Freshwater lens development in Schouwen-Duiveland

Exploring the potential of in-situ freshwater storage capacity of the subsoil under a changing climate

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Executive summary

Agriculture in Schouwen-Duiveland, which is an island of the Province of Zeeland in the Netherlands, exclusively depends on precipitation and freshwater lenses as water source. Under projected climate change and sea level rise, it will become vital to utilise the island's freshwater lenses to their full potential to increase agricultural robustness in periods of drought. However, this water can only be legally abstracted from a freshwater lens when this respective lens has reached a thickness of 15m.

Therefore, the aim of this research was to provide insight in the potential of freshwater lens development in Schouwen-Duiveland. First, the locations of where a 15m thick freshwater lens could theoretically be present were identified through a GIS analysis on six geophysical selection criteria. As a result of this analysis, 1459 hectares were identified as potentially suitable, which is 6% of the total land surface area of the island. In the case that all these locations would have a freshwater lens thickness of 15m, the total water storage capacity of the subsurface is 61,632,537 m^3. This number was calculated by incorporating the soil's porosity in a formula to determine the freshwater lens thickness. Furthermore, it was evaluated how much of the identified suitable area already meets the 15m thickness requirement. The findings showed that 60% of the identified locations do not meet this requirement yet.

This research also assessed factors that could limit freshwater lens enlargement. It was found that both presence of ditches and sea level rise have a negative effect on freshwater lenses. For sea level rise, it is projected that the freshwater lens volume will decrease with approximately 10%. Consequently, for the areas that have potential to reach a 15m thick, it is recommended to conduct additional research to assess which site-specific measures can be taken to enlarge the freshwater lens.

To conclude, the study showed that the freshwater provision for agriculture in Schouwen-Duiveland could be improved when a freshwater lens management plan for the identified areas would be initiated. Increased access to freshwater sources will contribute to the agricultural climate robustness of the island.

List of Abbreviations

BGH	-	Badon Ghijben-Herzberg
DEM	-	Digital Elevation Model
EC	-	Electrical conductivity
FRESHEM	-	FREsh Salt groundwater distribution by Helicopter ElectroMagnetic survey in the Province of Zeeland
GIS	-	Geographical Information Systems
KNMI	-	Koninklijk Nederlands Meteorologisch Instituut (Royal Dutch Meteorological Institute)
NAP	-	Normaal Amsterdams Peil, ± equal to mean sea level
SLR	-	Sea level rise

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Introduction

1.1 Background, context and problem statement

The Netherlands is worldwide renowned for its water management. By constructing dykes and sluices and using (wind)mills to pump out excess water, the Dutch have been able to shape their living environment. However, the changing climate poses a challenge to Dutch water management. It is expected that there will be more extreme weather conditions, resulting in more intense precipitation events and prolonged periods of drought (Seneviratne et al., 2012). Moreover, not only the intensity of weather events will change, also the frequency and timing of these events is on the verge of change (Seneviratne et al., 2012; van den Hurk et al., 2014). In the Netherlands, the summer of 2018 was characterised by high temperatures and low precipitation, together leading to a precipitation deficit forcing a hot, long drought (Buras et al., 2020). Yet, 2018 was not an exceptional year: the summers of 2019 and 2020 were also defined as drier than normal (KNMI, 2020).

The changing climate and its implications for water management in the Netherlands did not go politically unnoticed. The drought of 2018 motivated the Ministry of Infrastructure and Water to establish the 'Beleidstafel Droogte'. The goal of this 'Beleidstafel' is to make the Netherlands more resilient towards droughts by drafting advice and making recommendations for the future (Beleidstafel Droogte, 2019). One of these recommendations is to invest in retaining more water in the subsoil where possible and to combat salinisation. To execute the advised measures and to bridge knowledge gaps, Dutch governmental bodies allocated 800 million euros in total for the period 2022-2027 (Van Nieuwenhuizen Wijbenga, 2020).

Improving access to freshwater sources in periods of drought is crucial, not only to limit economical damage to the agricultural sector and to safeguard its productivity, but also to protect nature areas and to reduce fire risks (Beleidstafel Droogte, 2019). Next to the risk of drought itself, droughts can also reinforce salinisation processes, as the disappearance of freshwater pressure gives more room to capillary rise of saline groundwater (Stofberg et al., 2017). Coastal lowlands, such as the west of the Netherlands, turn more saline by the combined effect of soil subsidence, sea level rise (SLR) and changing seasonal precipitation schemes (Goes et al., 2009; Oude Essink et al., 2010; van Dijk et al., 2015).

