation patterns, and subsequently an increase in the intensity and frequency of extreme events (Jentsch et al., 2007; Wanders & Wada, 2015; Boonwichai et al., 2018; IPCC, 2021). Therefore, new policies shift their focus towards the robustness, sustainability, and climate-resistance of water systems, which is in line with the climate agreement (The National Water Plan, 2009; Klimaatakkoord, 2019).

One promising proposition for addressing water management challenges posed by climate change and autonomous salinisation is the implementation of the Improved Drainage System (Verbeterd Droogmakerij Systeem, hereafter "VDS"). The VDS approach involves maintaining a flexible surface water level within specified margins, with the minimum water level set to the former maximum water level (Fig. 1). Additionally, the maximum water level in the VDS system is set to match the sub-regional water system level, known as the "boezem," which allows water to flow gravitationally, eliminating the need for pumping stations and ditch flushing. To achieve this technically, the weirs are folded once the maximum water level, i.e., boezem level, is reached. This way, foreign water is not required for flushing the ditches, and water is only admitted into the polder when the water level falls below the minimum threshold. The higher surface water levels created in the VDS system are expected to reduce seepage flux by generating overpressure. Additionally, rainwater capture is expected to have a freshening effect on the water's salinity.

The primary goal of the VDS implementation is to minimize the movement of water in and out of the polder without unduly affecting the water quality, salinity levels, and waterlogging risks remain at acceptable levels. By adopting VDS, the aim is to strike a balance between effective water management and preserving the natural equilibrium of the polder's water system. The water demand for flushing, waterlogging risks, water quality, and water salinity are directly related to the water management. The changing climate and autonomous salinization will have implications for these processes that need to be projected onto the agricultural area in deep polders. VDS is further elaborated in section 2.7 and the settings are visualized in Figures 1 and 8.

1.1. Knowledge gap

De Louw et al. (2011) have contributed significantly to understanding and quantifying the sources of water and salt leading to surface water salinization in deep lying polders in the Netherlands, specifically caused by upward saline groundwater seepage. They conducted simulations based on two years of daily to weekly measurements in a Dutch polder catchment, revealing that preferential seepage via boils was the primary contributor to salinization, accounting for 66% of the total salt load and 15% of the total water flux. Delsman (2015) further expanded on this topic in his doctoral dissertation titled "Saline groundwater – surface water interaction in coastal lowlands," offering valuable insights into long-term geological factors and short-term dynamic processes affecting groundwater salinity distribution and exfiltration dynamics. His work sheds light on the divergent seepage fluxes in the area.

The studies conducted by De Louw et al. (2011) and Delsman (2015) have created a strong understanding of the current water system in the Haarlemmermeer polder in the current climate. Building upon their findings and measurements, this research creates a new water system for the Haarlemmermeer polder based on the principles of VDS management. Furthermore, this study addresses the impacts of climate change and autonomous salinisation on the water systems, presenting new insights into previously unexplored aspects.

The transition to VDS water levels is already being applied in areas which have undergone spatial development and where the land is no longer assigned to agriculture. However, it is important to note that these areas in which VDS is applied currently only have the VDS water levels in place, yet these areas are not isolated from the flushing of the polder. Consequently, there is a lack of field data available for the implementation and assessment of VDS. To enable polders to cope with ongoing climate change and autonomous salinisation, VDS must be implemented on a larger scale, in which agricultural areas are included.

Given the highly variable seepage fluxes and spatial variation in groundwater seepage composition, there is a need to study the approximation of these parameters in both the traditional water system and the VDS approach. Addressing this research gap and examining the response of both systems to future climate change and salinization will contribute to the scientific community's knowledge. Understanding the behavior of these water systems under changing conditions is crucial for informed water management strategies, especially amidst evolving environmental challenges, and will be beneficial for decision-making processes by waterboards.

1.2. Problem description

The divergent requirements of various stakeholders, including ecologists, the municipality, the waterboard, and farmers, make decision-making complex. The challenges posed by climate change and autonomous salinisation increase the urgency to prioritize measures that can effectively reduce water consumption in polder areas. The upscaling of VDS has consequences, but there is a crucial lack of knowledge to the extent of these consequences to make future-proof decisions.

Upward saline and nutrient-rich groundwater seepage results in salinisation and eutrophication of the surface waters (Deltares, 2015). An increased seepage flux or seepage salinity induces the freshwater demand to prevent salt damage on agriculture resulting from irrigation with brackish surface water. Additionally, the boezem is polluted by pumping brackish water to the boezem.

The implementation of VDS may also have negative consequences that are noticeable in the entire polder area. Some farmers are hesitant about the introduction of VDS as they express concerns that discontinuing the flushing process may lead to the salinization of ditches, rendering them unsuitable for irrigation purposes. Additionally, the flexible surface water level applied in the VDS, and subsequent higher groundwater level, excludes certain areas for the implementation of VDS. The minimal requirement of the unsaturated zone is 0.9m to

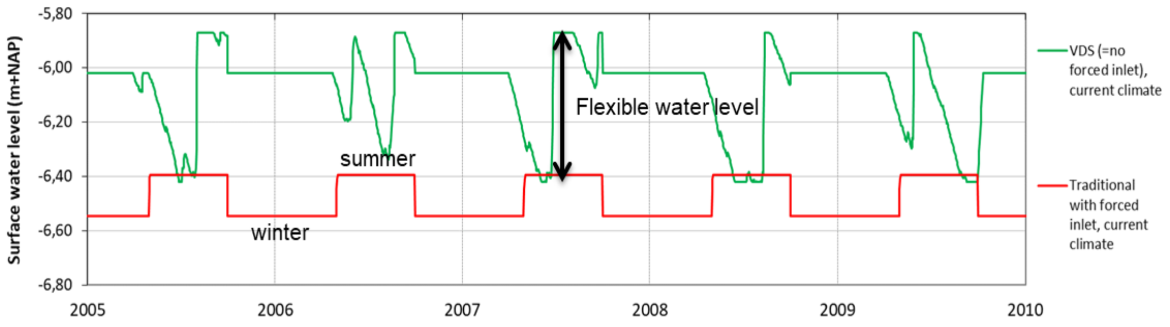

Figure 1. Illustration of surface water levels comparing the traditional water management (red) with the VDS management (green). The traditional management maintains a fixed water level of strict summer and winter settings (depending on the local drainage catchment), while the VDS management implements a flexible water level within margins. The upper margin of the VDS water level corresponds with the water level of the polderboezem (winter NAP -6,02m, summer NAP -5,87m) (created using the STOWA model).

prevent root damage and allow heavy machinery to cultivate the parcels, however, farmers prefer the depth of the unsaturated zone to be at 1.2m. The minimal requirement of 0.9m is documented in the Nota Peilbesluiten.

The spatial development from agriculture towards urban area, functional business area, greenhouse horticulture, and recreational area generates opportunities for a shift in water management. The shifting purpose of the area provides a window for change and the decrease of agriculture, which relied on the strict summer and winter water level management, can shift towards a flexible water level management. The governmental ruling known as "Bodem en Water Sturend" requires making water and soil the leading factors in development plans (Ministerie van Algemene Zaken, 2022). These add to the societal urgency of research on upscaling the VDS water system.

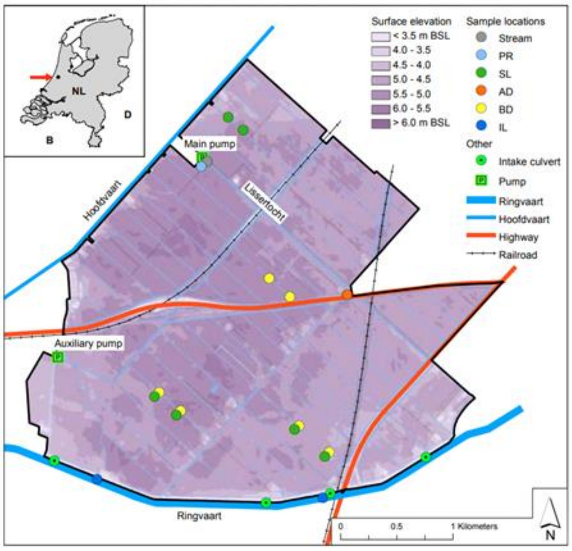

Figure 2. Study area; the Lissertocht catchment where Delsman et al. (2013) obtained their measurements. Featuring the surface elevation and sample locations of the PR: precipitation, SL: shallow, phreatic groundwater, AD: deep aquifer groundwater, BD: groundwater below ditches, and IL: inlet water. (Delsman et al., 2013)

1.3. Study area

The chosen study area is the Haarlemmermeer polder in Noord-Holland, the Netherlands. The area falls under the jurisdiction of the local water authority Hoogheemraadschap van Rijnland (hereafter "Rijnland"). The freshwater supply for agriculture is under pressure due to climate change and autonomous salinisation. Annually, approximately 35-50% of the freshwater intake from the boezem, Rijnland's inlet water, is used for flushing of the Haarlemmermeer polder. Therefore, to reduce the freshwater intake, Rijnland is exploring the prospect of upscaling the VDS to agricultural areas.

The Haarlemmermeer polder is divided into 63 local drainage catchments. The Lissertocht catchment (52º 13' latitude, 4º 36' longitude) served as reference area for the model because of the data availability and the large agricultural area in this regional catchment area. The surface elevation, main characteristics and sample locations from the data used are presented in Fig. 2 (Delsman et al., 2013). There are two pumping stations: vakgemaal Dr. J. P. Heye and vakgemaal Dr. J. P. Heyepad. The pumping station in the western part of the drainage catchment (Dr. J. Heyepad) is only used in case of extreme discharge events. Combined with five inlet points, the winter water level is maintained at -6.57mNAP and the summer water level at -6.42mNAP. The average surface level in this local catchment area is -4.72mNAP and the average hydraulic head at -4.42mNAP. The Lissertocht catchment lies adjacent to the boezem (Fig. 2). The surface water covers 2% of the area in the Lissertocht catchment, which is representative for the whole Haarlemmermeer polder. The presence of the paleochannel belt and the lithology of the Lissertocht catchment are depicted in Fig. 3. The lithology determines the transmissivity and, consequently, controls the seepage flux. The significant heterogeneity within the Lissertocht catchment, along with the presence of sand Holocene paleochannel belts and seepage boils, allows for upscaling the area to represent the entire polder.

1.4. Research objective

The goal of this study is to quantify the effect of implementing VDS compared to the traditional management on the freshwater demand, waterlogging risk, water quality, and water quantity in the agricultural area of the Haarlemmermeer and investigate the changes of these implications due to a future climate scenario and an autonomous salinisation scenario. Therefore, the implications of climate change and autonomous salinisation on both traditional water management and VDS management systems area assessed by providing a comprehensive evaluation of their responses to future stresses. The study aims to determine the effectiveness of traditional management in handling future challenges or whether alternative management approaches are required. Specifically, the waterlogging risks in the polder caused by climate change and the potential for salinity levels to surpass agricultural maximums due to salinisation are examined. Additionally, the modelling of VDS will determine its feasibility in agricultural areas, which is when agricultural salinity levels are not exceeded. The research outcomes will contribute to a better understanding of the adaptability and resilience of water systems under changing environmental conditions.

The water salinity is expressed in the chloride concentrations (Cl, g L^{-1}), as Cl^- is a dominant conservative anion (Yardley & Graham, 2002). Phosphorus (P) is the key factor that controls freshwater eutrophication in lowland catchments and therefore selected as indicator for water

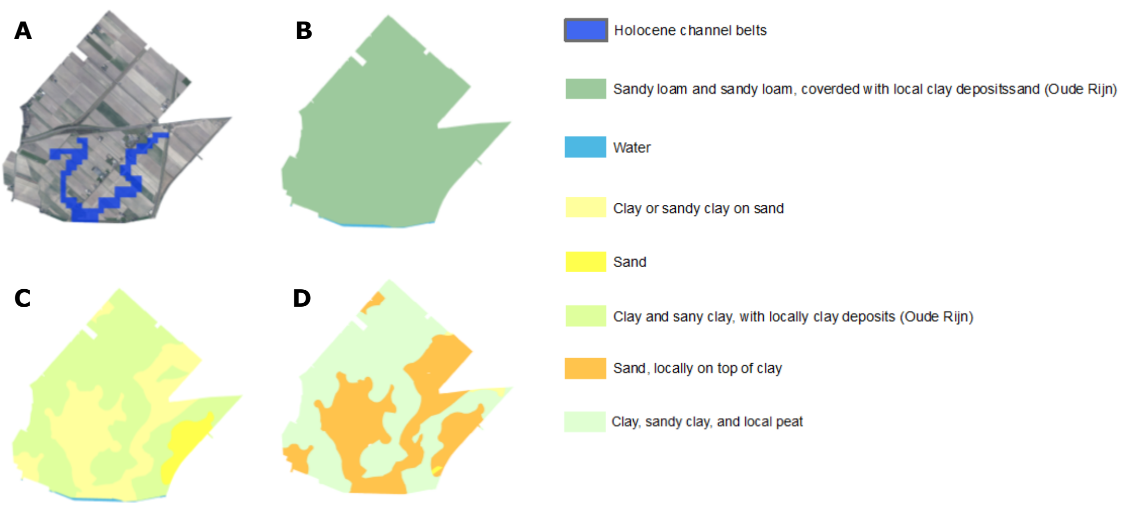

Figure 3. The Lissertocht catchment: A: Position of the Holocene channel belt. B: Lithology of the surface area. C: Lithology of 1 – 3m below surface area. D: Lithology of 3 – 5m below surface area. The upper aquitard layer of ca. 10 m soil consists of homogeneous loam (lichte kleigronden; minimum of 25-35% lutum, Formatie van Naaldwijk) with peat deposits (Formatie van Nieuwkoop, basisveen). The soil is classified as poldervaaggronden. (NHI data).

quality, together with nitrogen (N) (Mainstone & Parr, 2002).

This research assesses the consequences of upscaling the implementation of VDS to the agricultural area of the Haarlemmermeer polder. The following research question will guide the study:

In which agricultural areas in the Haarlemmermeer polder can the Improved Drainage System be implemented to diminish the demand for freshwater supply and reduce the waterlogging risks, while continuing a suitable water quality and salinity to fulfill the agricultural functions?

The following sub-questions are constituted to delve deeper into different aspects of the main research question and provide a comprehensive analysis of the topic:

SQ1. Which agricultural areas in the Haarlemmermeer are suitable for the application of VDS, considering the minimal depth of the unsaturated zone required for agricultural practices?

SQ2. How does the water level in the VDS management respond to extreme rainstorm events anticipated in the future climate compared to the traditional management?

SQ3: How does the freshwater demand in the VDS management respond to anticipated climate change compared to the traditional management?

SQ4. What is the effect of VDS on water quality i.e., phosphorous (P mg L^{-1}) and nitrogen (N mg L^{-1}) concentrations compared to the traditional management?

SQ5. How does the water salinity i.e., chloride concentrations (Cl, g L^{-1}), in the VDS management respond to anticipated autonomous salinisation compared to the traditional management?

SQ6. How does the average salinity in the entire Haarlemmermeer polder change under VDS management compared to the traditional management?

1.5. Hypothesis

The general hypothesis of this thesis states that the implementation of VDS in agricultural area improves water quality and decreases freshwater demand, without compromising on the water salinity and waterlogging prevention. The hypothesis is based on the following assumptions. First, raising the maximum water level to the boezem level has three potential improvements;

(1) VDS creates a seasonal storage of rainwater during the wet season, which provides a buffer during summer, and thereby reduces the freshwater demand;

(2) The rainwater collection improves the water quality and reduces the water salinity in the ditches;

(3) The overpressure reduces the seepage flux.

Additionally, the conversion of pumping stations into weirs, which enables an open water connection when the surface water level in the ditches reaches the boezem level and the weir folds away, offers the following advantages:

(4) During peak precipitation events, when the surface water level in the ditches reaches the boezem level, the subsequent open water network to the boezem allows for rapid discharge;

(5) Intake water will only be supplied when the water level is below the minimum, reducing the water demand of the polder.

Climate change is associated with an increase in the frequency and intensity of extreme events (Wanders & Wada, 2015; Boonwichai et al., 2018). The hypothesis posits that the current water system in the Haarlemmermeer polder is insufficiently equipped to cope with future precipitation events, leading to the exceedance of the maximum water level and subsequent waterlogging.

Autonomous salinisation refers to the gradual increase in salinity of seepage water due to continuous water extraction (Oude Essink et al., 2010). Hence, seepage water originating from greater depths, which results in higher concentrations of Cl. This increasing Cl concentration is expected to surpass the maximum threshold of 700 mg L^{-1} set by the Water Framework Directive (Kaderrichtlijn Water, KRW) for the traditional water management practices in the Haarlemmermeer polder.

The focus of this study lies on the agricultural growing season, which spans from April to October. This period experiences the highest demand for freshwater inlet, while its availability is at its lowest, amplifying salinity-related challenges to a maximum extent.

2. Theory

This section provides a comprehensive understanding of the geohydrological and historical context of the Haarlemmermeer polder, as well as a description of the traditional management and the VDS management. The geological evolution of the Haarlemmermeer, the historical development of the polder, and the water balance that influences its hydrological dynamics described.

2.1. Geology: paleo-geographical development

At the end of the Pleistocene (13000 B.C.) the sea level of the North Sea was -45m NAP, making the Haarlemmermeer covered by Pleistocene sands and a braided river system. Sea level rise during the Holocene transgression (5500 B.C., Fig. 4a) and subsequent groundwater level rise resulted in peat formation, known as 'Basisveen'. At the time, both shallow groundwater and deep groundwater were fresh water. The river system eroded part of the peat deposits. Further sea level rise resulted in sea intrusion (Fig. 4b). At the eroded parts of the impermeable peat deposits the sea water rapidly intruded the groundwater to great depth. From 2000 B.C. the marine influences decreased due to the development of beach barriers on the current coastline (Fig. 4c). Peat layers formed and the shallow groundwater became fresher due to rainwater infiltration. When people started to build levees and drain the land, this resulted in soil subsidence (1000 B.P.). Peat cutting resulted in the formation of the inland freshwater lake Haarlemmermeer, freshening the shallow groundwater (Fig. 4d). However, during flooding events, the saline water rapidly infiltrated the land through the areas where the peat had eroded away, subsequently sinking to greater depths due to its higher density. The lake was reclaimed into the Haarlemmermeer polder (250 B.P., Fig. 4e). The surface elevation of the Haarlemmermeer polder ranges from 4 – 7 m below mean sea level, the hydraulic head exceeds the surface water level, resulting in a seepage flux. The seepage flux is a mixture of the phreatic groundwater of the freshwater lens and deeper groundwater. The continuous seepage flux and water removal from the polder makes that the seepage water originates from increasing depths and the contribution of the freshwater lens reduces. Subsequently, the seepage becomes more saline. This process, known as internal autonomous salinisation, has detrimental effects on agriculture, ecosystems, and water resources, as high salinity levels can impede plant growth, degrade soil fertility, and compromise the availability of freshwater for human consumption (Oude Essink et al., 2010; James et al., 2013).