An area to which the combination of proneness to drought and salinisation applies is the island of Schouwen-Duiveland, the most northern island of the Province of Zeeland. Schouwen-Duiveland consists of Schouwen (west) and Duiveland (east), which historically were separate islands. Over time, these islands were connected through natural and anthropogenic processes. Schouwen-Duiveland has a total land surface area of 22,965 ha, of which 59% is designated for agricultural exploitation (CBS, 2021). Agriculture in Schouwen-Duiveland exclusively depends on precipitation as prime freshwater source, as illustrated in figure 1 (van Duinen et al., 2015). This precipitation infiltrates in the soil, where it can form shallow or thick freshwater lenses, depending on the soil type (e.g. De Louw et al., 2013; Pauw et al., 2015; Stofberg et al., 2017). However, the vulnerability of these freshwater lenses is high (Stofberg et al., 2017). Considering their vulnerability, it is only legal to extract water from a freshwater lens when such a lens has reached a thickness of over 15 meters (Waterschap Scheldestromen, 2013, p.14).

Figure 1. Geographical overview of the south-western delta, which the study area is part of. It demonstrates which peninsulas and islands of the Province of Zeeland have access to external water supply (in green) and which have not (in orange) (van Duinen et al., 2015).

Therefore, a pressing societal question is how to make the island of Schouwen-Duiveland more resilient from a freshwater availability perspective, and thus more climate robust. Different options for Schouwen-Duiveland's agricultural future are currently being evaluated. Potential options include realising external water supply via a pipeline (De Puupe, n.d.), improving in-situ water buffering and storage, or changing to different modes or agricultural practice (Lenkens, 2017).

Previous research by e.g. Pauw et al. (2015) and Oude Essink et al. (2018) found that improving in-situ water storage can be successful in Schouwen-Duiveland with the help of certain water management and storage techniques. Additionally, freshwater availability in the subsoil has been mapped, showing the thickness of the freshwater lenses for the island of Schouwen-Duiveland (Delsman et al., 2018; Siemon et al., 2019). This map displays current state of freshwater lenses, however, an overview of all locations that are theoretically suitable for freshwater lens development of over 15m thickness is not yet provided. Furthermore, it is not evident how much water needs to be available for groundwater recharge to optimally utilise the island's freshwater storage capacity and how these reserves should be managed in the near future.

1.2 Research question and research aim

There is a need to provide an overview of suitable locations for freshwater storage on the island and their potential water storage volume, so that decisions regarding alterations in the current water management practices can be better informed. Therefore, the research question guiding this research is formulated as follows:

What is the future potential for freshwater lens storage on the island of Schouwen-Duiveland?

Because of different research steps necessary to provide an answer to the main research question, this question was divided into the following three sub-questions.

1. At which locations in Schouwen-Duiveland is there potential for freshwater lens development of >15m thick?
2. How much water (in m^3) can theoretically be stored at these locations in the subsurface?
3. How much water (in m^3) would be needed to enlarge the freshwater lenses in suitable locations to 15m thickness and how is this total volume affected by climate change and sea level rise by 2050?

This research aims to explore how to make Schouwen-Duiveland more climate robust by identifying freshwater lens locations and their water storage potential. The identified locations will be mapped to make the results more insightful to stakeholders, such as farmers, water managers, and decision-makers. The research offers an overview of which areas are in need of a critical water management assessment, which can be used as supporting material for the local waterboard's, Waterschap Scheldestromen, 'Planvorming Wateropgave' (execution plan for Schouwen-Duiveland's water management).

Theory and concepts

The goal of this section is to present the relevant concepts used in this research that link to the (geo)hydrological properties of the area. This is followed by a visualisation of how these concepts link to each other, in the form of a conceptual framework (figure 3).

2.1 Concepts

Sea level rise (SLR)

In this research, sea level rise (SLR) is defined as the absolute rise of the sea level. Factors contributing to SLR are thermal expansion of seawater due to warming of the ocean and added water volume as a result of melting processes on land (IPCC, 2007). With respect to Schouwen-Duiveland, SLR is relevant, as the island borders the North Sea, the Oosterschelde and the Grevelingen. The connection between the North Sea and the Oosterschelde is an open connection, meaning that there is tidal influence in the Oosterschelde (Rijkswaterstaat, 2021). Regarding the Grevelingen, the connection to the North Sea is closed off with the Brouwersdam. The aim is to bring back tidal influence with an opening in the dam, which would be operational by 2027 (Getij Grevelingen, n.d.). Initially, this would lead to a surface water level of NAP -20cm in the Grevelingen, however, with projected SLR it becomes more critical to maintain this level (Deltares, 2019). This implies that the island of Schouwen-Duiveland is prone to the effects of SLR on its north, west and south sides.

Soil permeability

A soil's structure and the pore size of the sediment determine the soil's unsaturated conductivity and its water retention potential (Kutílek, 2004). Sandy soils are coarse and have larger pores than clayey soil types. Smaller pores can retain more water, however, they also impact permeability which influences water storage after a precipitation event. Sands have better permeability than clay, therewith facilitating higher water infiltration flows (Vogel, 2000).

Schouwen-Duiveland consists of two main landscapes: 'clay over peat areas' and 'creek ridges' (Beets et al., 1992). During the Holocene, clay and peat were deposited, forming a semi-confining layer over the area (Pauw et al., 2015). Thereafter, tidal creeks emerged, incising the clayey-peat layer, being active between 750 BC and AD 700. Later, these ancient creeks were slowly filled up with sandy deposits. The landscape subsequently inversed because of human land reclamation, which made the peat soils subside (Pauw et al., 2015). Hence, the first lower-lying creek nowadays appears as an elevated ridge in the landscape. For the research area, the sandy creek ridges are better suitable for freshwater storage than the clayey areas.

Soil subsidence

Peat soils, developed during the Holocene, are sensitive to soil subsidence under oxygen rich conditions (Querner et al., 2012). Subsidence can only be brought to a halt when groundwater tables are kept sufficiently high. However, drainage, which is necessary to promote suitable agricultural conditions, accelerates soil subsidence (Querner et al., 2012).

Groundwater recharge

Water available for groundwater recharge is governed by the difference in precipitation and evaporation. A precipitation deficit is defined as a negative difference between precipitation and evaporation (Zamani et al., 2016) and leads to less groundwater recharge. Under climate change, higher temperature averages and temperature extremes are predicted for

the Netherlands (van den Hurk et al., 2014). A precipitation deficit contributes to drought development, as there is less water available for infiltration.

Drought

'Drought' is defined as: "a deficit of water relative to normal conditions" (Sheffield & Wood, 2012, p.11). Both the region of where the drought occurs and the duration of the dry period determine the severeness of the drought (Lloyd-Hughes, 2014). Drought is a phenomenon governed by human decisions on e.g. land and water management, combined with natural climatic variability (AghaKouchak et al., 2021). Therefore, drought is a process which humans have impact on.

Although 'drought' is very context specific, it is still useful to differentiate between meteorological droughts and hydrological droughts, and how the one can propagate into the other. Meteorological droughts originate from precipitation deficits combined with higher temperatures, leading to more evaporation (Wang et al., 2016). When groundwater cannot be fully recharged because of meteorological droughts, droughts in soil moisture are forced, called hydrological droughts (Peters et al., 2003; Wang et al., 2016).

Salinisation

Salinisation is the increase of salt concentration in groundwater or surface water (Pauw et al., 2012). The chloride concentration (mg/L) in water is a good proxy of salinity and commonly used in studies describing groundwater dynamics in coastal regions. Salinisation is driven by soil subsidence combined with sea level rise (Oude Essink et al., 2010). Stuyfzand (1986) defined water types based on their chloride concentration. Freshwater has a concentration <150 mg/L, whilst saltwater has a concentration over 10,000 mg/L. Because of the relatively high salt concentrations in the province of Zeeland, the fresh-salt division line is set on 1500 mg/L (Oude Essink et al., 2018). Salinisation takes place in seepage areas, where the fresh-salt division is close to the surface and there is little resistance. Higher salt concentrations in ditches negatively affect freshwater lenses.

Freshwater lenses

A freshwater lens is formed by precipitation followed by infiltration. Generally, three freshwater lens types can be distinguished: (1) freshwater lenses in dune areas, (2) freshwater lenses under creek ridges, (3) shallow rainwater lenses (De Louw et al., 2019). The first two types are formed following the theory as described by Badon Ghijben and Herzberg, currently known as the Badon Ghijben-Herzberg (BGH) principle (Drabbe & Badon Ghijben,1888; Herzberg, 1901). This principle relates groundwater levels to the depth of the fresh-saline interface, see figure 2.

$$h = \frac{\rho_s - \rho_f}{\rho_f} H \qquad \text{(equation 1)}$$

Where h is the groundwater table relative to the sea level, H is the relative depth of the fresh-saline interface, and ρ_f and ρ_s the densities of fresh and saltwater (1000 kg/m^3 and 1025 kg/m^3, respectively).

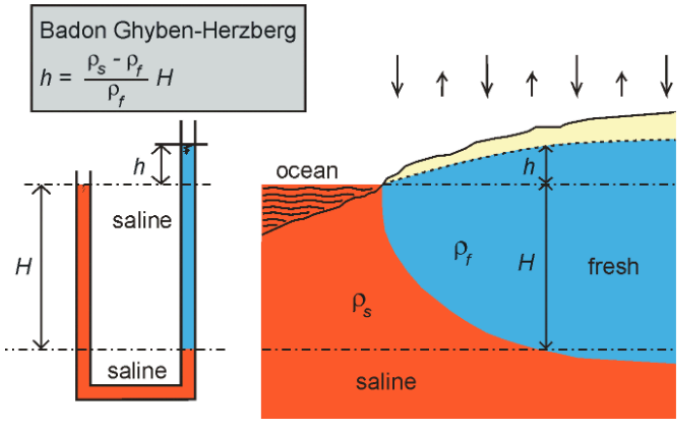

Figure 2. Visualisation of the variables of the BGH principle (Pauw et al., 2012).