The present geohydrology of the Haarlemmermeer polder consists of a semi confining layer formed by a Holocene clay layer with peat deposits, overlying an aquifer of Pleistocene fluvial sands (Van der Meulen et al., 2013). The aquifer of Pleistocene fluvial sands has a transmissivity of 4600 +/- 150 m^2d^{-1} (NHI, n.d.). The upper layer covering the aquifer consists of a heterogeneous Holocene estuarine clays, loamy sands, and peat deposits with widely varying depth. At most of the area, there is a thin (0.05 – 0.10m) layer of compressed peat deposits. The transmissivity of this layer is low due to the considerable hydraulic resistance of the Holocene layer (vertical hydraulic conductivity is 2400 +/- 750 m^2d^{-1}; NHI n.d.). At some places this peat layer has been eroded by the Holocene channel belts and is thus absent in the current geology.

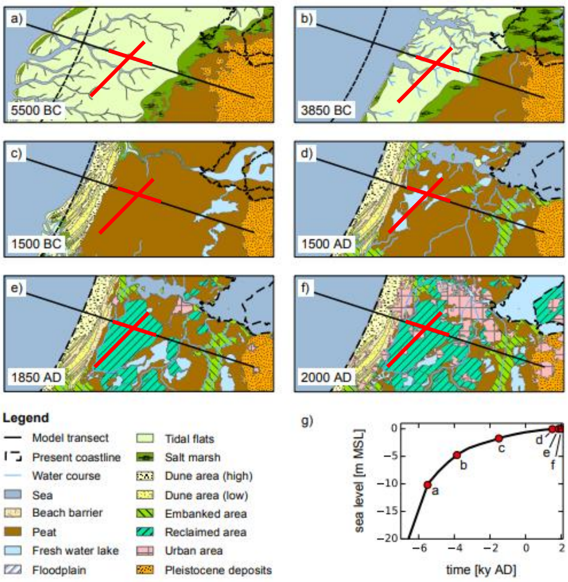

Figure 4. Overview of the Holocene paleo-geographical development (a-f) and sea level rise (g, Van de Plassche, 1982; Delsman, 2014). The red line indicates the location of the Haarlemmermeer polder.

2.2. History of the Haarlemmermeer polder

Following massive storms surges, the decision was made to drain flood prone areas in the Netherlands, creating the deep polder areas. The deep polders in The Netherlands are created for water flood safety as well as to provide agricultural land following the food scarcity resulting from the First World War (Van Baalen, 1993). A polder is an artificially embarked and drained catchment in which excess water continuously needs to be pumped out (Van de Ven, 2003). This thesis focuses on the Haarlemmermeer polder in Noord-Holland. Spanning an area of 180 km^2 this deep polder that was reclaimed from the former lake in 1852 has a present surface elevation between 4 to 7 m below mean sea level (Deltares, 2015). The Haarlemmermeer polder accommodates approximately 150,000 inhabitants and locates Schiphol airport, making the area of great value (ibid.). Around 75% of the polder is utilized for agricultural purposes which consists of approximately 300 agricultural businesses, with an economic scale exceeding €100 million (ibid.).

2.3. Water Balance

The long-term mean annual precipitation and the mean annual potential evapotranspiration are 840 mm and 590 mm, respectively (KNMI, n.d.). The total mean annual volume of water that is pumped out of the polder around 727 mm. This substantial difference between precipitation and the polder water discharge confirms the large contribution of seepage and admitted fresh water from the boezem to the polder discharge. The freshwater input at Gouda in a regular summer is 40 – 60 Mm^3 (Rijnland, 2008). This freshwater is needed to maintain the water levels, improve the water quality, and reduce the water salinity (Oude Essink et al., 2010).

2.4. Types of groundwater seepage

Adopted from Louw et al. (2010), three types of groundwater seepage in a deep polder with different flux and salt concentration are distinguished: (1) diffuse, background seepage through the Holocene semi confining layer, (2) preferential seepage through permeable, sandy paleochannel belts in the Holocene semi confining layer, and (3) intense preferential seepage via boils (Fig. 5). The three types differ in flux and salinity.

Diffuse background seepage is the upward flow from the Pleistocene aquifer layer through the Holocene semi confining layer to the surface water (Fig. 5). This layer consists of clay and peat, making the permeability, and thus the seepage flux, low. The Cl^- concentration is estimated around 100 mg L^{-1} according to Louw et al. (2010). During the Holocene transgression, steams and tidal channels have eroded the peat and overlying loam of the semi confining Holocene layer (Hijman et al., 2009). The presence of permeable, sandy paleochannel belts in the Holocene semi confining layer, and thus the absence of the resistant peat and clay, allow for a stronger preferential upwelling flux in these areas. Additionally, the Cl concentration of preferential seepage is higher, approximately 550 mg L^{-1} according to Louw et al. (2010). The diffuse seepage and preferential seepage are a mixture of the deeper groundwater and the freshwater lens (Fig. 6). This study combines the diffuse seepage and preferential seepage to

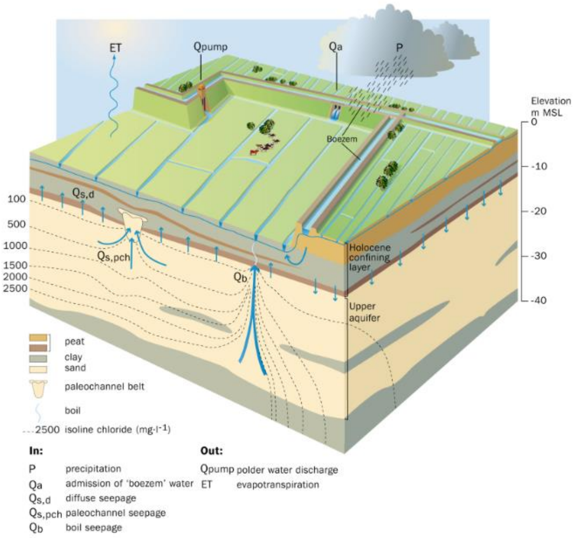

Figure 5. Geohydrology and water and salt fluxes in a lowland polder catchment area. Upward groundwater seepage from the upper aquifer can be divided into three different types according to De Louw et al. (2010): diffuse-, paleochannel-, and boil seepage. (From De Louw et al., 2011)

"phreatic seepage", because of the large heterogeneity in the area.

The discharge of seepage water through boils, also known as the boil discharge seepage, is considered the primary source of salt in surface waters within deep polders (ibid.). Boils refer to small vents in the semi-confining Holocene layer, through which water is rapidly discharged, causing the upconing of deeper and more saline groundwater. It is important to note that there is no mixing with the freshwater lens in this process. The Haarlemmermeer polder is estimated to have approximately 200 boils, with flux rates reaching up to 100 m^3 per day and variable salinities of up to 5000 g L^{-1} Cl^- (De Louw et al., 2010; Goudriaan et al., 2011). The deep groundwater infiltrated the aquifer during the marine transgression period of 8 – 3.8 kyr B.P. when the area was flooded by the sea (Post & Kooi, 2003; Section 2.1). The seepage water exfiltrating through boils directly enters the surface water. This water exhibits high salinity levels and is deeply anoxic (Delsman et al., 2013). The presence of paleochannel belts and reduced Holocene layer depth between ditches are linked to a significantly increased risk of boil development (De Louw et al., 2010).

Autonomous salinization refers to the process whereby the reduction of the freshwater lens, caused by extensive water extraction, results in water subtraction from greater depth (Fig. 6). As a consequence, the phreatic seepage becomes progressively more saline. However, the boil seepage, originating from greater depths, experiences minimal influence from the autonomous salinization process.

2.5. Water salinity in agricultural perspective

The water quality and salinity requirements of farmers vary depending on the cultivated crops. According to Nelis van der Bok, advisor at Delphy, most crops have a maximum tolerance for chloride of 600 milligrams L^{-1} and 0.48 to 0.96 grams of salt L^{-1}. Grains and sugar beets can tolerate higher chloride levels of up to 1,200 milligrams L^{-1} (De Olde, 2022).

To regulate salinity levels, Rijnland imposes a salinity threshold of 1.5 kilograms per cubic meter (equivalent to 1,500 milligrams L^{-1}) (Aydin et al., 2022). Regarding chloride concentrations, the KWR sets a threshold of 700 milligrams L^{-1}. Flushing dilutes the Cl concentrations at the catchment outlet from 3 grams L^{-1} to around 1.5 grams L^{-1}, as mentioned in the initial input, still significantly exceeds the concentration target of 0.6 grams L^{-1} set by Rijnland in 2008, according to Aydin et al. (2022).

The concentration of salt in the drainage poses an issue for irrigated agriculture. Increased salinity in the root zone elevates the osmotic pressure in the soil solution, imposing greater energy demand on plants to extract soil water required for evapotranspiration (Tanji & Kielen, 2002). When salinity surpasses a certain threshold, plant roots become unable to generate sufficient force to extract water from the soil, leading to water stress and reduced crop yields. The tolerance of plants to salinity varies among different crop types. Table 1 provides an overview of crops cultivated in the Haarlemmermeer polder and their corresponding salinity tolerance levels (Tanji & Kielen, 2002).

Table 1. Specific limits for different crops cultivated in the Haarlemmermeer polder (Tanji & Kielen, 2002).

	Limit (mg Cl L^{-1})
Potatoes	<500
Wheat	<1,200
Sugar beets	<1,900
Onions	<1,050

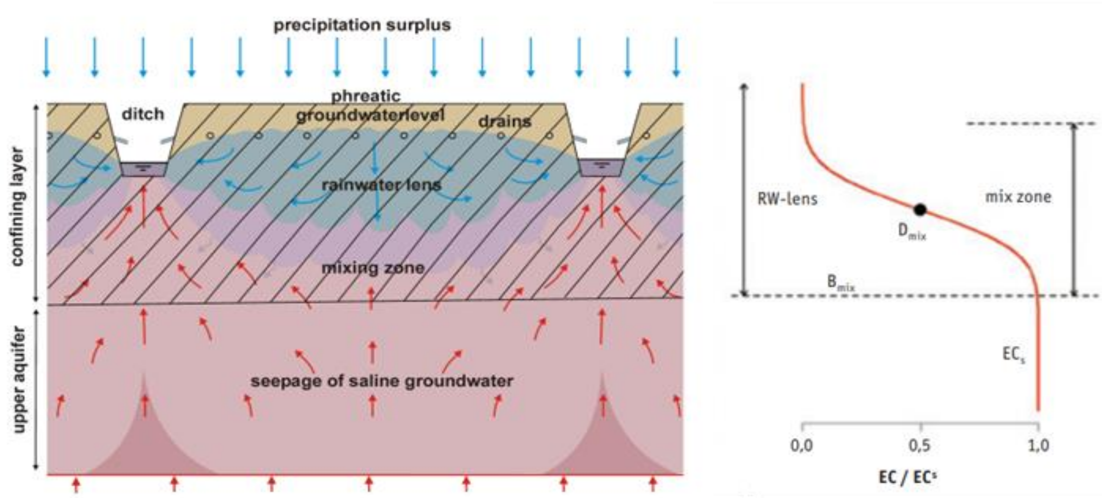

Figure 6. Left: The water bodies in a deep polder. At depth there is an upward flow of saline water and on top there is a freshwater lens with remnant water from the former lake added by rainwater. In between these is the mixing zone, which largely defines the salinity of the diffuse seepage (De Lauw et al., 2011). Right: The associated salinity of the water. At depth, the water is most saline because the density of water increases with salinity, this decreases in the mixing zone due to the freshwater lens, and becomes fresher at the surface due to rainwater contribution (De Louw et al., 2015)

In the Haarlemmermeer polder, the drainage system effectively establishes an upper threshold for the groundwater level, ensuring a maximum elevation. This enables efficient drainage during periods of intense precipitation and acts as a safeguard against root damage due to saline seepage. However, between the drains, the groundwater level can vary. In the Haarlemmermeer polder the groundwater level bulges between the drains due to the permanent seepage flux. As a result, to prevent bulging of the groundwater reaching the rootzone, the horizontal distance between the drains is very low in the Haarlemmermeer polder compared to other areas (Nota Peilbesluit; Van den Eertwegh, 2002).

Additionally, the iron in the seepage oxidates in the drains, which results in clogging of the drainage system (Fig. 7). In normal situations without seepage, the drainage systems work for about 20 years, while in the Haarlemmermeer fields they do not last for ten years at max (D. Molenaar, personal communications, February 23, 2023).

Figure 7. Iron oxidates in the drains, resulting in clogging of the drains. (Landgoed Klein Vennep, February 23, 2023).

2.6. Traditional water management

To maintain the surface water levels, the Haarlemmermeer polder is drained by ditches and irrigation systems. In wet periods, water is pumped out by pumping stations (gemalen) to the higher lying canal, the Hoofdvaart. Two pumping stations at each and of the Hoofdvaart pump the water surplus to the Ringvaart, which surrounds the Haarlemmermeer polder and forms the border for the Haarlemmermeer municipality. The pumping station in the south is Gemaal Leeghwater and the pumping station in the north, which conveys the water surplus to the sea via the Noordzeekanaal, is Gemaal Lijnden. The water inlet at gemaal Leeghwater is controlled by the salinity of the water in the Hoofdvaart; from April to October water is the water inlet at Leeghwater starts when the salinity of the discharge water at pumping station Lijnden exceeds the 600 mg CL L^{-1} (Deltares, 2015). In summer water is brought in from the Hollandse IJssel, which is fed by the Rhine. In extremely dry periods, when salinisation occurs in the Hollandse IJssel, the Klimaatbestendige Water Aanvoervoorziening (KWA, Climate-proof Water Supply Facility) comes into effect. This provides alternative water supply routes.

The Haarlemmermeer polder is divided into 63 different local drainage catchments, each of which has a different minimum and maximum surface water level. The water inlet is admission from the boezem via 74 inlet points. The vast majority of water (approximately 80%) is introduced through small, unmeasured inlets (Deltares, 2015). However, for the Lissertocht catchment, the water admission is measured.

2.7. VDS water management

The VDS water management comprises a flexible surface water level between margins for which the upper margin is the boezem level, making pumping stations and flushing redundant. VDS argues a “natural, free fluctuation within a bandwidth”, which means that a flexible water level (20-30 cm) is maintained between the current summer water level in the drainage catchment and the water level in the polder basin (Fig. 8). The upper margin of the VDS water level corresponds with the water level of the polderboezem (winter NAP -6,02m, summer NAP -5,87m). The minimum water level throughout the year is set to the former summer water level and thus depending on each local drainage catchment. For the Lissetocht catchment this is -6.42m. The maximum water level equals the boezem level, which is -5.87mNAP in summer and -6.02mNAP in winter. The open connection when the maximum water level is reached, e.g., the boezem level is reached and the weirs fall, there is gravitational flow to the boezem. There is no forced inlet water to accommodate flushing; water is only admitted to the polder when the water level falls below the minimum threshold.

The higher water level reduces the difference in hydraulic head with the aquifer and consequently decreases the seepage flux compared to the traditional water management. The criteria for implementing VDS encompass the following factors: a minimum depth of the unsaturated zone of >0.9 meters based on the maximum water level, a connection to either the boezem or an area that already has VDS in place, and a contiguous area of at least 50 Ha.

VDS is anticipated to enhance water quality and decrease salinity by retaining good quality rainwater and reducing the influx of saline and nutrient-rich seepage due to the overpressure from higher water levels. Moreover, eliminating redundant pumping stations saves time and energy, resulting in a more resilient water system. Additionally, the open connection to the boezem when boezem level is reached allowing for gravitational flow fully avoids water logging risks.

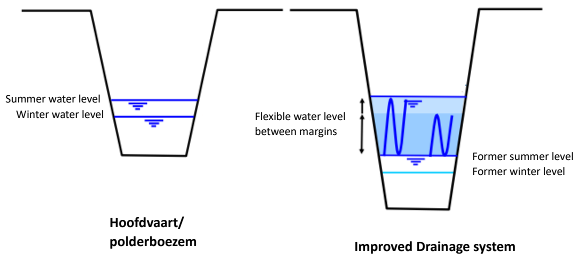

Figure 8. Settings of the Improved Drainage System (VDS).

3. Method

The implementation of VDS in the Haarlemmermeer polder was modeled to determine the effects in agricultural areas. A research framework was created to provide an overview (Fig. 9). The framework illustrates how several scenarios are used as input in a water balance model. The scenarios were chosen to best to answer the research questions. In the following paragraphs, the individual parts of the research design are discussed.

3.1. Research design

SQ1; *Which agricultural areas in the Haarlemmermeer are suitable for the application of VDS, considering the minimal depth of the unsaturated zone required for agriculture?* is addressed by employing GIS

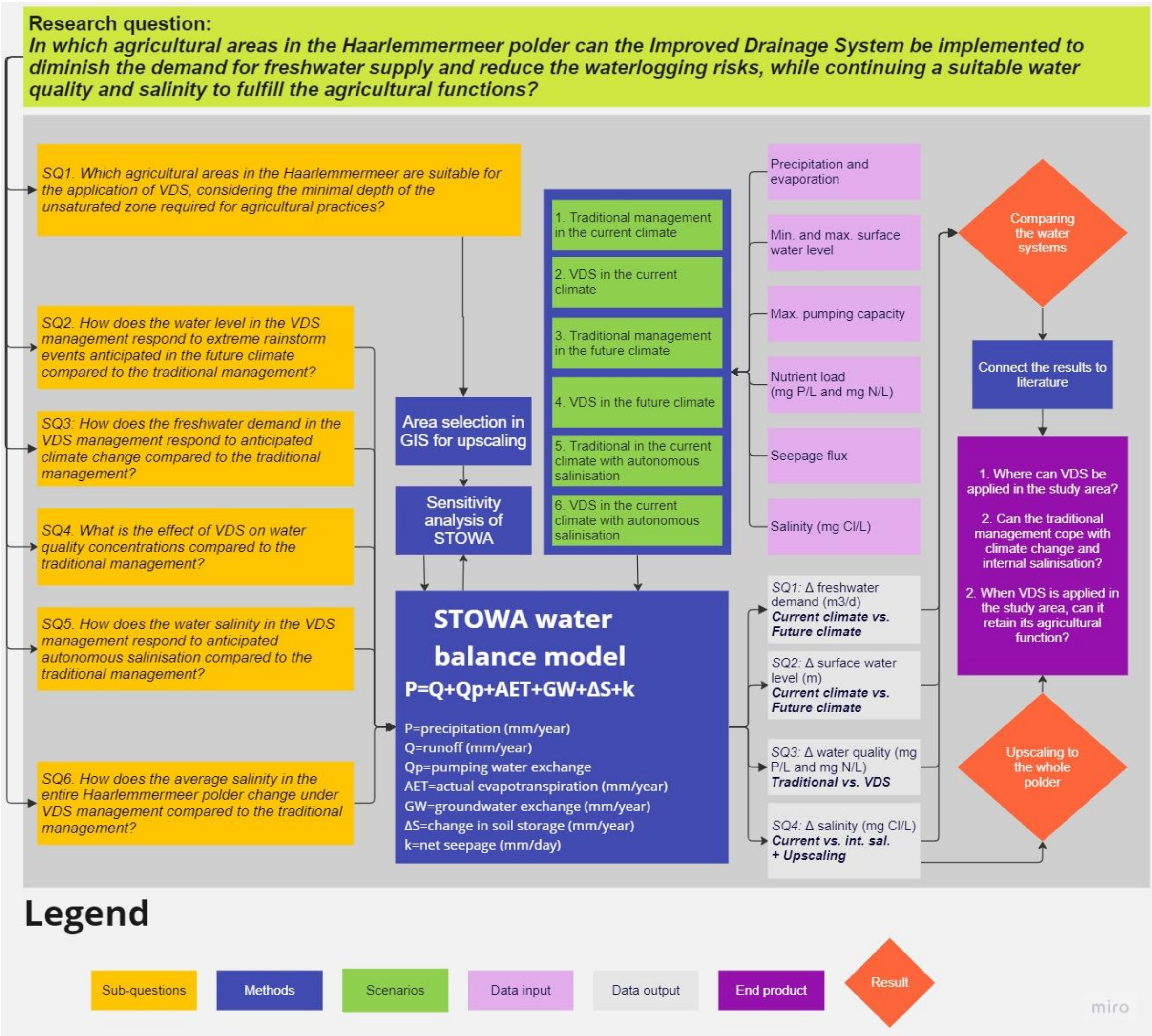

Figure 9 Research design. The sub-questions are answered by the STOWA model, Fig. 10 further elaborates the model. The sensitivity analysis determines which parameters exert most influence on model results and how sensitive the model is to inferences of the input parameters. The outcome of the sensitivity analysis provides the selected properties to represent the area (e.g., the water level fluctuation, the dept of the Holocene layer which is related to the seepage flux, and the water salinity of the seepage). The depth of the unsaturated zone is assumed to be constant for the area selection, GIS is used to define the suitable area for VDS in the Haarlemmermeer polder. The input values for the four scenarios are indicated in pink and the output in grey. The output of the model, related to the sub-questions, are changes in freshwater demand, surface water level, water quality, and salinity for the scenarios. This output is compared and connected to literature. The product answers the research question.