The above implies that, theoretically, increasing the groundwater level (*h*) by 1 meter would create a freshwater lens of 40 meters deep. In the case of sea level rise, *H* will rise. If *h* cannot rise similarly to *H*, because of drainage, salt water will intrude the freshwater lens and the fresh-saline interface will move upwards (Pauw et al., 2012). Saltwater intrusion in a freshwater lens can also originate from over-extraction, leading to upward movement of the fresh-saline interface called upconing.

Water management
The surface water in Schouwen-Duiveland is managed by the waterboard Scheldestromen. Via ditches, sluices and pumps, excess precipitation is effectively discharged. The focus of the waterboard is to create a water system which is 'climate-proof' (Waterschap Scheldestromen, 2020). Their main task is to guarantee safety and prevent flooding events. Recently, this focus has been expanding and now also starts including retaining water where possible to be more resilient towards droughts. Therein, the ditch pattern and their function will have to be reviewed.

Water users also play a substantial role in water management. As AghaKouchak et al. (2021) state, water scarcity is also an anthropogenic phenomenon. If freshwater lens thickening succeeds at the identified suitable locations, the role of the user as water manager will become more important (Lopez-Gunn, 2003).

2.2 Conceptual framework
The relations between the concepts outlined above and their direction of interaction is explained by including these concepts in a conceptual framework as presented in figure 3. The concepts can be divided into three categories, namely *factor, process*, and *product*.

Temperature, groundwater recharge, sea level rise, soil permeability, and soil subsidence are *factors* influencing the *processes* drought and salinisation. A higher temperature forces sea level rise and drought development. Moreover, soil permeability influences infiltration and evaporation rates. Sandy soils are more susceptible to drought than clay, since bigger pores ease groundwater evaporation. However, high permeability can also combat drought, as permeable soil types better facilitate the generation of a freshwater buffer in the subsurface. Lastly, soil subsidence enhances seepage of saline groundwaters, forcing salinisation.

The *process* drought impacts the freshwater lens, i.e. the *product*, directly and indirectly. The direct impact of drought on the freshwater lens is that there is less groundwater recharge. Indirectly, drought reinforces the *process* of salinisation, which in turn negatively

influences the size of the freshwater lens. Because of an upward movement of the fresh-salt interface, the freshwater lens will shrink.

The blue dashed line encapsulates the five concepts impacted by the concept water management. Soil subsidence can be slowed down by performing adequate water management. Similarly, soil properties could steer the type of management. Therewith, the area would be better resilient towards droughts and salinisation is limited where possible, leading to improved freshwater lens water management.

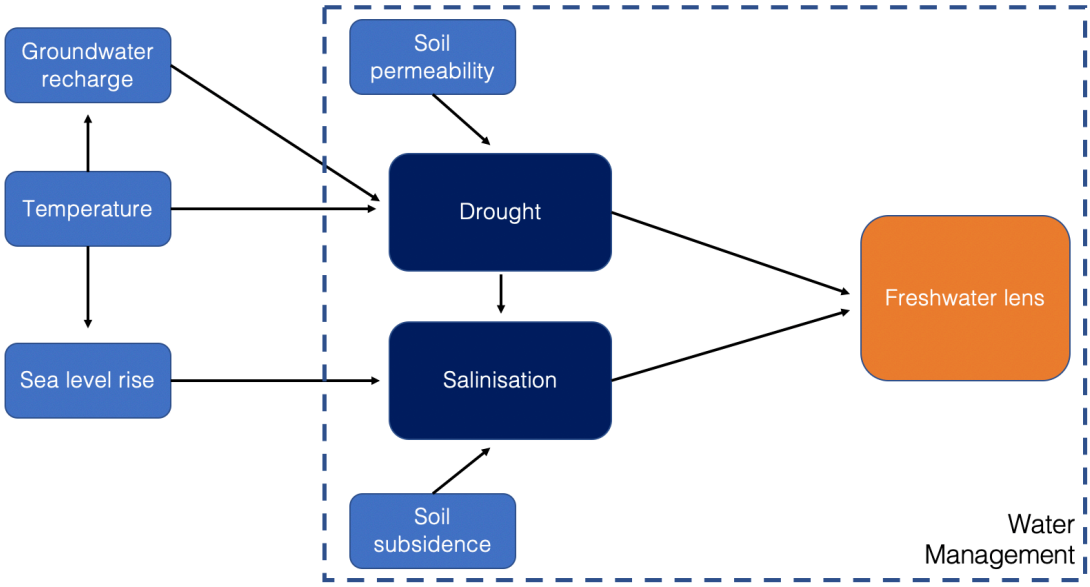

Figure 3. The relations between the factors (in blue), the processes (in dark blue) and the product (in orange) visualised in a conceptual framework.

Methodology

In this section, the methods used to collect and analyse data to generate insight in the theoretical potential of freshwater lenses in Schouwen-Duiveland, now and in the future, is presented.

3.1 Outline study area

The research was performed for the island of Schouwen-Duiveland, which is the most northern island of the Province of Zeeland. The choice for this area was based on the urgency to identify subsurface water storage potential, since the island naturally does not have access to external freshwater supply (van Duinen et al., 2015).

The dune area at the 'Kop van Schouwen', at the western side of the island, serves as drinking water production area, as illustrated in figure 4. Freshwater, originating from the Haringvliet, infiltrates and is pumped up again after at least 30 days (Evides, n.d.). A freshwater lens of >80m is present in this dune area (Siemon et al., 2019). However, because of the area's drinking water provision function, the freshwater lens in the dune area at the 'Kop van Schouwen' does not fall under the scope of this research and was excluded from analysis.

Figure 4. Drinking water production area (marked by a blue line) and locations of extraction wells (marked by black dots) at the 'Kop van Schouwen' (west side of Schouwen-Duiveland) as adapted from Provincie Zeeland (2015).

3.2 Identifying suitable locations

In order to be able to quantify the potential of freshwater storage on the island, first the sub-question covering which areas on the island are suitable for freshwater storage needed to be answered. This identification of suitable areas was based on six geophysical selection criteria, as modified from research conducted by Sommeijer (2013) in Walcheren, the island south of Schouwen-Duiveland. The selection criteria as used by Sommeijer (2013) could be

implemented in this research, because the main features of the two islands correspond. First, the hydrogeological setting is comparable, as agriculture at both locations is exclusively dependent on precipitation and the presence of freshwater lenses as water source (van Duinen et al., 2015). Thereby, the island is surrounded by saline water, forcing saline seepage and increasing proneness to salinisation (Zuurbier et al., 2015). Secondly, the stratigraphy of the two islands is comparable. Both islands have Holocene deposits consisting of tidal channels, flats and lagoonal sediments, which alternate with overlying peat beds present at the ground surface (Beets et al., 1992; Stafleu et al., 2011). The channels were filled with sands, enhancing the permeability on those creek ridges (Siemon et al., 2019).

3.2.1 Data collection: selection criteria

To generate an overview of suitable freshwater storage locations in Schouwen-Duiveland, the following geophysical selection criteria were applied:

1. The ground surface should be at or above 0 cm NAP;
2. Soil type should not be classified as 'clay' or 'peat';
3. The area cannot be 'built area';
4. The location should be an infiltration area (no occurrence of seepage);
5. The depth of the fresh-saline interface (1500 mg Cl^-/L) should be at least 5m below the ground surface;
6. There should be no presence of confining layers within the first 20m of the subsurface relative to NAP.

(*1*) The Digital Elevation Model (DEM) of the Netherlands was used as input data. This raster data can be freely accessed and downloaded with a 5 x 5m resolution (AHN_DTM_5m) (PDOK, n.d.-b). (*2*) Data on occurring soil types was retrieved via the waterboard Scheldestromen. The criterion that the soil should not classified as 'clay' or 'peat' is based on the condition that the soil needs to have a sufficiently high hydraulic conductivity for a freshwater lens to develop (Sommeijer, 2013). For clay and peat, this conductivity is too low. The soil type map presents the distribution of the main soil type classes of the first meter of the subsurface, signifying the importance of sufficient hydraulic conductivity enabling infiltration. (*3*) Built area was excluded from the analysis, as infiltration is hampered in built environments, for example due to soil compaction (Yang & Zhang, 2011). The data required for including this criterion (Top10NL-Plaats_kern) (PDOK, n.d.-a) was downloaded from the GIS L-drive, provided access to by Utrecht University. (*4*) Raster data on infiltration and seepage fluxes on the island was provided by the waterboard Scheldestromen. Seepage and infiltration fluxes during winter were analysed, as the winter season would most likely be used to enlarge freshwater lenses. (*5*) Data for the depth of the fresh-saline interface were acquired via Dataportaal Zeeland (Provincie Zeeland, n.d.). Within the research programme FRESHEM ((FREsh Salt groundwater distribution by Helicopter ElectroMagnetic survey in the Province of Zeeland), the probability of groundwater chloride concentrations were modelled and mapped (Delsman et al., 2018). The "1500 mg Cl^-/L midden grensvlakkenkaart" (interface map) was used in the data analysis. Regarding criterion (*6*), presence of clay layers in the subsoil was defined as a confining layer. It is only allowed to extract water from a groundwater reserve when this reserve has a depth greater than 15m (Waterschap Scheldestromen, 2013). Therefore, the last criterion set by Sommeijer (2013) is that there should be no confining layers within 20m from the soil surface. The subsurface model GeoTOP v1.4 was employed to check for confining layers. The data presented in this model is based on extrapolations of borehole descriptions, for which Zeeland has an excellent dataset (Stafleu et al., 2011). For each analysis performed in GeoTOP v1.4, the model provides insight in model uncertainty.

For the selection criteria 1-5, maps were generated that display which data is used and the distribution of the respective data over the study area. An overview of these individual maps can be found in Appendix A.

3.2.2 Data analysis: mapping locations

For each individual selection criterion, it was assessed how much the respective criterion contributed to the exclusion of unsuitable area for freshwater storage. Combining these data layers with the defined criteria was used as a method to mask out these unsuitable areas using ArcGIS 10.8.1, provided by Utrecht University.