(Geographic Information System) to establish the minimum depth of the unsaturated zone when the VDS is implemented. This is explained in section 3.5. The remaining RQ’s are answered by conducting the following, underlying steps comprising the scenarios displayed in the Research design (Fig. 9, green boxes):

1. A water balance model of the traditional management was created given a set of input data based on the Lissertocht catchment in the current climate. The output shows the freshwater demand, water level, water quality (N and P concentrations), and water salinity (Cl concentration).

2. This water balance model was altered to represent the VDS management in the current climate. The temporal changes in the P and N concentrations were compared for the traditional management (scenario 1) and the VDS management (scenario 2) to deduct the changes in water quality (SQ4).

3+4. The traditional water system (scenario 1) and VDS water system (scenario 2) were modelled for a future climate scenario. The water level for the traditional management in the current climate (scenario 1) was compared to that in the future climate (scenario 3) to deduct if the traditional water system can cope with climate change or that measures are needed to prevent waterlogging risk (answering SQ2). Additionally, the changes in the freshwater discharge for inlet water were compared to find the changes in freshwater requirement in a future climate (SQ3).

5+6 The traditional water system (scenario 1) and VDS water system (scenario 2) in the current climate were modelled for a salinisation scenario. The temporal distribution of the Cl is inspected to deduct if the traditional water system can continue to provide suitable salinity for irrigation purposes (<700 mg Cl L^{-1}, KRW), and how VDS responds to salinisation (SQ5).

To answer SQ6. and to assess the implications of a larger spatial scale, the effect of VDS on the water salinity compared to the traditional management for the whole Haarlemmermeer polder was identified. This was accomplished by an area selection in GIS to divide the entire polder into representative sub-areas. The salinity is then modeled for the Lissertocht catchment area with the input values representing the sub-areas. The salinity data obtained from these specific areas was then extrapolated to estimate the overall salinity of the entire Haarlemmermeer polder. This extrapolation enabled to make assumptions regarding the potential effects of upscaling VDS to the entire polder in comparison to the traditional management (main RQ). This method is further explained in section 3.6.

During this process the selected model was tested for suitability and flexibility by executing a sensitivity analysis (Section 3.4). This selection implies that the properties and measurements of this specific catchment are utilized to model the different scenarios mentioned above. It is important to note that there is limited data available for the other local drainage catchments within the Haarlemmermeer polder. Therefore, variations in water depth and other specific characteristics among the different catchments have not been considered in the model. However, measurements, such as the forced water inlet, have been conducted in the Lissertocht catchment. Furthermore, for the purpose of this effect study, an area of $100m^2$ is chosen as a representative unit. This allows for a more logical assessment of the effects within this defined area, facilitating the estimation of broader impacts and simplifying the upscaling process to the entire Haarlemmermeer polder.

3.2. Area selection

GIS was employed to select the study area. Subsequently, a sensitivity analysis in STOWA was conducted to identify parameters that are sensitive to change. For these sensitive parameters, input values were estimated using

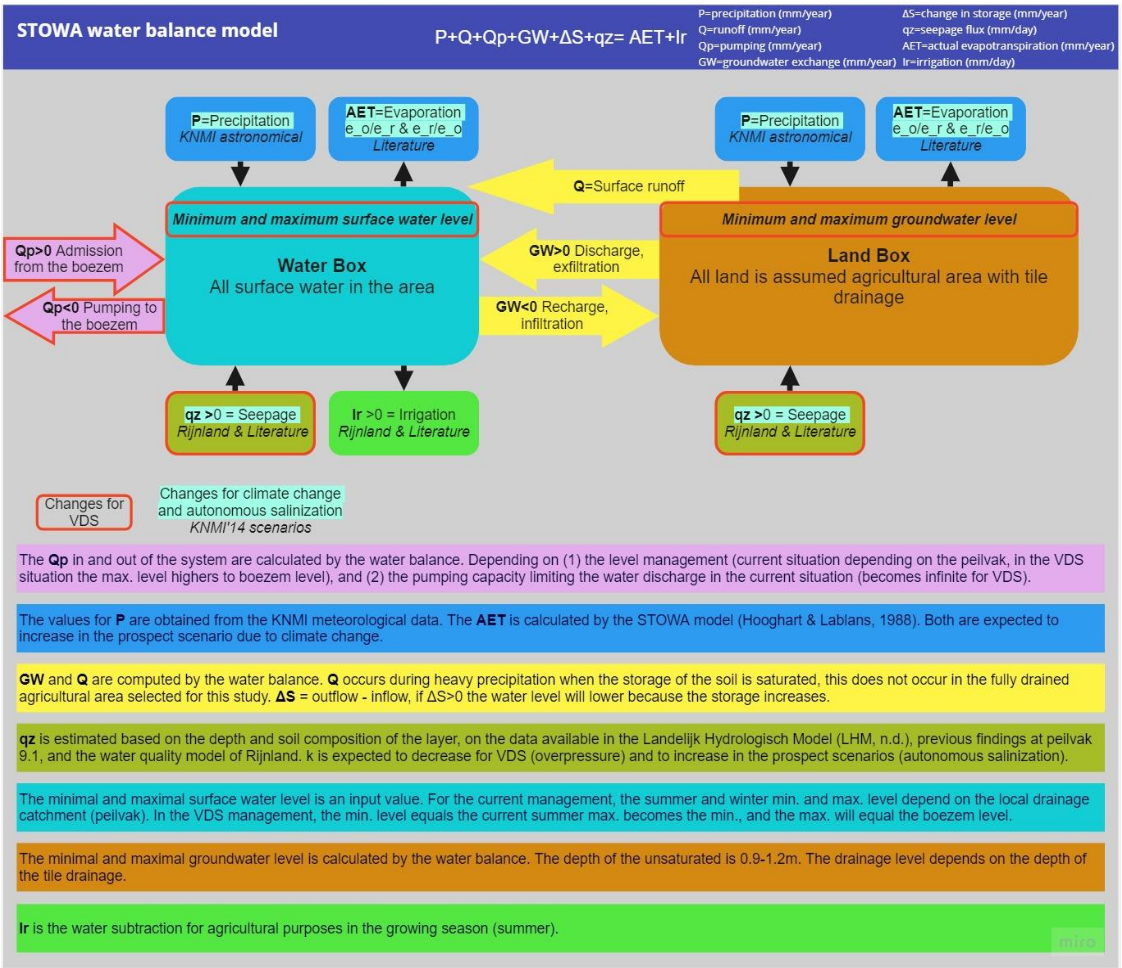

Figure 10. Schematical display of the data ingoing and outgoing water fluxes considered in STOWA. The Water Box and Land box each consist of homogeneous properties to represent the water behavior. The parameters changed by the implementation of VDS are outlined in red. The parameters effected by climate change and autonomous salinisation are highlighted in blue. The cursive text indicates the data source. The textboxes under the water balance describe the input values, changes for implementation of VDS, and the response to the future situation.

information from both GIS data and relevant literature.

The method for area selection was originally proposed and implemented by Boas Prins, a trainee at Rijnland. It was replicated in this study to enhance the understanding of the underlying theory and facilitate the learning process.

First, all agricultural parcels were selected in for the Haarlemmermeer. Subsequently, parcels with surface water levels that were already at or above the boezem level were eliminated. Then, the parcels suitable for implementing VDS were identified based on the depth of the unsaturated zone when connected to the boezem. The depth of the zone, which corresponds to the drainage system depth, should be a minimum of 0.9m as specified in the Nota Peilbesluite, and preferably greater than 1.2m to accommodate agricultural activities involving heavy machinery.

The 'peilenkaart_Haarlemmermeer' from the Rijnland geodatabase and the 'AHN4_zwaar' (AHN4 - Download Kaartbladen, n.d.) elevation data were utilized. A fixed water level of -5.87m NAP was assigned to each parcel. This water level was uniformly applied across all parcels. Subsequently, the difference between the median height of each parcel and the assigned 'peil_boezem' value was calculated to determine the drainage level, representing the depth of the unsaturated zone. The results were classified into three categories: red indicating unsuitable parcels (drainage depth <0.9m), yellow indicating moderately suitable parcels (drainage depth 0.9m – 1.2m), and green indicating suitable parcels (drainage depth >1.2m).

3.3. Model

The water balance model utilized in this study is developed by "Stichting Toegepast Onderzoek Waterbeheer" (STOWA), a Dutch knowledge center for water boards and provinces, in collaboration with Witteveen & Bos and Waternet (Tanis, Schep, & van Dijk, 2018). The STOWA model is based on the principles of the Water Balance and Darcy's Law (Darcy, 1856). As shown in Figure 10, the STOWA model divides the study area into two simplified boxes, each characterized by homogeneous properties to represent the water behavior in specific areas. One box comprises all water in the area (Water Box), and the other box represents the agricultural land (Land Box). Figure 10 provides a visual representation of the STOWA model, where the input values influenced by the implementation of VDS are outlined in red, and the parameters affected by climate change and autonomous salinisation are highlighted in blue. The cursive text indicates the source of the data used in the model. The model operates at a daily resolution, using incoming precipitation and evaporation data as input. Seepage fluxes in summer and winter, as well as maximum pumping capacity, are also considered as daily input values, along with other fluxes. In contrast to spatially distributed modeling, this approach employs point-based input values, and consequently provides information specific to that particular location.

The minimum and maximum water levels for the water box are defined, as well as the depth of the riverbed. To maintain the desired water levels, certain actions are taken. When the water level falls below the defined minimum value, water is admitted replenish and maintain the minimum water level. Conversely, if the water level surpasses the maximum threshold, the excess water is pumped out to ensure the maximum water level is maintained. Additionally, a fixed freshwater input can be incorporated to enforce freshwater input, representing the flushing in the traditional management.

The ingoing water fluxes include precipitation (input, KNMI meteorological data), seepage (input, estimated), groundwater discharge (computed by the Water Balance), surface runoff (computed by the Water Balance), and water admission from the boezem (computed by the Water Balance).

The outgoing water fluxes include the evaporation (input, KNMI meteorological data), groundwater infiltration (computed by the Water Balance), and pumping to the boezem (computed by the Water Balance). The water consumption for irrigation is incorporated into the model by extracting the irrigation water from the water box during the summer months. Since the STOWA model does not include a specific input value for irrigation, this irrigation amount is accounted for by subtracting it from the water box through the "downward seepage" input parameter.

The difference between the ingoing and outgoing fluxes results in the change of storage (computed by the Water Balance). When the outflow exceeds the inflow, this results in a positive storage and the water level decreases. When the inflow exceeds the outflow, this results in a negative storage and the water level rises.

The pumping (Qp) manages the water exchange between the boezem and the water box. Qp is calculated by the water balance and depends on the level management and the pumping capacity limiting the water discharge. The precipitation (P) and actual evapotranspiration (AET) data are input data.

Groundwater exchange (GW) and surface runoff (Q) are computed by the water balance. Runoff occurs during heavy precipitation when the storage of the soil is saturated. The change in storage (ΔS) is the outflow minus the inflow. The seepage flux (k) is variable in the area.

To provide insight in the effects on the water balance, the current and future anticipated scenarios were quantified based on a set of parameters that describe the water system in the Lissertocht catchment. The output of the STOWA model includes inflow and outflow of the water box, the surface water level, fraction distribution of the water box, and the P and Cl concentrations. N concentrations were added to the formulas. The used input data was sampled at different locations in the study area (Appendix A, cp. Fig. 2; Delsman et al., 2013). These extremes were exaggerated and used as input in the sensitivity analysis (Appendix F).

The time frame of the analysis equals the hydrological years 1997 to 2021 as it stretches from 01.01.1996 to 31.12.2021. For the future climate scenario, the time frame equals the hydrological years 1997 to 2001 as it stretches from 01.01.1996 to 31.12.2001 conform the data availability of the WH2085 scenario. The measured water level was used to validate the model.

3.4. Sensitivity analysis

Many parameters were known from previous research; however, some parameters are unknown. Additionally, there is significant spatial and temporal variation, which leads to uncertainty of the known input data based on measurements. Beven (1989) argues that the fundamental problems in the application of physically based models for practical prediction in hydrology result from limitations of the model due to the properties that cannot be measured and the effective model parameters that describe these properties. The large variety and insecurity of the input parameters have a consequence on the output depending on the parameters' sensitivity. Therefore, a sensitivity analysis of the STOWA model is used to determine parameters sensitivity to change. The sensitivity to changes of each parameter and the uncertainty of each parameter determines the reliability of this effect study. The model research was therefore performed in phases. In each step, the reference situation with the traditional management and the situation with VDS were considered and compared. Based on the results following from the parameter extremes, a qualitative assessment of the output was conducted to determine if the parameter is sensitive to change (yes/no).

The sensitivity analysis identifies the model parameters which exert most influence on model results in STOWA. The sensitivity analysis is conducted to determine: (1) which parameters are insignificant and can be assumed constant in the model, (2) which parameters are most influential to the output variability, and (3) what consequence results from changing a given input parameter (Hamby, 1994). Additionally, it is important to note that there is a connection between the qualitative assessment of the output and the uncertainties associated with the model parameters input; the measures used for the input values have great temporal and regional variabilities amplifying the uncertainty for parameters sensitive to change.

The sensitivity analysis is performed over a catchment area of 100m^2 with 5% water to simplify the calculations and amplify the effects on the water system. The whole area is drained agricultural soil. The sensitivity analysis and area selection excluded the depth of the unsaturated zone. The depth of the unsaturated zone is closely linked to the depth of the drainage system and must be a minimum of 0.9-1.2 meters to support agricultural activities. The assumption was made that the total area examined in the STOWA model meets the criteria for VDS implementation, including minimum depth of >0.9m, the connection to the boezem, and the minimal contiguous area of 50 Ha.

In the first step of the sensitivity analysis, the element concentrations were set to zero to indicate the effect of different properties to the fluxes and water quantity. Then, the transition from a water system fed by freshwater inlet to a water system characterised by seepage was constructed to indicate the sensitivity of the elements P, N, and Cl. The evaluation of the output results forms a qualitative assessment of the sensitivity to change of the parameter concerned. The outcome of the sensitivity analysis provides the selected properties to represent the area.

3.5. Input values

The scenario analyses are performed over a catchment area of 100m^2 with 2% water, the surface water area was obtained by GIS. The surface area has been selected as such as it enables upscaling to other areas by maintaining the proper ratios. The whole area is assumed to be drained agricultural soil, as it concerns an impact study of the agricultural land. For the current situation, the initial water level is -6.40mNAP and the depth of the streambed is -7.0mNAP, resulting in an average water depth of 0.60mNAP. For the VDS situation, the initial water level is -6.20mNAP and the depth of the streambed remains -7.0mNAP, resulting in an average water depth of 0.80mNAP.

The precipitation and actual evapotranspiration data for the current climate is provided by the KNMI meteorological data (KNMI - Daggegevens Van Het Weer in Nederland, n.d., measuring station 240; Schiphol.). The model displaying the future climate was created using the precipitation and actual evapotranspiration data of the KNMI'14 WH2085 scenario (KNMI'14-klimaatscenario's, n.d., measuring station 240; Schiphol.). The WH2085 scenario expresses the most extreme projections for the year 2085, characterized by the highest frequency and intensity of extreme weather events. The WH2085 scenario is projected over existing precipitation and evaporation data from 1996 to 2002. For a fair comparison, the reference data over which the WH2085 is projected is used instead of the data used in previous mentioned steps.

The phreatic seepage is estimated by the hydraulic resistance of the top layer, by using the Landelijk Hydrologisch Model (LHM, Delta Data Viewer). The phreatic seepage flux is estimated to be 0.5 mm d^{-1} in the Lissertoch catchment based on the seepage LHM models provided by the NHI (Appendix B1), as well as measurements conducted by Delsman et al. (2013) as reported in the literature. The salinity of the phreatic seepage is estimated 550 mg Cl L^{-1} relying on measurements conducted by Delsman et al. (2013) and the Cl measured directly below the confining layer (NHI; (Appendix B2). The boil flux is adopted from Deltares (2013) and is estimated to be 0.3 mm d^{-1} with a salinity of 4500 mg Cl L^{-1}. This represents a considerably large flux and high salinity. However, EGV-routing measurements of the salinity in the Lissertocht exceeds the 1000 mg Cl L^{-1}, supporting the estimations (Appendix B3). The autonomous salinisation scenario is represented in an increase in the Cl concentration of the phreatic seepage, which is reflected in the salinity of the drainage water. The boil seepage is assumed to remain unchanged, as the boil seepage originates from larger depth and does not mix with the freshwater lens. The internal salinisation is estimated to increase the Cl concentration of the phreatic seepage to 2200 mg Cl L^{-1} based on the projection of the freshwater-saline water interface by Delsman et al., 2014 (Appendix B4).

The water subtraction for irrigation is incorporated into the model by extracting 8 mm d^{-1} from the water box during the summer months. This estimation is based on expert knowledge from Rijnland. The forced inlet represents the flushing mechanism in the traditional water management. In the summer months, from the first of April until the first of October, the forced inlet is set at 0.83 mm d^{-1} in (Delsman et al., 2013; Deltares, 2015). This value, which is essential for simulating the traditional management scenarios, is derived from previous studies that conducted measurements specifically in the Lissertocht catchment. The nutrient load presented in Table 2, is based on the measurements by Delsman et al., 2013 (Appendix A). The nutrient load and salinity of the drainage water is computed based on the relative difference between the contributions of rainwater and phreatic seepage water within the composition of the drainage water (Appendix D1). Boils excluded from input for the drainage water because these are mostly directly under the ditch and not on land, thus thereby not influencing the drainage water.