The datasets employed consisted of two types of spatial data: raster and vector data. Only vector data allows the user to create new layers from the original dataset that for example show only the infiltration locations. Therefore, all raster data (DEM, infiltration and seepage fluxes, and the fresh-saline interface) were reclassified into two classes with the split value being the respective defined criterion. Thereafter, the reclassified raster data were converted to vector data. By using the ArcGIS tools *intersect* and *erase*, potential suitable locations for freshwater storage based on criteria 1-5 could be identified.

These potential suitable locations were qualitatively assessed for presence of confining clay layers with the subsurface model GeoTOP v1.4 by drawing transect lines. The cross-sections of the transect lines show the probability of clay presence in the first 25m from the ground surface. A probability of 0-0.2 implies that there is 0-20% chance that that entire cell as presented in the model consists of clay. For this research, a suitability judgement per cross-section was carried out. Herein, it was assumed that a probability of clay of >0.6 within the first 20m of the subsurface is unsuitable for freshwater storage and extraction.

Based on the identified suitable locations (criteria 1-5) and the subsurface analysis (criterion 6), a new shapefile layer was manually drawn in ArcGIS. Manually drawing this layer reduced the accuracy of the exact suitable locations. However, it was the only method by which the two analyses could be combined to generate one result. Furthermore, the surface area of this new layer based on criteria 1-6 was calculated in ArcGIS. These steps aided in formulating an answer to the second and third sub-question.

3.3 Calculating potential freshwater storage

3.3.1 Data collection: volume calculations

The most accurate freshwater lens volume estimations result from field scale modelling efforts. These numerical studies are site-specific, implying that it is difficult to directly translate field scale findings to a regional scale (Eeman et al., 2011). For this research, a simplified theoretical approach based on Van Dam (1983), Snel (2014), and Oude Essink & Pauw (2018) was followed to estimate the freshwater volume in m^3 per hectare of surface area. One m^3 equals 1000 litres of water. In this calculation, changing climatological factors, such as changing precipitation and evaporation patterns were not taken into account. The formula applied to calculate the volume of the freshwater lenses reads as follows (Snel, 2014):

$$V = 0.25 * \pi * L * H * (1 + \alpha) * \varphi \qquad \text{(equation 2)}$$

Table 1 shows the definition of the parameters present in the formula. Thereby, it also presents the input values used in calculating the volume.

Table 1. Explanation of the parameters and input values of equation (2).

Parameter	Unit	Definition	Input value
V	m^3/m'	Volume in cubic meters for depth *H* over width *L*	n.a.
L	m	Width of the freshwater lens	100
H	m	Thickness of the freshwater lens; depth of the fresh-saline interface	15
α	-	$\frac{\rho_s - \rho_f}{\rho_f}$ density difference between fresh- and saltwater	0.025
φ	-	Porosity: space in the sediment to store water in	0.35

The width of the freshwater lens (*L*) is set to 100m, as this allowed calculating the volume per ha. This approach was also taken by Snel (2014) and proved to be useful for simple calculations. A width of 100m is rather narrow, however, the surface areas of potential suitable locations vary, also because of varying ditch occurrence as further elaborated on in section 3.3.2.

The densities of freshwater, ρ_f, and saltwater ρ_s, are 1000 kg/m^3 and 1025 kg/m^3, respectively. This results in a density difference (α) of 0.025.

The porosity (φ) of a material can vary between 0 and 1. For the sediments present in the identified suitable areas, the porosity is assumed to be 0.35. This number is generalised for the entire area for workability purposes and based on previous research as conducted by Oude Essink et al. (2010) and Pauw et al. (2012).

The BGH-principle, as discussed in section 2.1, combined with Darcy's Law leads to a one-dimensional, steady state approximation of the thickness of the freshwater lens (*H*) (Van Dam, 1983; Oude Essink & Pauw, 2018). In order to be able to extract and use water from the freshwater lens sustainably, the thickness needs to be at least 15m (Waterschap Scheldestromen, 2013, p.14). Therefore, in the scenario sketch in which extraction can take place from all suitable locations, *H* is set to be 15m. However, *H* is normally influenced by other factors and calculated as presented in equation (3).

$$H = \sqrt{\frac{xf(-x+L)}{\alpha K(1+\alpha)}} \qquad \text{(equation 3)}$$

The three new parameters in equation (3) are explained in table 2, as also treated by Oude Essink & Pauw (2018).

Table 2. Explanation of the parameters and input values of equation (3).

Parameter	Unit	Definition	Input value
f	m/day	Continuous groundwater recharge	n.a.
x	m	Distance to nearest ditch, expressed as fraction of L	0.5*L*
K	m/day	Hydraulic conductivity	5

Under natural conditions, the thickness of the freshwater lens is governed by the groundwater recharge, f. *H* is maximal when x is set to 0.5*L* (Oude Essink & Pauw, 2018). For *K*, the average hydraulic conductivity is assumed to be 5 m/day for the entire area under analysis. This assumption was based on hydraulic conductivity data describing sandy subsoils, as also included by Snel (2014) and is an approximation of the *K* value used by (Oude Essink & Pauw, 2018).