Table 2. Input values STOWA model. The drainage water concentrations are a formula added in Excel for the fractional distribution of seepage and precipitation.

	Flux	Cl (mgL^{-1})	PO_4 (mgL^{-1})	NO_3 (mgL^{-1})
Precipitation	Input	6.1	0.12	3.1
Phreatic seepage	Input	550	13.6	2.1
Drainage water	Model calc.	Fraction	Fraction	Fraction
Boil seepage	Input	4500	2.52	1.1
Inlet water	Model calc.+ input flushing	136	0.12	8.1

3.6. Upscaling to the whole polder

The upscaling process to the entire Haarlemmermeer area was conducted based on the area selection and scenario analysis. The scenario analysis yielded the salinity of the water box for both the traditional management and VDS management in the current climate. The area selection identified the specific areas within the polder where VDS could be implemented. These VDS-applicable areas were further divided into comparable sections, each assigned a fitting Cl concentration. Subsequently, the fraction of each area was multiplied by its corresponding Cl concentration to estimate the overall salinity when considering VDS implementation throughout the entire polder.

A literature study was conducted to identify appropriate ranges for the parameters that are susceptible to change, ensuring they cover at least 80% of the Haarlemmermeer polder area. The partitioning of the agricultural area in the Haarlemmermeer polder into distinct subregions and providing representative input values for the characterization of each subregion allows for upscaling. By delineating these subregions, the aim is to capture the heterogeneity of the study area and account for variations in the relevant input parameters (parameters sensitive to change; Appendix F). The subregional representation of input values enables the subsequent upscaling of the VDS to the whole agricultural area of the Haarlemmermeer polder. The division is bases on the following parameters resulting from the sensitivity analysis: phreatic seepage flux, phreatic seepage salinity, boil seepage flux, and the boil seepage salinity.

The area selection provides a distinction into three subregions based on the elevation head (Fig. 11) and the resistance of the Holocene layer, which is greatly influenced by the presence of peat (Fig. 12). High groundwater levels at the edges of the area correspond to high seepage fluxes due to the higher water levels (as mentioned before; the surface water level is assumed to equal the groundwater level) and thus significant difference in hydraulic head difference ($\Delta\varphi = h_{i2} - h_{i1}$). The border area represents an average GW level, resulting in a low seepage flux. In the central area, the GW levels are relatively low, resulting in a lower seepage flux. These variations in GW levels and corresponding seepage flux are taken into consideration when selecting the specific areas within the polder for further analysis and evaluation.

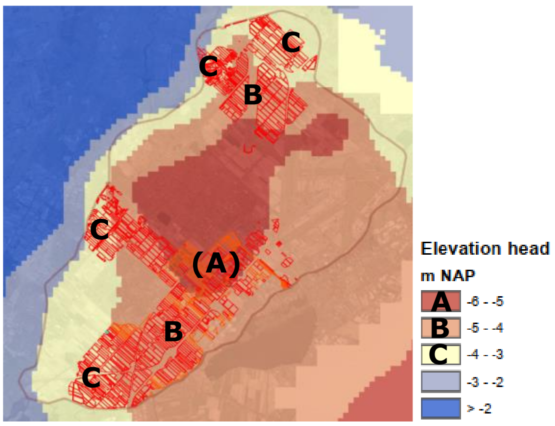

Figure 11. Elevation head (NHI) ranging from -3 to -6mNAP in the Haarlemmermeer polder. The marks indicate the area deviation corresponding with Table 4; A represents an area with a low phreatic seepage flux due to the smaller head difference at the center, B represents an area with a moderate seepage flux, and C denotes an area with a low seepage flux. Note that the brackets around "A" in the center due to the assumption of a higher seepage flux in this area. This assumption is based on the soil composition, resulting in a lower resistance and thus a potentially higher seepage flux.

The seepage flux was estimated using Darcy's Law. For traditional management in area B, the Transition zone, the phreatic seepage flux was calculated as follows:

$$qz = \frac{\Delta\varphi}{c} \quad \rightarrow \quad 5.0 * 10^{-4} = \frac{-4 - -6.57}{5140}$$

The phreatic seepage flux depends on the head difference between the phreatic groundwater and the piezometric levels in the aquifer, as well as the vertical hydraulic resistance of the Holocene aquitard. Table 3 presents the input values for the subregions. There is a wide range, however, the range from 0.25 – 0.75 mm d^{-1} day covers over 80% of the polder (Appendix C3).

Table 3. Phreatic seepage flux for area A, B, and C.

	Diffuse seepage (mm d^{-1}) Traditional Winter	**Diffuse seepage (mm d^{-1}) Traditional Summer**	**Diffuse seepage (mm d^{-1}) VDS Winter**	**Diffuse seepage (mm d^{-1}) VDS Summer**
	-6.57m NAP	*-6.42m NAP*	*-6.22 NAP*	*-6.145 NAP*
A Centre (-5.3)	0.25	0.22	0.18	0.16
B Transition zone (-4)	0.50	0.47	0.43	0.42
C Edge (-2.7)	0.75	0.72	0.68	0.67

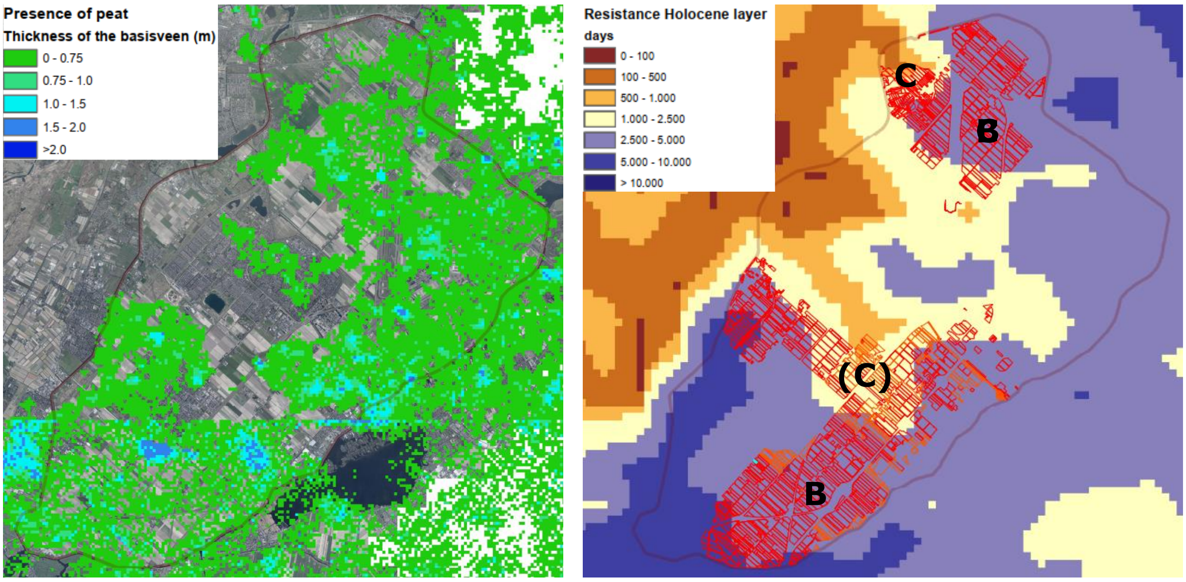

Figure 12. The left figure indicates the presence of the peat (Basisveen; Rijnland GIS database) and corresponding thickness of the layer (ranging from 0 – 2.0m) showing the absence of peat at the locations of the Holocene paleochannel (Appendix C2). The right figure shows the resistance characteristics of the Holocene layer (NHI), revealing that the absence of peat is translated into a comparatively lower resistance at the locations where peat is absent. The marks indicate the area deviation corresponding with Table 4; A represents an area with a low phreatic seepage flux due to the high resistance of the Holocene layer at the specified area, B represents an area with a moderate seepage flux, and C denotes an area with a low seepage flux. Note that the brackets around "C" in the center due to the assumption of a higher seepage flux in this area. This assumption is based on the head difference, resulting in a lower resistance and thus a potentially higher seepage flux.

The salinity of the phreatic seepage flux is indicated by the Cl measurements directly under the semi confining layer. This data is obtained from NHI (Appendix C1). The phreatic seepage is a mixture of the seepage with the freshwater lens. In this study, a chloride concentration of 550 mg Cl L^{-1} is assumed for the phreatic seepage. This value serves as an approximation for the average chloride concentration within the mixture.

Boils are mapped using EC-routing (Appendix C2). However, not all boils are mapped because not all the ditches could accommodate the measuring equipment. In this study two options are taken into account: the boil seepage high flux and the boil seepage low flux. The boil seepage high flux is representative for the Lissertocht catchment and calculated using Darcy's Law (Appendix D2). The boil seepage low flux is the boil seepage flux high flux divided by 4 (Appendix D3) and is representative for the selected area where less boils are expected; the areas without Holocene channel belts and with a higher hydraulic resistance of the Holocene layer.

The boil seepage salinity has been measured by Delsman et al. (2013). The salinity measured ranges from 4534–6590 mg Cl L^{-1} (Appendix A). To make the number of calculations manageable, the salinity of the boil flux is assumed constant at 4500 mg Cl L^{-1}.

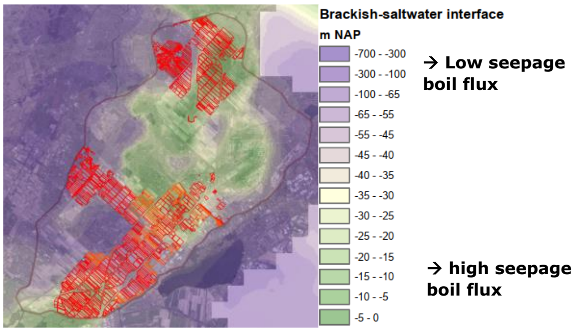

Figure 13. The brackish-saltwater interface resulting from seawater intrusion. The shallower interface corresponds to Fig. 4d. In this study, the presence of seepage boils and their associated seepage flux is assumed to be indicated by the shallower interface for simplicity. The deep brackish-saltwater interface (purple) indicates a low boil seepage flux, and the shallow brackish-saltwater interface (green) indicates a high boil seepage flux.

For traditional management in area A, the Centre, the Cl concentration can be calculated as follows:

For traditional management in B Transition zone: Cl drainage = 0.49 mm d^{-1} seepage and 1.0 mm d^{-1} rainwater → (4.85*Cl seepage + 10*Cl rainwater) / 14.85 = (4.85*550 + 10*6.10) / 14.85 = 183.7 mg Cl L^{-1}

In the STOWA model, the Cl concentration in the drainage water is translated as:

*= (((seepage flux summer + seepage flux winter)/2) * concentration diffuse seepage + (1* concentration precipitation)) / (((seepage flux summer + seepage flux winter)/2) + precipitation)*

The outcomes for the subareas are presented in Appendix D1. The same method has been applied for the P and N concentrations.

Table 4. Seepage fluxes for area A, B, and C.

	Diffuse seepage (mm d^{-1}) Traditional Winter	**Diffuse seepage (mm d^{-1}) Traditional Summer**	**Diffuse seepage (mm d^{-1}) VDS Winter**	**Diffuse seepage (mm d^{-1}) VDS Summer**
	-6.57m NAP	*-6.42m NAP*	*-6.22 NAP*	*-6.145 NAP*
A Centre (-5.3)	0.25	0.22	0.18	0.16
B Transition zone (-4)	0.50	0.47	0.43	0.42
C Edge (-2.7)	0.75	0.72	0.68	0.67

The iterations of the calculations executed are summarized in the matrix shown in Appendix E. Following the GIS analysis of the area and corresponding properties, the following deviation is made for the extrapolation:

25% has no agriculture and thus irrigation is inactive. The seepage flux is estimated category B for 75% and C for 25%. Within these subareas, 50% has high boils and 50% low boils.

75% is agriculture and thus irrigation active. The seepage flux is estimated category A for 10%, category B for 40%, and C for 50%. Within subarea A the boils are low, and in subareas B and C 50% has high boils and 50% low boils.

First, the total Cl concentrations for the areas with and without irrigation are calculated. For the Area not assigned to agriculture, this consists of the output of “no irrigation”: (37.5% * B high) + (37.5% * B low) + (12.5% * C high) + (12.5% * B low).

For the area assigned to agriculture, this consists of the output of “with irrigation”: (10% * A high) + (20 * B high) + (20% * B low) + (25 * C high) + (25% * C low).

Using this deviation, the area not assigned to agriculture and the area assigned to agriculture are combined by ratio to define the Cl concentration in the whole polder for the traditional management and VDS management.

3.7. Analysis

The model results compared visually the effects on the water inlet, water level, nutrient contend, and salinity. These outcomes were linked to the freshwater demand, waterlogging risk, water quality, and water salinity. The differences between the traditional management and the VDS management in the current climate, future climate, and autonomous salinisation scenario were analyzed.

For a fair comparison of the water demand between the traditional management and the VDS management, the yearly cumulative discharge was calculated without forced inlet (flushing) for both management types. The temporal scale was displayed over the years 2015 and 2016, however, the calculations were based on the total time span ranging from 01.01.1996 to 31.12.2021 in the current climate. For the future climate scenario, the time frame stretches from 01.01.1996 to 31.12.2002 conform the data availability of the WH2085 scenario.

4. Results

This section presents the results obtained from the study, which aimed to investigate and analyze various aspects related to the effect of implementing of the VDS water management on the freshwater demand, water logging risks, water quality, and water salinity. This was executed for the traditional water management and the VDS management in current climate scenario, future climate scenario, and a scenario representing autonomous salinisation in the Haarlemmermeer polder. The results provide insights into the water demand, water logging risks, water quality, and water salinity. The analysis conducted in this study involved GIS analysis and STOWA modeling utilizing data from NHI, and measurements provided by previous studies performed by De Louw and Delsman. The results are presented in a structured manner, organized according to the sub-questions, and incorporating the applicable scenarios. These findings contribute to a deeper understanding of the traditional water system, provide new insights in the effect of applying a VDS water system, and asses the future outlook of both systems and thereby shed light on their potential implications and effectiveness. The discussion and interpretation of the results will be provided in the subsequent sections, offering further insights and analysis.

SQ1. *Which agricultural areas in the Haarlemmermeer are suitable for the application of VDS, considering the minimal depth of the unsaturated zone required for agricultural practices?*

The parcels in the Haarlemmermeer polder that presently lie below the boezem level are highlighted in Figure 14. The depth of the unsaturated zone when elevating water levels to their maximum (equivalent to boezem level) is shown (assuming the groundwater level equals the surface water level). Green designates parcels suitable for VDS with a depth >1.2m and yellow indicates moderately suitable parcels with depths ranging from 0.9 to 1.2m. The red shading represents unsuitable parcels with depths <0.9m. In the enlarged view, the focus is on the Lissertocht catchment, revealing a notable proportion of unsuitable parcels within it.

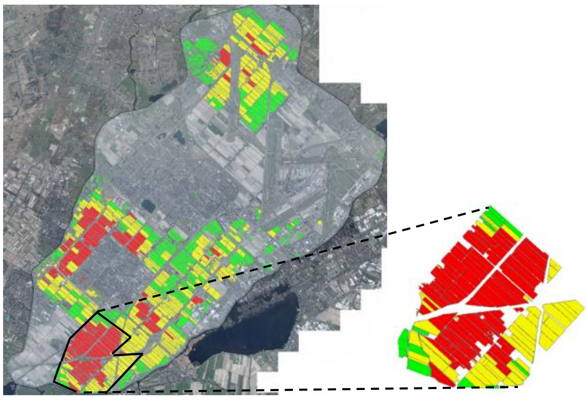

Figure 14. The parcels in the Haarlemmermeer that are currently below boezem level are colored in the figure. The depth of the unsaturated zone when rising the water levels to the maximum (equals boezem level); green indicates parcels suitable for VDS with a depth of >1.2m, yellow indicates moderately suitable parcels 0.9-1.2m, and red indicates unsuitable parcels <0.9m. The enlarged view depicts the Lissertocht catchment, revealing that a substantial portion of it consists of unsuitable parcels.

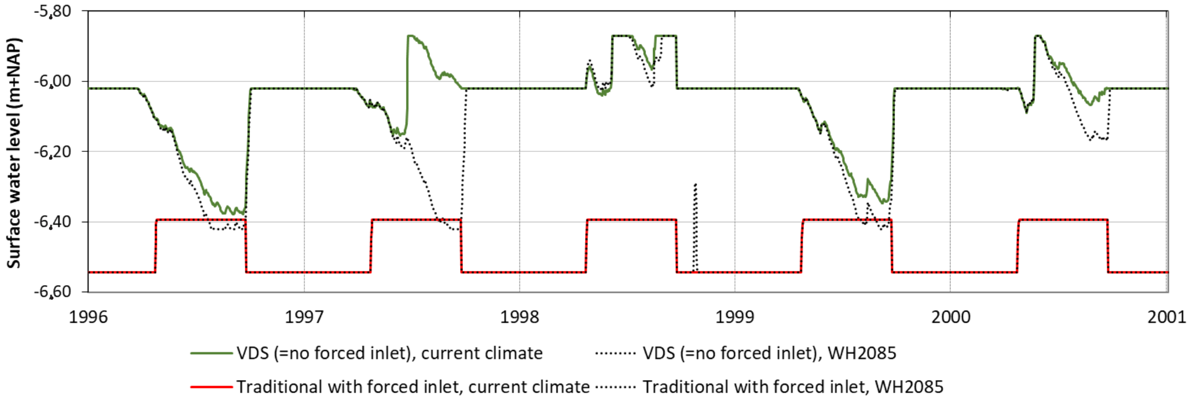

Figure 15. The surface water levels for the traditional management (red) and the VDS management (green) in the current climate and in the future climate scenario WH2085 (dotted lines) projected over the years 1996-2001. Irrigation is active. In the VDS management, there is no exceedance of the set maximum level (-6.02mNAP winter, -5.87mNAP summer). In the traditional management in the current climate the water level continues in the settings. In the future climate scenario WH2085, there is exceedance of the maximum set surface water level in the beginning of the winter season in 1998.

SQ2. *How does the water level in the VDS management respond to extreme rainstorm events anticipated in the future climate compared to the traditional management?*

Waterlogging risks are determined by the occurrence of exceedance of the set maximum water level. Figure 15 depicts the surface water levels for the traditional management and the VDS management with active irrigation and without flushing in the current climate and the WH2085 future projection for the years 1996 to 2001. In the VDS management, the set maximum level is not exceeded in the current climate as for the future climate. On the other hand, in the traditional management, there is an occurrence of surface water level exceedance at the onset of the winter season in 1998. The total rainfall in the summer was considerably higher in the summer 1998 compared to the surrounding years (Table 5). Additionally, the maximal precipitation on a day and the total precipitation in October in the year 1998 were higher in the WH2085 projection compared to the reference climate (Table 6).

Table 5. The total precipitation from May 1 – October 1 (mm) for the reference climate and the WH2085 projection of the future climate over the years 1996-2001

Hydrological year	Total precipitation May 1 – October 1	Total precipitation May 1 – October 1
	Reference climate	**WH2085 projection**
1996	235	177
1997	290	207
1998	464	479
1999	326	323
2000	315	226

Table 6. The maximal precipitation on a day (mm day^{-1}) and the total precipitation (mm month^{-1}) in October 1998 for the reference climate and the WH2085 projection of the future climate in the year 1998.

	Max P on a day in October 1998 (mm d^{-1})	**Total P in October 1998 (mm month^{-1})**
Reference climate	16.8	86.6
WH2085 projection	21.8	100.7

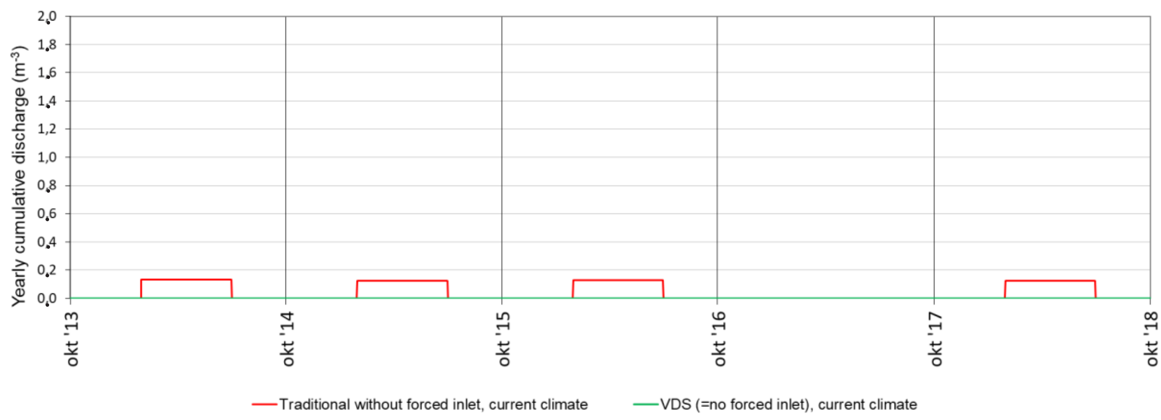

Figure 16. The yearly cumulative discharge of the inlet water (m^3) over the years 2013-2018 in the current climate, the irrigation is inactive. For the traditional management without forced inlet (red) there is a neglectable freshwater inlet needed to reach the minimum water level in summer (<0.2$m^3 year^{-1}$). For the VDS management (green) no freshwater inlet is needed to maintain the minimum water levels.

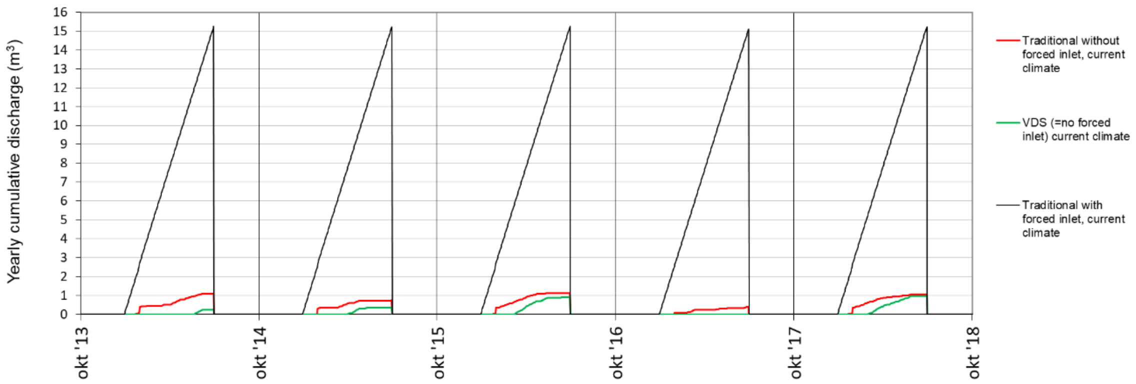

Figure 17. The yearly cumulative discharge of the inlet water (m^3) over the years 2013-2018 in the current climate, the irrigation is active. The traditional management without forced inlet (red) has a higher freshwater inlet needed to reach the minimum water level in summer compared to the VDS management (green). Notable is that no freshwater inlet is required in the summer om 2016 in the VDS management. The traditional management with forced inlet (black) depicts it is constant for each year at 15.24 $m^3 y^{-1}$.

SQ3. *How does the freshwater demand in the VDS management respond to anticipated climate change compared to the traditional management?*

For a fair comparison of the water demand between the traditional management and the VDS management, the yearly cumulative discharge is calculated without forced inlet (flushing). The yearly cumulative discharge of the inlet water over the years 2013-2018 in the current climate without irrigation for the traditional management and the VDS management are shown in Figure 16. The yearly cumulative discharge of inlet water in the traditional management is very low (<0.2m^3), occurring only at the beginning of the summer season. The VDS management requires no inlet water. Thus, there is no inlet water needed to maintain the minimum water levels for both the traditional and the VDS management when the irrigation is inactive.

Therefore, to facilitate a comparison of freshwater demand between the traditional management and the VDS management, it is imperative that irrigation is active.

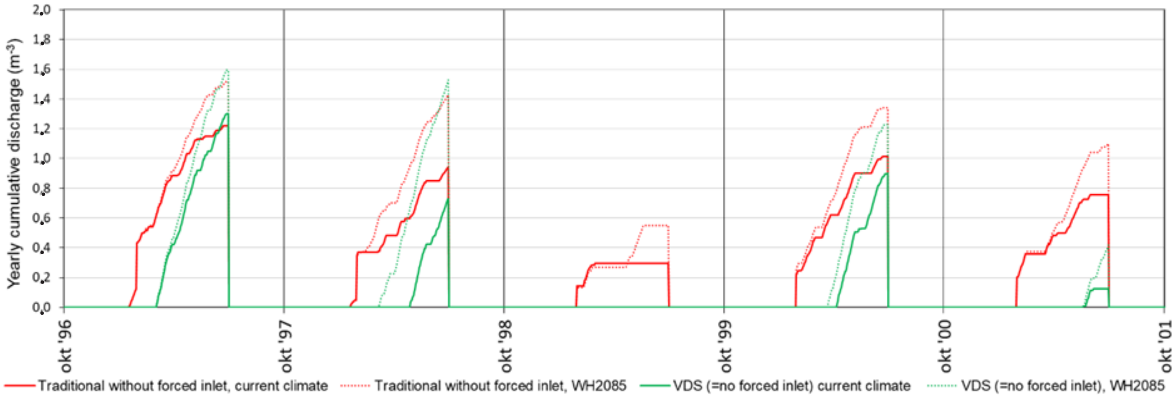

Figure 18. The yearly cumulative discharge of the inlet water (m^3) in the current climate (solid lines) and the future climate WH2085 (dotted lines) projected over the years 1996-2001 with the irrigation active. The traditional management (red) has a higher freshwater inlet needed to reach the minimum water level in summer compared to the VDS management (green), except for the first year considered (1996). The future climate scenario WH2085 increases the yearly cumulative discharge of the inlet water for both the traditional management and the VDS management. The VDS management has a reduction of 51% of the inlet water demand compared to the traditional management in the future climate WH2085 scenario, calculated over the total timespan (1996-2001).

When adding irrigation to the STOWA model for the same situation; the current climate without forced inlet water, the output significantly changes; water inlet is needed in both the traditional management and VDS management to maintain the set minimum water level in summer (Fig. 17). Remarkably, still no inlet water was required for the VDS management during the summer of 1998. In this year, the precipitation was significantly higher compared to the other years (Table 5).

Figure 18 presents the annual cumulative water inlet discharge for both the traditional management without forced inlet and the VDS management, encompassing both the current climate scenario and the future climate scenario WH2085, with active irrigation. The water inlet is always higher in future climate scenario WH2085 compared to the current climate scenario. Remarkably, no inlet water was required for the VDS management during the summer of 1998. The overall water inlet is higher for the traditional management approach without flushing compared to the VDS management. However, it is important to note that in the first two years of implementation, this difference may not be fully reflected. The VDS management has a reduction of 51% of the inlet water demand compared to the traditional management in the future climate WH2085 scenario (Fig. 18).

SQ4. *What is the effect of VDS on water quality i.e., phosphorous (P g L^{-1}) and nitrogen (N g L^{-1}) concentrations compared to the traditional management?*

The assessments of water quality indicators P and N, corresponding with PO_4 and NO_3 (mg L^{-1}) concentrations, should be regarded as approximate estimations. The provided graphs in Fig. 19 are based on area B with high boils (seepage flux ranging from 0.42 - 0.5 mm d^{-1},

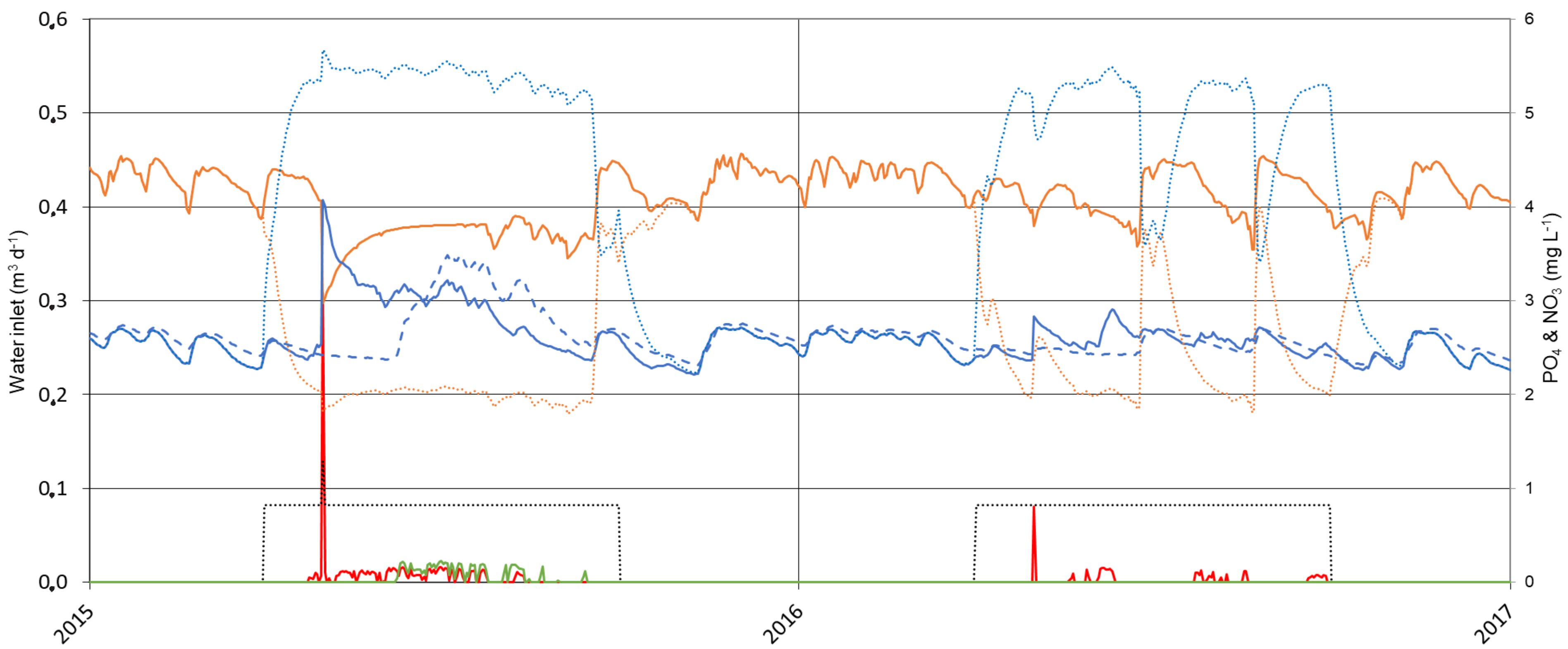

Figure 19. The water quality expressed in P and N. The left axis indicates the water inlet in the current climate with irrigation for the traditional water management without forced inlet (red solid line), traditional management with forced inlet (black dotted line), and the VDS management (green solid line). The right axis presents the phosphorus and nitrate concentrations in the current climate with irrigation for the traditional water management without forced inlet (solid lines), traditional management with forced inlet (dotted lines), and the VDS management (dashed lines).

boil flux 0.30 - 0.32 mm d^{-1}) and encompass a two-year period spanning 2015 and 2016. The year 2015 represents the prevailing event where inlet water is typically required for VDS to maintain the prescribed minimum water level. In contrast, 2016 portrays the exceptional occurrence when no inlet water is needed for VDS, neither for the situation with and without irrigation activated.

Traditional water management without forced inlet (solid lines) is best represented in the year 2016 where the water inlet is nearly zero. Compared to the traditional water management with forced inlet (dotted lines), the phosphorus strongly decreases with freshwater input and the nitrate strongly increases with freshwater input. In the VDS management (dashed lines), the water inlet is zero. For VDS, the phosphorus concentration is slightly lower and more constant compared to the current management without forced inlet. The nitrate is slightly higher in the VDS management compared to the traditional management without forced inlet. For a more comprehensive perspective, Appendix G encompasses the outcomes obtained under the assumption of irrigation being deactivated.

SQ5. *How does the water salinity i.e., chloride concentrations (Cl, g L^{-1}), in the VDS management respond to anticipated internal salinisation compared to the traditional management?*

Fig. 19 indicates an increase in the water salinity following internal salinisation for the traditional management and for the VDS management. Additionally, the salinity in the VDS management is higher compared to the traditional management. The traditional management with flushing rises from ca. 1000 mg Cl L^{-1} to ca. 1250 mg Cl L^{-1}, an increase of 25%.

SQ6. *How does the average salinity in the entire Haarlemmermeer polder change under VDS management compared to the traditional management?*

The effect of VDS on the water salinity has been modeled for the three representative areas A, B, and C following the area selection and input value determination for the current climate (Appendix H). Again, the years 2015 and 2016 are presented. The Cl concentrations are always higher in the summer period in the VDS management compared to the traditional management. The Cl concentrations for upscaling to the whole polder is presented in Figure 21. The results indicate consistently higher salinity levels in the VDS management (green lines) compared to the traditional management with flushing (black lines) (Fig. 21, Appendix H).

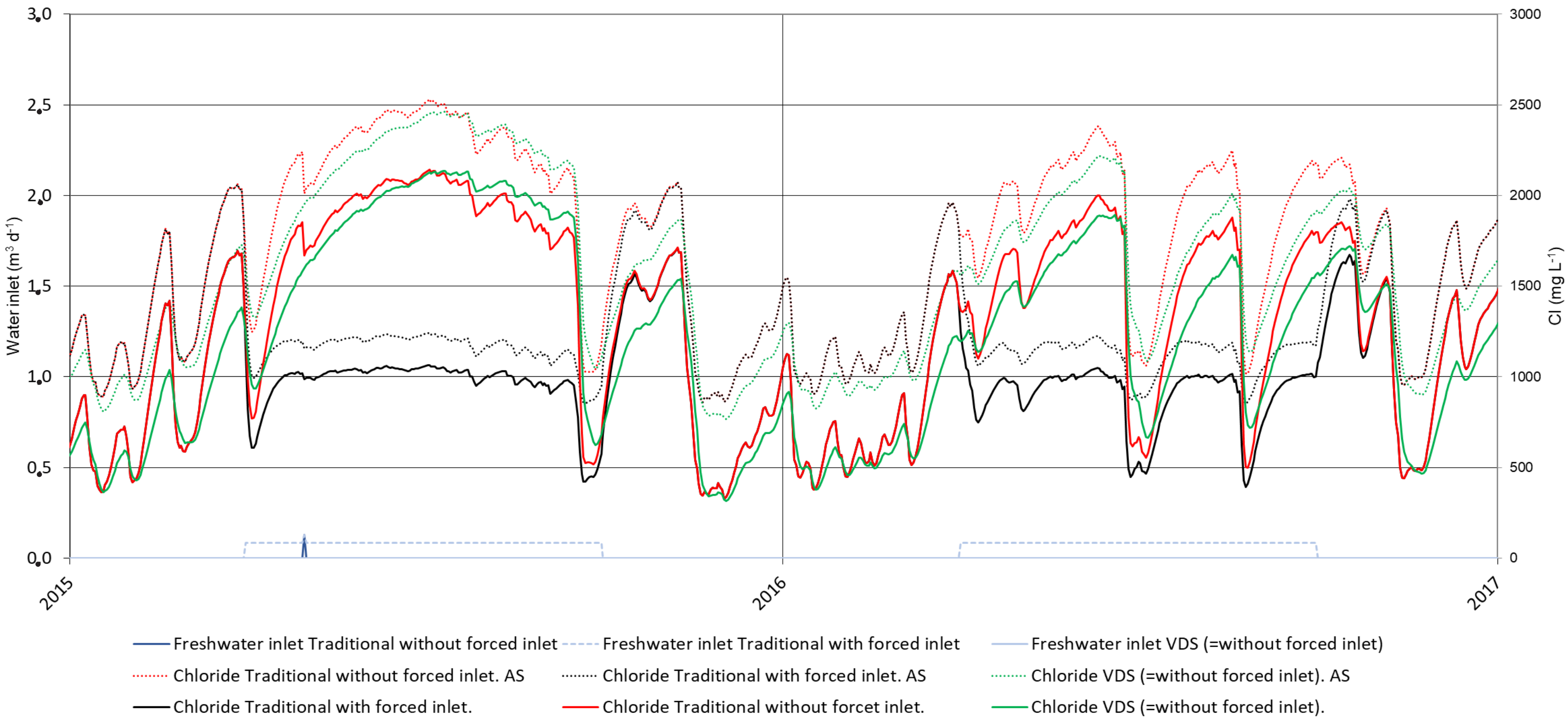

Figure 20. Chloride concentrations in the ditch during periods of inactive irrigation are depicted. The solid lines represent the salinity levels in the current climate, considering the existing seepage salinity, while the dotted lines illustrate the salinity under anticipated internal salinisation (AS) conditions. Specifically, the salinity of the phreatic seepage experiences a fourfold increase, rising from 550 to 2200 mg Cl L^{-1}. The chloride concentrations are depicted for different management approaches: traditional management without forced inlet (red), traditional management with forced inlet (black), and VDS management (green), spanning the years 2015 and 2016. The corresponding water inlet conditions are indicated by the solid lines. Notably, internal salinisation leads to a 27% rise in calculated chloride concentrations across the entire time frame (1996-2018).

Figure 21. Cl concentrations for upscaling to the whole polder. 25% of the area is not assigned to agriculture; this consists of the output of “no irrigation”: (37.5% * B high) + (37.5% * B low) + (12.5% * C high) + (12.5% * B low). 75% of the area is assigned to agriculture; this consists of the output of “with irrigation”: (10% * A high) + (20 * B high) + (20% * B low) + (25 * C high) + (25% * C low).