3.3.2 Data analysis: factors affecting volume

The calculated volume results from a simplified theoretical approach. However, in reality, this volume is affected by amongst others the type of water management strategies in place. These are locally varying factors and therefore difficult to include in equation (2). For example, presence of ditches can negatively affect the size of a freshwater lens (Goes et al., 2009). To visualise which potential suitable locations for freshwater lens development are impacted by the presence of ditches, an overlay analysis was carried out. Data describing the location and waterflow direction of primary and secondary ditches was combined with the created GIS layer showing suitable freshwater locations based on criteria 1-6. As the characteristics of primary and secondary ditches are different, for both ditch types a map has been created. Primary ditches can discharge more water than secondary ditches, as they are wider and deeper. Yet, the abundance of secondary ditches is greater.

Furthermore, the salt concentration of the surface water in these ditches impacts the freshwater availability as well (Goes et al., 2009). The best and most recent data available for Schouwen-Duiveland originate from a project called 'Natuurlijk Zoet', initiated by the municipality of Schouwen-Duiveland, the Province of Zeeland, waterboard Scheldestromen and ASD (the agricultural association of Schouwen-Duiveland) and is led by the consultancy firm Acacia Water (Living Lab Schouwen-Duiveland, 2020). Twenty farmers measured the EC-value of the ditches in their surroundings every two weeks over a timespan of two years, which started in January 2019.

In this research, 'Natuurlijk Zoet' data on ditch salinity between Brouwershaven and Zonnemaire was selected for analysis. The reason for focusing on this part of Schouwen-Duiveland was that in this area the frequency of measurements was high compared to other areas. The data retrieved via an interactive interface 'Fixeau' (Natuurlijk Zoet, n.d.) was filtered and grouped per season in Microsoft Excel. Each measurement point in the selected area for analysis was required to have at least four measurements per season. The calculated seasonal averages of the measurements were imported in ArcGIS, classified and presented as coloured dots on a map. The colours represent EC-values in mS/cm. An EC-value of 3.0 mS/cm roughly translates to a chloride concentration of 1500 mg/L (Pauw et al. 2015). Combining presence of ditches and their EC-values can improve insight in the actual freshwater storage capacity of a specific site in Schouwen-Duiveland.

3.4 Determining enlargement and future dynamics

3.4.1 Data collection: enlargement

The calculated potential freshwater volume (as described in section 3.3) represents a theoretical volume for a fresh-saline interface depth of 15m. Since a 15m thickness is legally required before abstraction is permitted, this depth was chosen to perform calculations with for all areas. However, the FRESHEM data (Appendix A.5) show that not all locations have a depth of 15m. For these locations, it is necessary to know how much freshwater would need to be available for (active) infiltration to enlarge the freshwater lens to a depth of 15m. In ArcGIS, the FRESHEM "1500 mg Cl^-/L midden grensvlakkenkaart" interface map was combined with the created GIS layer showing suitable areas based on criteria 1-6, with the aim to identify the suitable areas with an interface depth of >5m and <15m. For these newly drawn polygons, surface area in ha and the average depth of the fresh-saline interface was determined. These two were used as input for calculating the freshwater volume difference between 'H=15' and 'H=average depth' for the respective polygon.

3.4.2 Data analysis: water availability and SLR

After collecting data on the amount of freshwater (in m^3) needed to enlarge the freshwater lens to 15m thickness in all potential suitable locations, this amount was compared to the natural freshwater availability per year in the respective area. The aim of this comparison was to assess the feasibility of enlarging the freshwater lens in these locations.

The average groundwater recharge for Zeeland is 169 mm/year, for which 1981-2010 was the reference period as applied by the KNMI (Oude Essink & Pauw, 2018; van den Hurk et al., 2014). A groundwater recharge average of 169 mm/year translates to 1690 m^3/ha/year. The recharge average was multiplied with the surface area of the potential suitable locations that need recharge (in ha). This calculation is based on the assumptions that the reference period is representative for the current situation on the island and that all groundwater recharge water available could actually be used for infiltration.

Projections of precipitation and evaporation are captured in four KNMI'14 climate scenarios for 2050, based on the IPCC climate change scenarios of the fifth assessment report. The scenarios are placed in a matrix with two axes: (1) the temperature rise (G for moderate and W for warm) and (2) the change in air stream patterns (L for low and H for high) (KNMI, n.d.). For each of these scenarios, the change in groundwater recharge was determined and the effects on the freshwater lens potential were analysed.

The Dutch sea level is projected to rise with 5.5 mm/year in the two W (warm) KNMI'14 scenarios for 2050 (van den Hurk et al., 2014). To include the severeness of projected SLR on the volume of the freshwater lenses, findings from two Deltares reports by Van Baaren et al. (2016) and Oude Essink & Pauw (2018) were applied to the Schouwen-Duiveland case.