6

5. Discussion

5.1. Discussion of the results

The hypothesis stated that the existing water system in the Haarlemmermeer polder is not adequately equipped to handle these future precipitation events, resulting in the exceedance of the maximum water level set and subsequent waterlogging, and thus needing water management adaptation measures. Figure 14 indicates the parcels that meet the criteria for implementation based on the minimum unsaturated zone depth requirement. These findings address SQ1. *Which agricultural areas in the Haarlemmermeer are suitable for the application of VDS, considering the minimal depth of the unsaturated zone required for agricultural practices?* The parcels identified as suitable for VDS implementation provide a clear response to this question. The areas that area currently unsuitable for VDS implementation would require surface level elevation to achieve the required unsaturated zone depth, a measure that has significant costs.

The conversion of pumping stations into weirs in the VDS management, which enables an open water connection when the surface water level in the ditches reaches the boezem level and the weir folds away allowing for rapid discharge of excess water, was expected to be needed to cope with climate change which imposes peak precipitation events that the traditional management could not cope with. The sensitivity analysis showed that the VDS management can indeed withstand all peak rainfall events (Appendix F), even enduing extreme unrealistic precipitation events. This can be explained by the assumption made in the STOWA model that the pumping capacity for the VDS management is considered infinite. As a result, the model does not account for any limitations or constraints on the pumping capacity in the context of VDS implementation.

The projections of the most extreme future climate scenario WH2085 were modeled for the traditional management to allow for a comparison. The results, depicted in Figure 15, indicate a singular occurrence where the pre-established maximum surface water level is surpassed. This specific event takes place at the commencement of the winter season in 1998. The total rainfall in the summer was considerably higher in the summer 1998 compared to the surrounding years (Table 5). Additionally, the maximal precipitation on a day and the total precipitation in October in the year 1998 were higher in the WH2085 projection compared to the reference climate (Table 6). These factors have contributed to the exceedence of the set maximum water level. However, it is important to note that such surpassing occurs with minimal frequency and intensity. This can be explained by the considerable depth of the unsaturated zone, which equals the drainage depth. This answers sub-question 2*: How does the water level in the VDS management respond to extreme rainstorm events anticipated in the future climate compared to the traditional management?* As a result, the traditional water management system does not necessitate additional measures to mitigate waterlogging risks, contrary to the initial hypothesis.

The general hypothesis of this thesis stated that the implementation of VDS in agricultural area improves water quality and decreases freshwater demand, without compromising on the water salinity and waterlogging prevention. This was hypothesized based on the assumption that VDS creates a seasonal storage of rainwater during the wet season, which provides a buffer during summer, thereby reducing the inlet water demand.

That water saved in VDS by discontinuing the flushing of the polder is self-evident. However, for a fair comparison, the traditional management's forced inlet approach has also been compared to VDS management. The results of the water input show that without irrigation, there is no water inlet needed to sustain the set minimum water level in the traditional management without forced inlet as for the VDS management (Fig. 16). When irrigation is active, both the traditional management and the VDS management necessitate inlet water; however, the traditional management consistently exhibits a higher demand compared to the VDS management (Fig. 17). Notably, in the year 2016, the VDS management does not require any inlet water. This can be attributed to the significant precipitation that occurred during that year.

Regarding the water demand in the WH2085 future climate scenario, the VDS management exhibits a higher total inlet water requirement compared to the traditional management in the initial two years (1996 and 1997) (Fig. 18). Notably, the discrepancy in the inlet water requirement for the VDS management is pronounced in the year 1997, which corresponds to the significant water level difference depicted in Figure 15. Importantly, it is shown that the VDS management indeed achieves a substantial 51% reduction in inlet water demand compared to the traditional management when considering irrigation in the context of the WH2085 future climate scenario (Fig. 18). This answers sub-question 3. *How does the freshwater demand in the VDS management respond to anticipated climate change compared to the traditional management?*

The rainwater collection in the VDS management was expected to improve the water quality and reduce the water salinity in the ditches. The STOWA model has proven insufficient to make conclusive statements regarding the impact of VDS on water quality. The assessments of water quality indicators P and N, corresponding with PO_4 and NO_3 (mg L^{-1}) concentrations, should be regarded as approximate estimations. Therefore, sub-question 4. *What is the effect of VDS on water quality i.e., phosphorous (P g L^{-1}) and nitrogen (N g L^{-1}) concentrations compared to the traditional management?* remains unanswered.

However, sub-question 5*. How does the water salinity i.e., chloride concentrations (Cl, g L^{-1}), in the VDS management respond to anticipated autonomous salinisation compared to the traditional management?* can be answered based on the outcome of this research. Figure 20 presents the Cl concentrations for the years 2015 and 2016 under inactive irrigation conditions (solid lines current climate scenario, dotted lines autonomous salinisation scenario). Notably, the Cl concentrations in the traditional management without flushing are observed to be higher in comparison to those in the VDS management.

This implies the effective reduction of Cl concentrations through rainwater capture implemented by the VDS management. However, when comparing to the Cl concentrations of the VDS management with those of the traditional management with flushing, the former consistently demonstrates higher Cl concentrations.

Autonomous salinisation was expected to increase the Cl concentration. Figure 20 shows that the four times larger salinity of the phreatic seepage results in a 27% increase in the Cl concentration in the water. This corresponds to earlier finding by TNO (2007) that showed that compared to the current situation, salinisation is projected to increase by 30% by 2050 due to internal autonomous salinisation in deep polders. This increasing Cl concentration translated to the real world is expected to surpass the maximum threshold of 700 mg L^{-1} set by the Water Framework Directive (Kaderrichtlijn Water, KRW) for the traditional water management practices in the Haarlemmermeer polder and thus askes for mitigation and adaptation measures to ensure the sustained availability of freshwater for irrigation within this region.

All figures presenting the outcomes of the STOWA modeling over subareas A, B, and C (Appendix H) show that the implementation of VDS always results in a higher salinity in the summer season. In the winter this sequency is reversed. This again implicates that the hypothesis that rainwater collection in the VDS management reduces the salinity is disproven. The rainwater contribution does not outweigh the seepage flux in either of the subareas. Furthermore, it is consistently observed that the salinity levels in the area with low boil seepage are lower compared to the area with high boil seepage, which is in line with the hypothesis (Appendix H). However, when considering low boil seepage, the salinity of the water concerning the VDS management around the set maximum KWR threshold of 700 mg L^{-1}, implying that VDS could be implemented at areas with low boil fluxes while continuing its agricultural functions. This is in line with the findings of De Louw et al. (2004) that states that boil seepage attributes around 60% to the salinisation of surface water. The upscaling to the whole polder displayed in Figure 21 for the traditional management with flushing and for the VDS management. The salinity in summer for traditional management is estimated around 800 mg Cl L^{-1}, while the VDS management is estimated to be 1250 – 1400 mg Cl L^{-1}. This implies that upscaling VDS to the whole Haarlemmermeer polder including the agricultural land makes the water of insufficient salinity to allow for irrigation. These findings answer sub-question 6. *How does the average salinity in the entire Haarlemmermeer polder change under VDS management compared to the traditional management?*

The overpressure created by the higher water levels in VDS management was expected to reduce the seepage flux. Table 3 displays the calculated seepage fluxes for the sub-areas calculated using Darcy’s Law. It shows that indeed the phreatic seepage flux is lower in the VDS management compared to the traditional management, however, the difference does not make a significant difference in the generated outcomes. TNO (2007) found that raising the water levels only contributes to a significant decrease in the head difference when the water level is raised considerably. Additionally, they concluded that in most areas this rise in water level is not feasible due to the agricultural land use. This is in line with the findings of this study regarding the parcels with suitable depth of the unsaturated zone when VDS is implemented (Fig. 14)

The main research question is: *In which agricultural areas in the Haarlemmermeer polder can the Improved Drainage System be implemented to diminish the demand for freshwater supply and reduce the waterlogging risks, while continuing a suitable water quality and salinity to fulfill the agricultural functions?*

The VDS can be implemented in some area of the Haarlemmermeer polder depending on the flux and salinity of the diffuse- and boil seepage. However, implementation of VDS always increases the salinity in the summer, thereby compromising on the agricultural functioning.

The flux and salinity of the diffuse- and boil seepage can be derived from the freshwater–saline water interface. The freshwater-saltwater interface gives insights into the flow patterns of the groundwater and thus the seepage flux. Moreover, the identification and mapping of the freshwater-saltwater interface facilitates the assessment of groundwater quality and the identification of areas prone to saltwater intrusion. It aids to the design of sustainable water management strategies, allowing for the preservation of freshwater resources and the prevention of saltwater contamination.

The freshwater – saline water interface plays a crucial role in determining the location and flux of seepage boils. It helps identify areas where the interface is shallow and where the upward pressure of groundwater may cause the formation of boils.

5.2. Comparable research

The implementation of flexible water level management has been tested in a field study conducted in the Lange Weide Polder. Additionally, there are studies regarding the sealing of seepage boils.

Local water authority De Stichtse Rijnlanden, which have the jurisdiction of the area bordering the Eastern part of the Rijnland district, have implemented the flexible water level management in the 'Toekomstbestendige polder Lange Weide' (climate resistance of the Lange Weide polder) (De Stichtse Rijnlanden, 2022). The flexible level management was implemented to mitigate land subsidence, reduce greenhouse gas emissions, and water quality improvement. This was executed over an area of 310 Ha within one local drainage system, involving 28 landowners of which 13 farmers. The farmers and the local water authority worked together to optimize the system, which is a great example of the effect of stakeholder involvement, engagement, and participation.

By involving landowners and farmers in decision-making processes, the partnership ensures that their interests, concerns, and expertise are considered, resulting in a more effective and inclusive water management strategies. Additionally, it strengthens community resilience: The collaboration between the water board, farmers, and other stakeholders contributes to building a resilient community. By collectively addressing water-related challenges, such as flooding or drought, the collaboration enhances the community's ability to adapt and respond effectively to changing conditions. This shared responsibility and resilience-building approach create a sense of ownership and empowerment among stakeholders.

Furthermore, boils can be sealed by injecting material below the upper aquifer. Sealing at the surface has been tried, however, this resulted in the emerge of new boils next to the sealed boil (De Lauw et al., 2013). Additionally, the sealing of boils results in a local pressure increase around the sealed boil, resulting in increased diffuse seepage near the sealed boil as well as increased upheaval risk of the subsurface (TNO, 2007; De Lauw et al., 2013). However, diffuse seepage has a much lower salinity compared to boil seepage, thus the net Cl load can be significantly reduced (TNO, 2007), making the measure worth considering.

The three most suitable injection fluids that can be used to close the boils are expanding polyurethane, curing gels, Dammer, and Bentonite (TNO, 2007). Expanding polyurethane is less suitable for the Haarlemmermeer polder due to the low reaction rate of the curing process (ca. 1.5 minutes), which could result in escape of the intended leakage area due to the high seepage flux. Furthermore, the uncured form of expanding polyurethane has adverse environmental effects. Curing gels have adverse environmental effects in the uncured form as well, however, the reaction times vary from one second to over one day and the material is said to be environmentally friendly when cured. Dammer is a mixture of clay, cement, and lime. Dammer hardens upon contact with water, effectively fill the void spaced. Bentonite consists of clay particles that swell when in contact with water, sealing the affected area. Sealing by the injection of fluids has proven successful in repairing leaks that occurred during construction activities.

Another option is Biosealing. In this method, nutrients are injected into the soil to activate bacteria in the subsurface, initiating erosion to accumulate particles in the area that needs to be sealed. For the boils, this area lies below the semi confining layer at the point of the boil. The nutrients injected into the soil through Biosealing are natural substances and therefore environmentally friendly. Biosealing has been successfully applied multiple times, including during the construction of the aqueduct created for the high-speed railway under the Ringvaart in the Haarlemmermeer (Lange, 2008).

5.3. Discussion of the method

This study did not attempt to quantify the uncertainty of the STOWA model, and therefore there is no claim to its validity other than as a conceptual tool. Nevertheless, judging from comparisons to measured water levels, the STOWA model has proven suitable for this study, as it effectively represents the water distribution in the polder, as well as the flow fluxes into and out of the polder using the water balance and Darcy's Law. The important differences between the traditional management and the VDS water system occurring over the modeled period are well represented by the STOWA model. Consequently, the outcomes related to water levels, water inlet demand, and chloride concentrations can be estimated ensuring the reliability of these results. The results provide substantial and reliable outcomes to answer the research questions on the waterlogging risk, water demand, and salinity.

However, no conclusions can be drawn regarding the effects on water quality. The inputs concerning the P and N distribution have a considerable spatial and temporal variability, while an average is assumed in the input for the STOWA model, which employs point-based modeling. This variability renders the outcomes regarding P and N concentrations and their response to inlet water unreliable. In this context, a hydrological model that employs spatially distributed modeling such as SOBEK, which can simulate complex flow and chemical processes in the water, would be more appropriate. SOBEK can capture the intricate spatial and temporal variations in P and N distribution. Nevertheless, the application of SOBEK falls beyond the scope of this research, thereby excluding any conclusive statements regarding the impact of VDS on water quality.

The findings of this study are constrained by the influence of the input parameters' unreliability, resulting from significant spatial variability. Therefore, this study does not provide a definitive answer regarding the suitability of a specific location for the implementation of VDS to answer the main research question. Additionally, the large parameter uncertainty makes the STOWA model unfit to make robust choices for the area suitable for the implementation of VDS in the Haarlemmermeer polder. However, the outcome of the sensitivity analysis does prove useful for practical implications as it indicates the parameters that need to be defined in order to determine if the area is suitable for the implementation of VDS.

The upscaling of VDS to the entire Haarlemmermeer polder is a preliminary approximation. The GIS data used for the area deviation and assessment of the input values predominantly relies on models, and the deviation in the area is dependent on many assumptions and simplifications. Regarding the boil seepage input reliability, it should be noted that in the boil measurements there is a lack of data as well. The measurements are executed using an ECT-routing which detects the boils by recording peaks of increased salinity and temperature. Consequently, the boils with a lower salinity are not recorded, resulting in a sample bias. Nevertheless, the generated extrapolated results provide valuable insights into the potential impact of upscaling VDS to the whole Haarlemmermeer polder compared to current management practices within the stated assumptions.

This research has made many assumptions for simplification, some are stated here. First, the salinity of the freshwater inlet differs; further from the boezem the water will be more saline, while in this research one concentration is assumed for the inlet water. The flushing water does not disperse equally throughout the catchment; it follows preferential routes through the catchment (Rozemeijer et al., 2012; Aydin et al., 2022). Furthermore, the inlet water is assumed to be sufficient, while in reality, the freshwater availability is limited by the Rhine discharge. Additionally, the water table is assumed to be horizontal in the STOWA model calculations, the bulging and sinking of the groundwater level are not considered (Beven, 1989). Adding to this is the distance between tile drains and the depth of the tile drains, which are not included in the model. Furthermore, the seepage flux is an input value in STOWA based on the average of the summer and winter maximum for VDS, while in reality it depends on the height of the water level. Future studies could develop a feedback loop in the model to include the water level fluctuations into the calculation for the seepage flux.

A minor shortcoming in this study follows from the water abstraction for irrigation purposes. The water abstraction for irrigation purposes is added to the model over the six months in summer, while it should be in three months (May, June, and July). A second minor shortcoming follows from the unregistered inlet water by farmers who temporary create an additional intake period, and the closure of one of the inlet culverts. However, these minor shortcomings have another aspect; the water subtracted from the ditch for irrigation purposes adds to the water in the drainage, which is not included in the STOWA model.

The nutrient balance the answers could not be found by using STOWA, because of the temporal and spatial variability of the input parameters. Additionally, the interaction with sediments and the effect of hypoxic or anoxic conditions in the VDS management that could occur when there is no flushing, are not included. Van den Eertwegh et al. (2006) have shown through solute balances that the salt and nutrient loading of the surface water are clearly affected by both agricultural and drainage activities and concluded that the drainage activities and their surface water quality aspects need to be studied in an integrated way.

In light of the autonomous salinisation scenario, different adaptation and mitigation measures should be invested. An adaptive approach could involve investigating different crop types that exhibit higher tolerance to salinity in irrigation water, while also being capable of thriving with roots in fresher water. A mitigation approach could focus on providing insights into the options for sealing seepage boils and estimating the associated costs, thereby contributing to the practical applications following this study. Another potential solution is the capture and removal of salt, which could be further investigated. Extracting water from the seepage boils to be desalinated to create drinking water is also a promising approach, although the disposal of the resulting brine poses a significant challenge. A pilot project involving pumping brackish seepage from the Horstermeerpolder was conducted by the local water authority, Amstel, Gooi en Vecht, with the aim of investigating the feasibility of this method (Van Zout Kwelwater Naar Drinkwater, n.d.).

5.4. Academic value and value for Rijnland

While validating the shortcomings of the STOWA model, the model does prove to be an adequate conceptual tool for this effect study.

The water system is now modeled for the VDS, thereby providing a comprehensive understanding of its effects within the system. Additionally, the academic value of this study lies within the parameters that influence the water system, discovered by the sensitivity analysis. The sensitivity analysis shows that the flux and salinity of the phreatic seepage and boil seepage are the defining factors to conclude if VDS can be implemented in the area of interest. This finding shows the importance of understanding the freshwater-saline water interface when conducting the area selection for VDS implementation. These insights provide practical significance for Rijnland. The inclusion of VDS in the STOWA model and the recognition of influential parameters by the sensistivity analysis provide valuable insights that can be used by Rijnland in the decision-making processes.

Utilizing the STOWA model as a functional predictive instrument for the area suitable for the implementation of VDS is highly based on the validity of the input values and the properties of the focus area. When considering increased intensity and frequency of extreme temperature and precipitation values used as input for the future climate scenario, the model calculates an exceedance of the maximum set water level. However, this exceedance is modest and is not expected to result in water logging. Therefore, adaptation and mitigation measures are not needed for the traditional water management in the Haarlemmermeer polder.

6. Conclusion

To conclude, this section briefly states the answers to the research questions. The results depicted in Figure 14 present the parcels that are tested for the suitability of the implementation of VDS considering the minimal depth of the unsaturated zone required for agricultural practices.

The results of water levels during peak discharge in the most extreme future scenario, highest intensity and frequency of extreme weather events by the year 2085, indicates that the traditional management in the Haarlemmermeer polder are capable of handling the anticipated rainstorm events (Fig. 15). Consequently, it implies that climate change does not require measures for the traditional management approach in mitigating waterlogging risks within the polder. Climate change does impose stress on the water system; however, water management is the driving factor.

The implementation of VDS the Haarlemmermeer polder has proven effective in reducing the freshwater demand by eliminating the flushing. To ensure a comprehensive evaluation, this study compared the required inlet water for traditional management without flushing to the water demand for VDS. Without irrigation, no inlet water is needed to maintain the minimal set water levels in the VDS management as well as in the traditional management (Fig. 16). The analysis revealed that the VDS management achieves a substantial 51% reduction in inlet water demand compared to the traditional management when considering irrigation in the context of the WH2085 future climate scenario (Fig. 18).

The STOWA model is unfit to answer the effect of VDS on the water quality, excluding any conclusive statements regarding the impact of VDS on water quality compared to the traditional management.

Figure 20 shows that the four times larger salinity of the phreatic seepage results in a 27% increase in the Cl concentration in the water for the VDS management compared to the traditional management in the WH2085 future climate scenario.

The implementation of VDS always results in an increase in the salinity compared to the traditional management. Internal autonomous salinisation increases the salinity in both the traditional management and the VDS management, implying that internal autonomous salinisation does require adaptive measures for the traditional management approach in mitigating increased Cl concentrations in the surface water within the polder.

To conclude; the VDS management can be applied in some part of the study area while maintaining its agricultural function. The area can retain its agricultural function depending on the boil seepage flux and salinity. The most important conclusion following this study is that VDS does not improve the water salinity of the water system; the rainwater capture does not outweigh the effect of flushing. The aim of this research was to assess if VDS can be implemented in the agricultural area of the Haarlemmermeer polder without compromising the functioning of the water system. The results show that the VDS always results in a higher salinity of the water compared to the traditional management. However, VDS can be applied in certain agricultural areas in the Haarlemmermeer polder while maintaining the agricultural functions, not in all parts of the polder the chloride will be suitable for the current crops. In some area of the Haarlemmermeer polder VDS can be applied, depending on the salinity of the seepage water, the number of boils in the area, and the depth of the freshwater – saline water interface. Water boards should consider investing in this data to enable informed decision-making.

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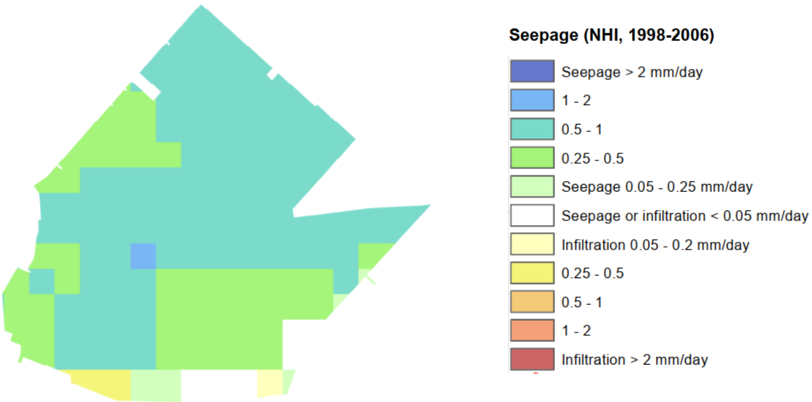
Appendix A

The mean and range of the chemical composition of the components that contribute to the surface water (Delsman et al., 2013). The stream was measures date from March 2011 – October 2012. The precipitation (PR), inlet water (IL), groundwater below ditches (BD), and shallow groundwater (SL, the rainwater lens) were measured monthly, the deep aquifer groundwater was measured twice at sporadic times. The locations are indicated in Figure 2.

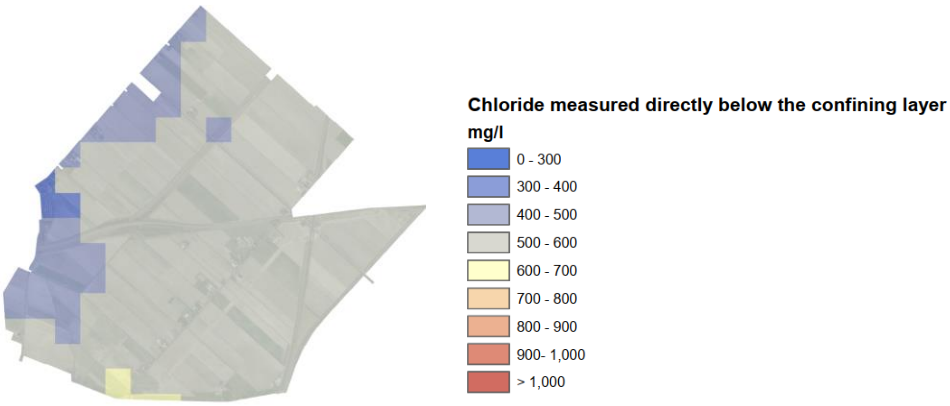
	Cl (mg L^{-1})	**PO_4 (mg L^{-1})**	**NO_3 (mg L^{-1})**
Precipitation (PR)	6.1	0.12	3.1
	1.1-22.1	0.02-0.52	0.1-7.1
Inlet water (IL)	136	0.12	8.1
	113-167	0.02–1.72	0.1–32.1
Boil seepage (AD)	5453	2.52	1.1
	4534–6590	1.22–3.62	0.1–4.1
Phreatic groundwater, (SL)	75	0.32	2.1
	34–169	0.02–5.42	0.1–7.1
Diffuse seepage under ditches (BD)	336	13.62	2.1
	134–840	0.02–49.52	0.1–18.1

Appendix B

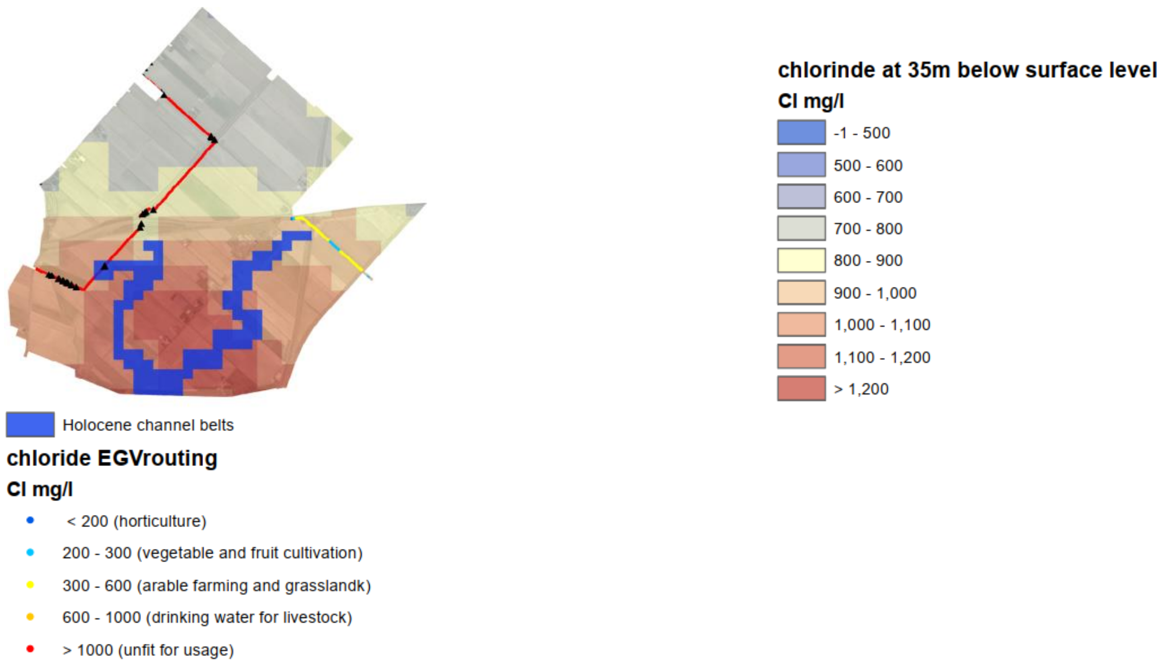
The seepage properties in the Lissertocht catchment are presented in B2-B3. The salinity in the internal salinisation scenario is based on the Cl concentrations modeled by Delsman et al. (2014), presented in B4.



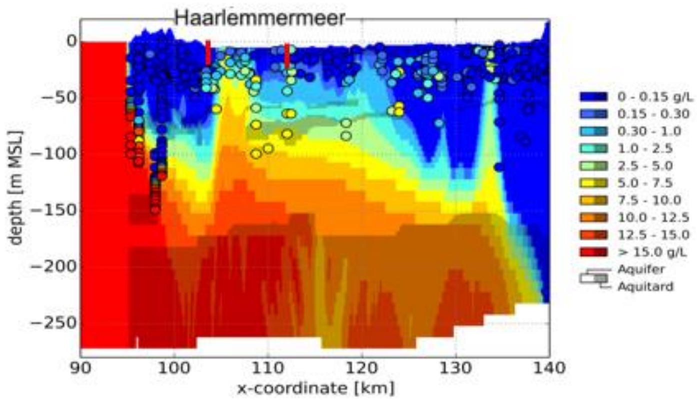
B1. Seepage flux in Lissertocht catchment (NHI).



B2. Cl measured directly below the semi confining layer in Lissertocht catchment (NHI). This is an indication for the salinity of the phreatic seepage.



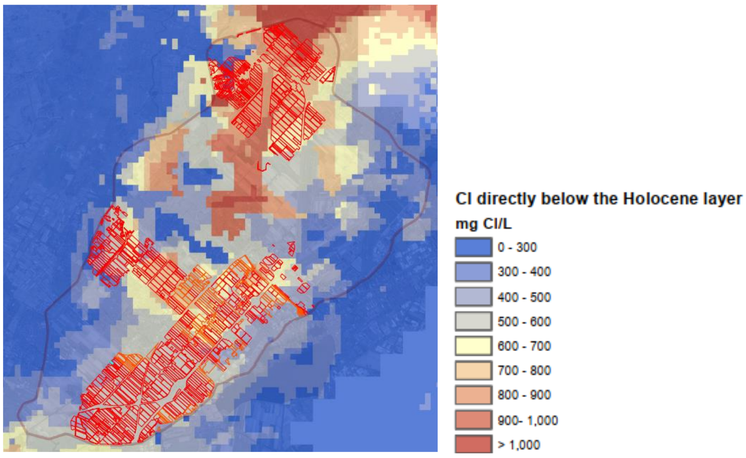
B3. Location of the Holocene channel belt in blue (Rijnland). The Cl measured in the ditches by EGV-routing, the discovered seepage boils are indicated with black triangles (Delsman et al., 2013). The Cl measured at 35m below surface level is an indicator for the salinity of the seepage boils (NHI).



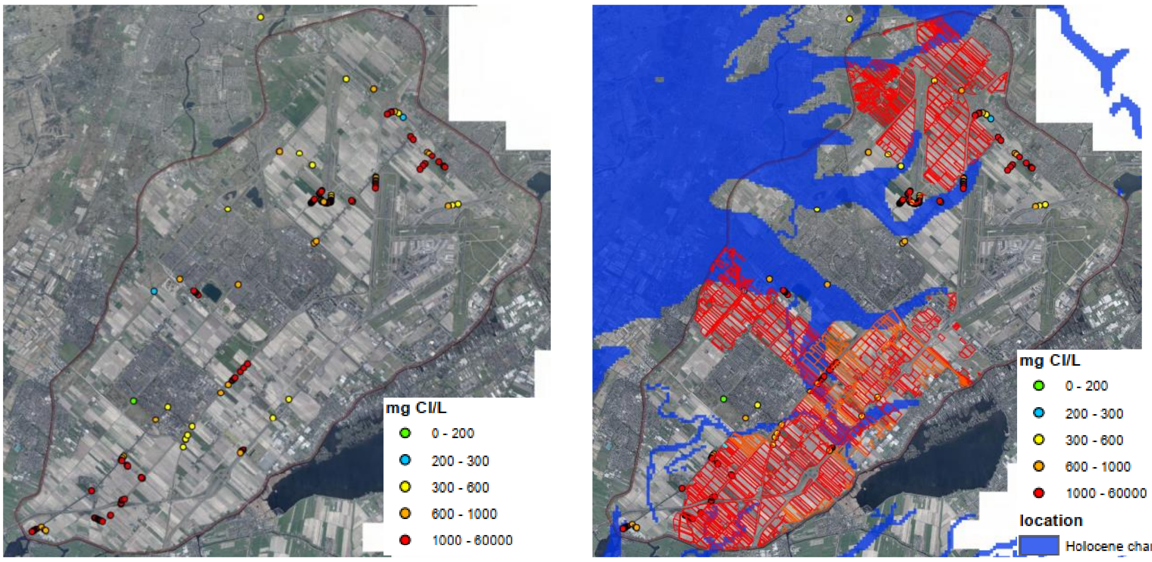
B4. Chloride measurements and modeled chloride concentration at AD 2010 used as estimation for the internal autonomous seepage (Delsman et al., 2014). The Haarlemmermeer is indicated between the red bars of the Holocene channel belt in blue (Rijnland).

Appendix C

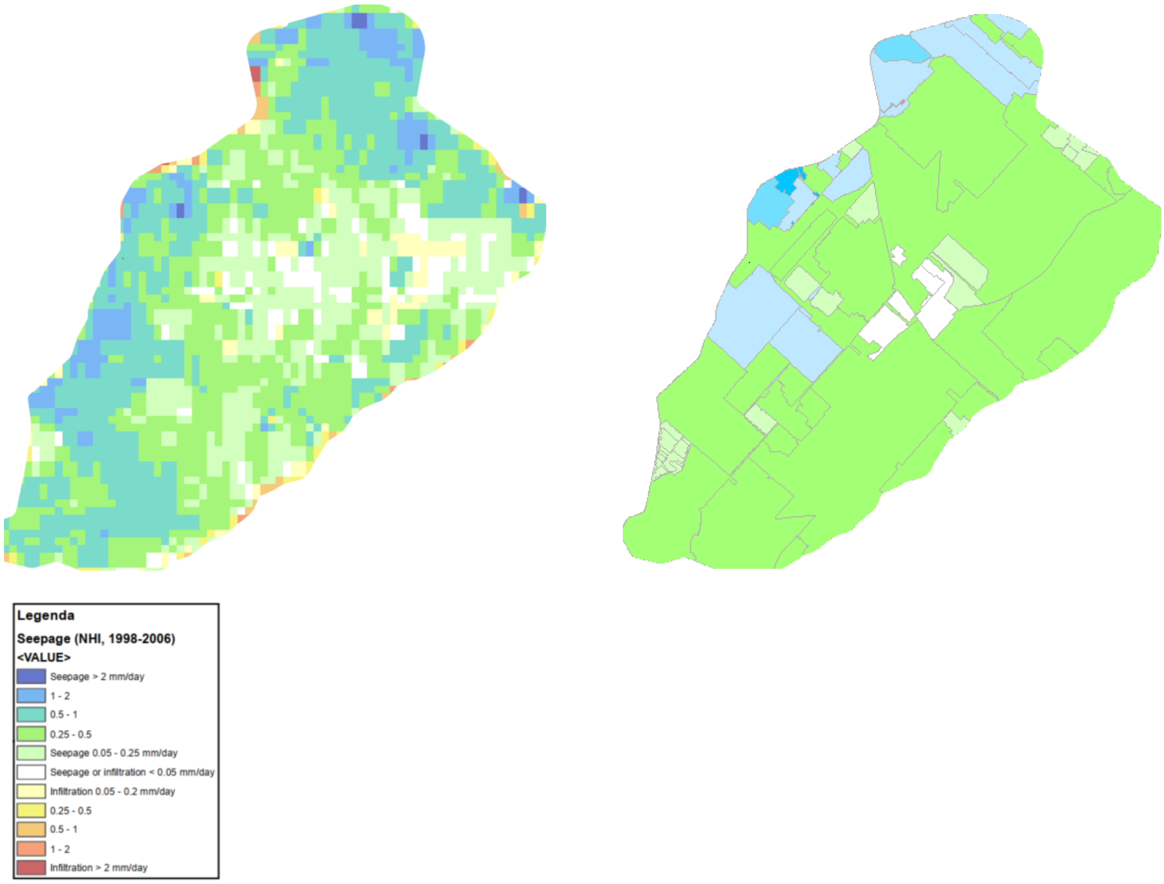
The seepage characteristics within the Haarlemmermeer polder are described. This information is employed to validate the input parameters and to facilitate the upscaling procedure.



C1. Chloride measured directly below the Holocene layer (NHI).



C2. Left: Seepage boils observed in the Haarlemmermeer polder (Rijnland Geo Database). Right: The map displayed on the left overlaid with the layer illustrating the distribution of Holocene channel belts (Rijnland Geo Database). Mind that the boils are only presented for the measured ditches.



C3. Left: Seepage flux in the Haarlemmermeer polder. Right: Average seepage flux for each regional catchment area (Adopted from the Rijnland GIS database, based on the NHI data source).

Appendix D

The input data used in the STOWA model is presented in the following tables.

D1. Cl concentration of the drainage water for areas A, B, and C.

	Concentration drainage (mg Cl L^{-1}) Traditional Winter	**Concentration drainage (mg Cl L^{-1}) Traditional Summer**	**Concentration drainage (mg Cl L^{-1}) VDS Winter**	**Concentration drainage (mg Cl L^{-1}) VDS Summer**
	-6.57m NAP	*-6.42m NAP*	*-6.22 NAP*	*-6.145 NAP*
A Centre (-5.3)	109.6	109.6	81.13	81.13
B Transition zone (-4)	183.7	183.7	168.3	167.3
C Edge (-2.7)	236.5	236.5	225.3	225.3

D2. Boil seepage ***high*** flux for area A, B, and C.

	Boil seepage flux (mm d^{-1}) Traditional Winter	**Boil seepage flux (mm d^{-1}) Traditional Summer**	**Boil seepage flux (mm d^{-1}) VDS Winter**	**Boil seepage flux (mm d^{-1}) VDS Summer**
	-6.57m NAP	*-6.42m NAP*	*-6.22 NAP*	*-6.145 NAP*
A Centre (-5.3)	0.32	0.31	0.30	0.30
B Transition zone (-4)	0.32	0.31	0.30	0.30
C Edge (-2.7)	0.32	0.31	0.30	0.30

D3. Boil seepage ***low*** flux for area A, B, and C.

	Boil seepage flux (mm d^{-1}) Traditional Winter	**Boil seepage flux (mm d^{-1}) Traditional Summer**	**Boil seepage flux (mm d^{-1}) VDS Winter**	**Boil seepage flux (mm d^{-1}) VDS Summer**
	-6.57m NAP	*-6.42m NAP*	*-6.22 NAP*	*-6.145 NAP*
A Centre (-5.3)	0.08	0.08	0.08	0.08
B Transition zone (-4)	0.08	0.08	0.08	0.08
C Edge (-2.7)	0.08	0.08	0.08	0.08

Appendix E

The iterations of the STOWA model utilized regarding the salinity in the current climate projection of the subregions which are used in the upscaling process. Note that this matrix does not encompass future scenarios that account for climate change and autonomous salinisation. This needs to be executed for both the traditional management without flushing, the traditional management with flushing, and for the VDS management, as well as for the irrigation on and off.

		Phreatic seepage, Drainage water			Phreatic seepage flux			Boil seepage flux high			Boil seepage flux low		
		A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Phreatic seepage, Drainage water	**A**	x	1	2	3	4	5	6	7	8	9	10	11
	B		x	12	13	14	15	16	17	18	19	20	21
	C			X	22	23	24	25	26	27	28	29	30
Phreatic seepage flux	**A**				x	31	32	33	34	35	36	37	38
	B					x	39	40	41	42	43	44	45
	C						x	46	47	48	49	50	51
Phreatic seepage flux high	**A**							x	52	53	54	55	56
	B								x	57	58	59	60
	C									x	61	62	63
Phreatic seepage flux low	**A**										x	64	65
	B											x	66
	C												x

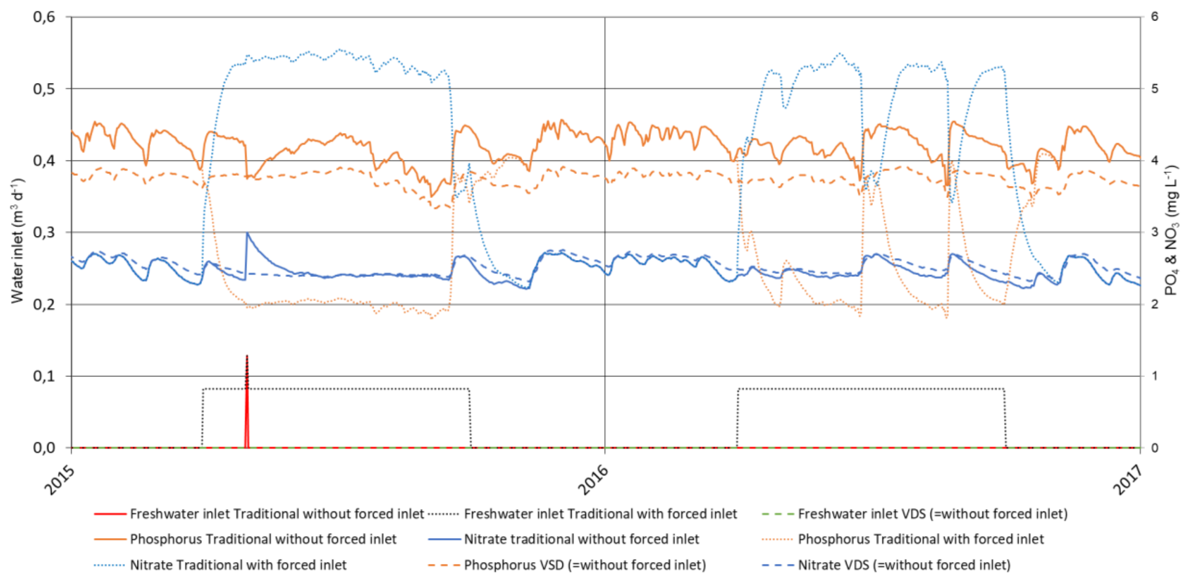
Appendix F

The input parameters for the sensitivity analysis, corresponding indicators, and the model outcome of the parameters' sensitivity to change. The bold values are the reference values, the other values are amplified extreme values.

	Flux	**Cl (mg L^{-1})**	**Indicator**	**Sensitive to change**
A1. Phreatic seepage	**1.0** mm d^{-1}	100 **500** 1000	Salinity	**Yes**; the increase in salinity of the phreatic seepage results in a substantial increase of the salinity in the water box.
A2. Phreatic seepage	0.50 mm d^{-1} **1.0** mm d^{-1} 10 mm d^{-1}	500	Salinity Nutrients	**Yes**; by increasing the phreatic seepage, the fraction becomes substantially great that it fully determines the salinity.
B. Drainage	Model calculated	100 **650** 1000	Salinity	**Yes**; this has a substantial effect on the water balance, because the selected area is presumed to be fully drained.
C. Surface runoff = GW discharge	Model calculated	30 **75** 200	Salinity	**No**; because of the fully drained area and the set groundwater level.
D1. Boil seepage	0.01 m^3d^{-1} **0.03 m^3d^{-1}** 0.1 m^3d^{-1}	5500	Salinity Nutrients	**Yes**; for the higher margin, the fraction of boil seepage becomes greater, resulting in an extreme increase in the salinity due to the high Cl concentration.
D2. Boil seepage	0.03 m^3d^{-1}	4000 **5500** 7000	Salinity	**Yes**; high concentrations greatly influence the salinity.
E1. (Forced) inlet water	*Winter*: Model calculated *Summer*: 0.1 m^3d^{-1}	100 **150** 200	Salinity	**No**; the effect on the water balance is only for the current situation, but the effect is minimal.
E2. Forced inlet water in summer	*winter* 0 m^3d^1 *summer* 0.05 m^3d^{-1} **0.1 m^3d^{-1}** 1.35 m^3d^{-1}	150	Salinity Nutrients Surface water level	**Yes** *for traditional*; by increasing the forced inlet water, extreme precipitation is simulated. For the traditional management, this results in exceedance of the set maximum water level, which is evaluated as very sensitive to change. **No** *for VDS*; This is not the case for VDS, because of the infinite pumping capacity simulating the gravitational flow to the boezem.
F. Fractions GW discharge = recharge	0.03 d^{-1} **0.5 d^{-1}** 0.9 d^{-1}	-	Fractional distribution Nutrient content	**No**; because of the fully drained area and the set groundwater level. Note: it does influence the time in which the groundwater responses to change.
G. Storage (-)	0.05 **0.3** 0.8	-	Surface water level	**No**; because of the fully drained area and the set groundwater level.

Appendix G

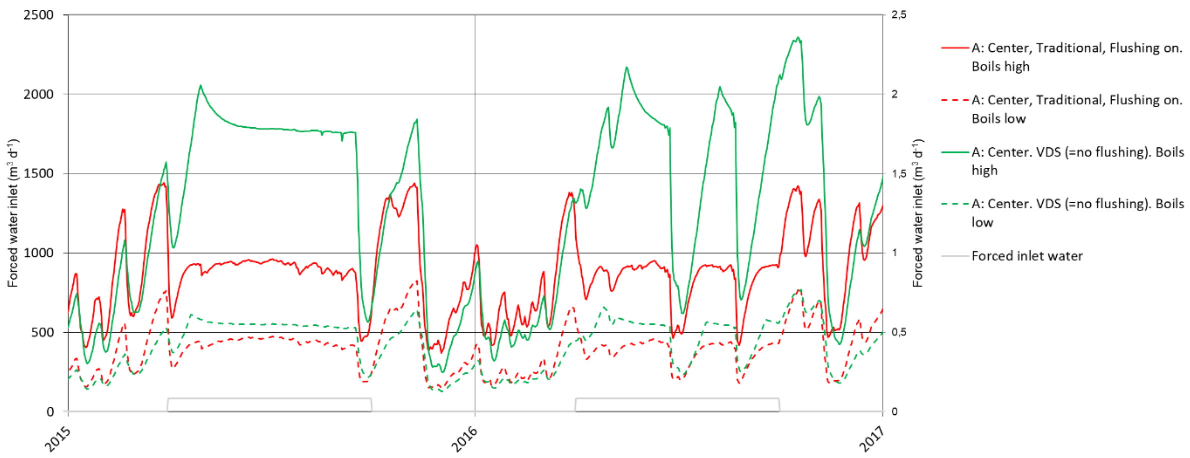
For a more comprehensive view on the effect of VDS on the water quality, the results for the P and N are presented without irrigation. The left axis indicates the water inlet in the current climate without irrigation for the traditional water management without forced inlet (red solid line), traditional management with forced inlet (black dotted line), and the VDS management (green solid line). The right axis presents the phosphorus and nitrate concentrations in the current climate without irrigation for the traditional water management without forced inlet (solid lines), traditional management with forced inlet (dotted lines), and the VDS management (dashed lines).



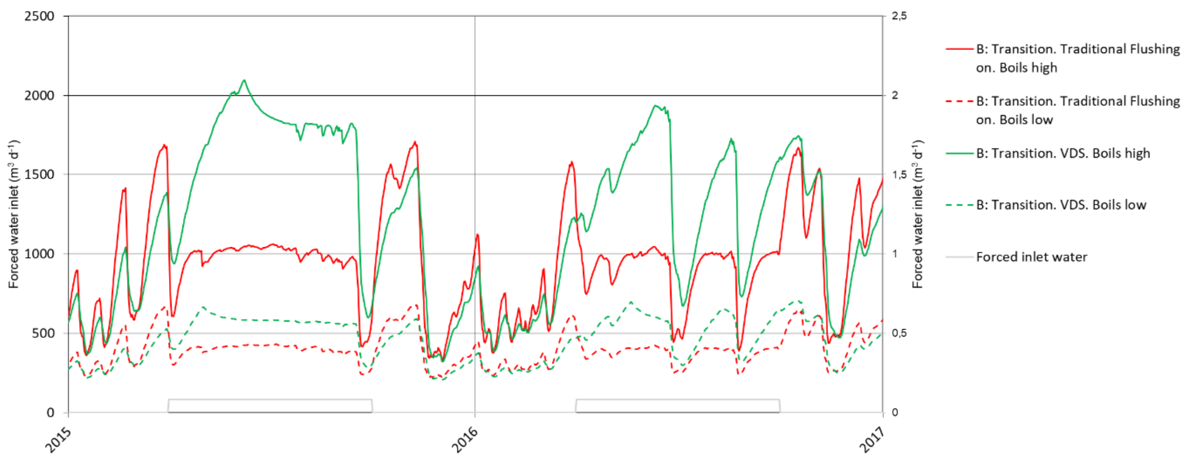
Appendix H

The following graphs depict the Cl concentrations for the years 2015 and 2016 in areas A, B, and C. The first presentation includes cases with activated irrigation, followed by the scenarios without irrigation. These outcomes serve as the basis for upscaling to the entire polder, which is presented in Figure 21.

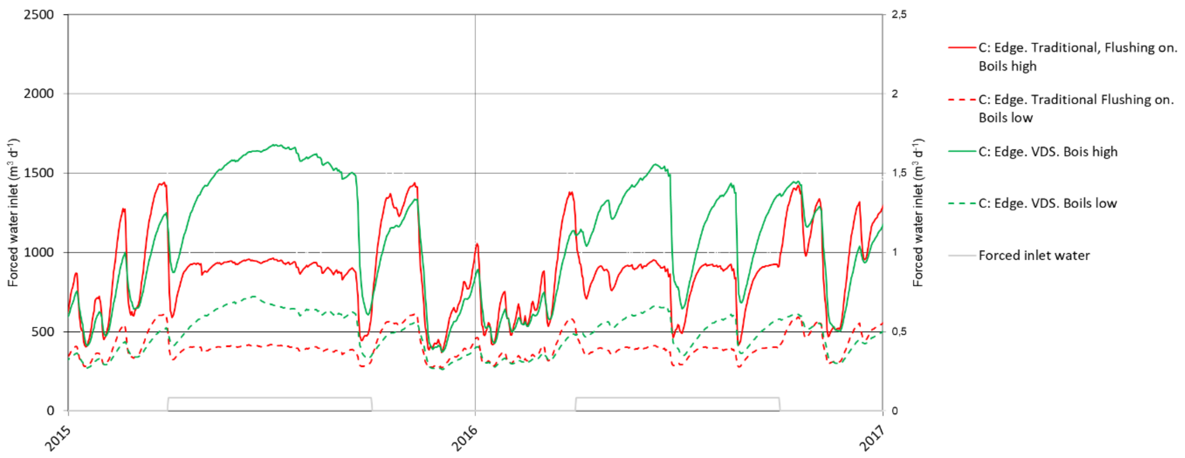
Irrigation active



H1. Cl concentrations in the current climate with irrigation active in area A (lowest phreatic seepage flux) with irrigation over the years 2015 and 2016. The traditional management with flushing (red) and the VDS (green) for the boils high (solid lines) and boils low (dashed lines). The traditional management with flushing results in a lower Cl concentration compared to the VDS management for both the high and low boil flux.

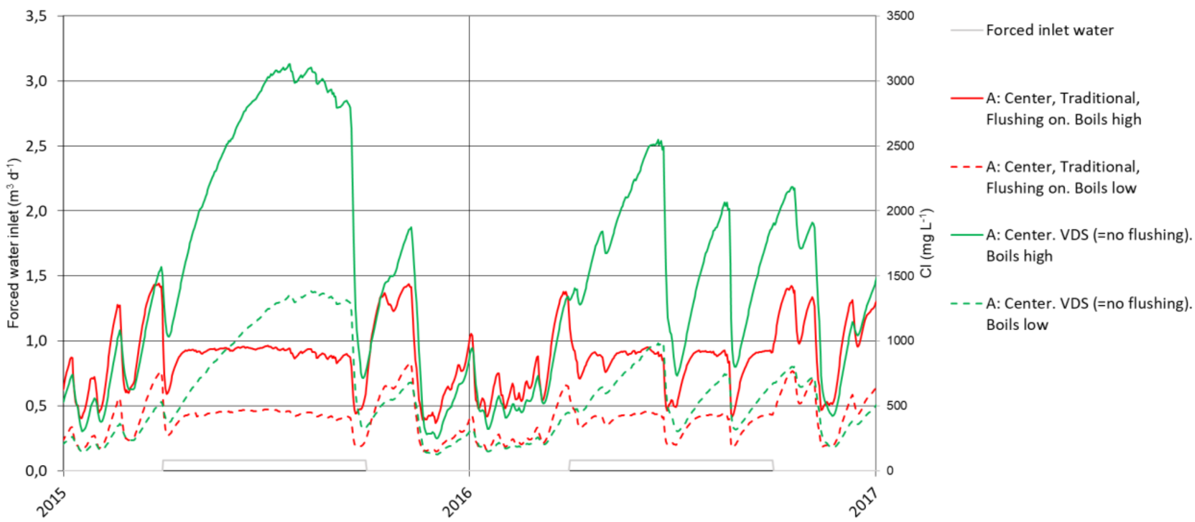


H2. Cl concentrations in the current climate with irrigation active in area B (moderate phreatic seepage flux) with irrigation over the years 2015 and 2016. The traditional management with flushing (red) and the VDS (green) for the boils high (solid lines) and boils low (dashed lines). The traditional management with flushing results in a lower Cl concentration compared to the VDS management for both the high and low boil flux.

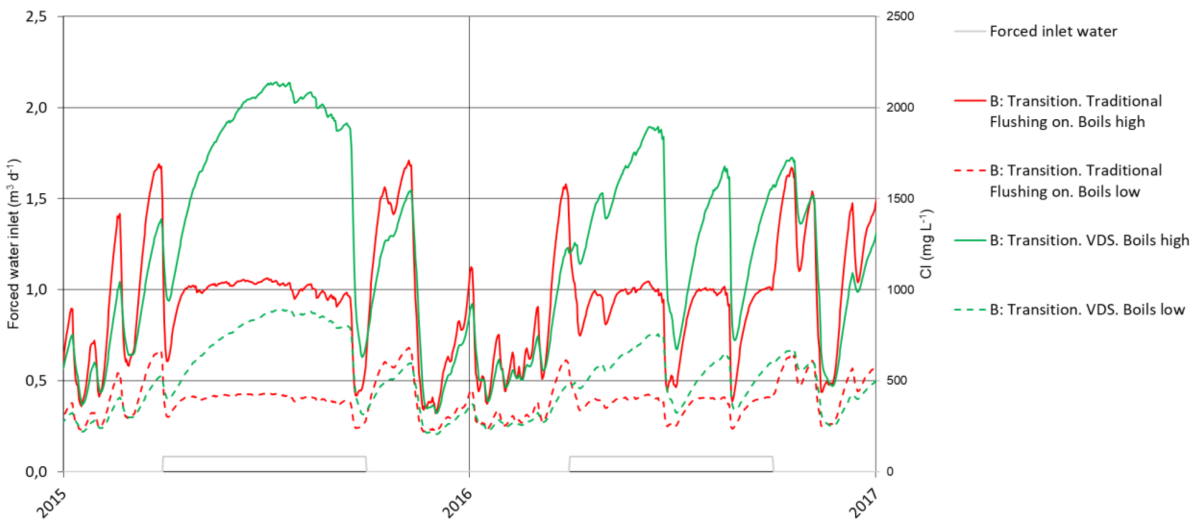


H3. Cl concentrations in the current climate with irrigation active in area C (highest phreatic seepage flux) with irrigation over the years 2015 and 2016. The traditional management with flushing (red) and the VDS (green) for the boils high (solid lines) and boils low (dashed lines). The traditional management with flushing results in a lower Cl concentration compared to the VDS management for both the high and low boil flux.

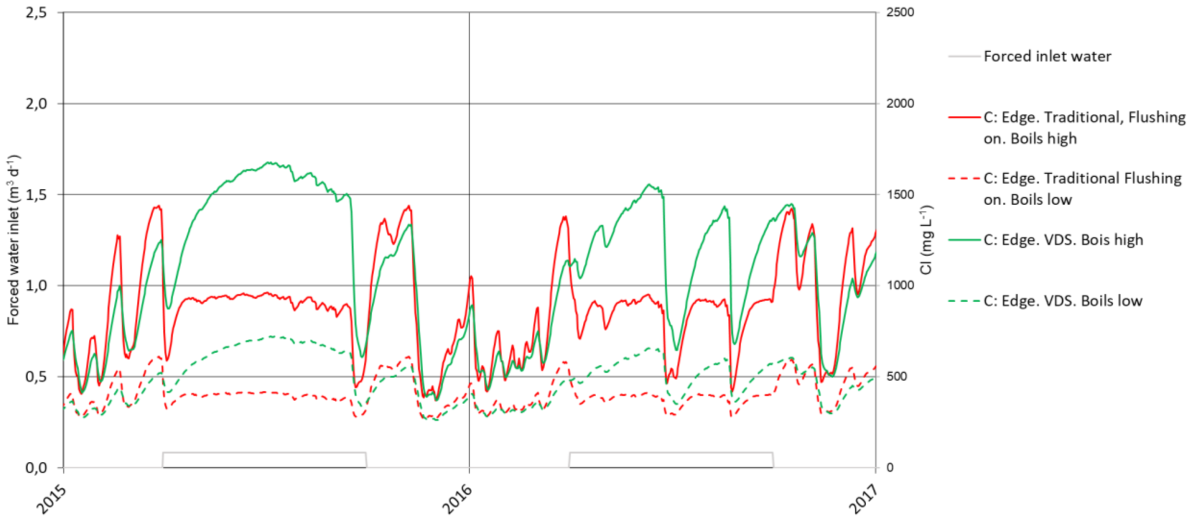
Irrigation inactive



H4. Cl concentrations in the current climate with irrigation inactive in area A (lowest phreatic seepage flux) with irrigation over the years 2015 and 2016. The traditional management with flushing (red) and the VDS (green) for the boils high (solid lines) and boils low (dashed lines). The traditional management with flushing results in a lower Cl concentration compared to the VDS management for both the high and low boil flux.



H5. Cl concentrations in the current climate with irrigation inactive in area B (moderate phreatic seepage flux) with irrigation over the years 2015 and 2016. The traditional management with flushing (red) and the VDS (green) for the boils high (solid lines) and boils low (dashed lines). The traditional management with flushing results in a lower Cl concentration compared to the VDS management for both the high and low boil flux.



H6. Cl concentrations in the current climate with irrigation inactive in area C (highest phreatic seepage flux) with irrigation over the years 2015 and 2016. The traditional management with flushing (red) and the VDS (green) for the boils high (solid lines) and boils low (dashed lines). The traditional management with flushing results in a lower Cl concentration compared to the VDS management for both the high and low boil flux.