Results

4.1 Suitable locations

Selection criterion 5 contributes the most to masking out unsuitable area for freshwater storage. By including only criterion 5, 66.1% of the total land area is excluded from further suitability assessment. Table 3 shows the suitable area left after including a second, third, fourth and fifth criterion. The order of including the criteria is based on which criterion caused the greatest reduction in suitable area. The complete assessment of each criterion's – individual and combined – contribution to area exclusion can be found in Appendix B.

Table 3. Overview of suitable area for freshwater storage in percentage after consecutively including criteria.

Criterion	Combined with criterion	Suitable area (% of total land area)
5	4	16.6
5, 4	2	12.4
5, 4, 2	1	9.8
5, 4, 2, 1	3	9.1

Figure 5 shows the geographical location of these potential suitable areas, based on criteria 1-5. Most identified potential suitable areas are located in Duiveland, the eastern side of the island. The former tidal creek can be recognised in the positioning of part of the potential suitable locations (the blue patch from north to south, east of Zierikzee), as creek ridge features (e.g. elevated and sandy subsoil) match criteria 1 and 2. Moreover, figure 5 also shows the location and direction of the transect lines that were drawn to include criterion 6.

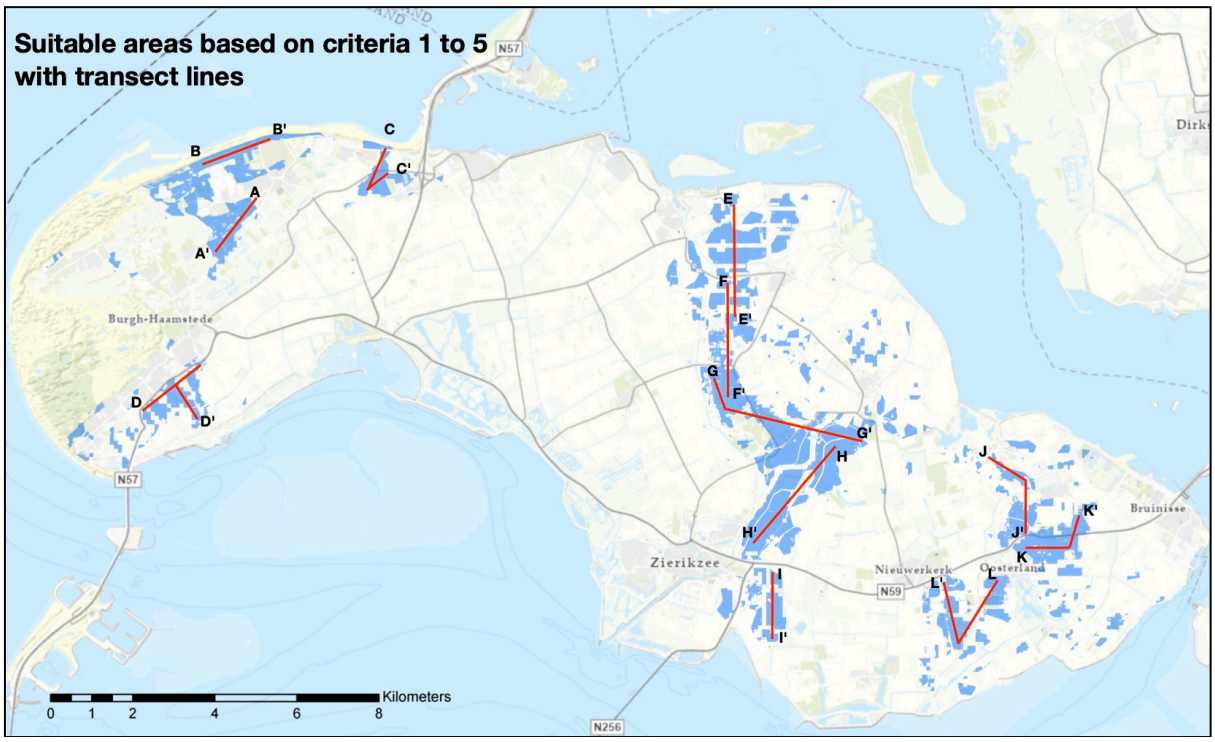

Figure 5. Identified suitable areas after implementing criteria 1-5 (in blue) and the location and direction of the drawn transect lines (in red).

The suitability judgement of the subsurface area shows that 4 cross-sections are considered unsuitable (line A-A', B-B', D-D', and L-L'), 6 cross-sections are considered suitable (line C-C', E-E', F-F', G-G', I-I', and J-J'), and 2 are considered partly suitable (line H-H' and K-K'). For these latter two transect lines, part of the line was suitable. For H-H',

the middle part of the line was cancelled out from further analysis. For K-K', the first half kilometre of transect line was excluded from further analysis. A visualisation of the transect cross-sections and their suitability judgement can be found in Appendix C.

Figure 6 presents the potential suitable locations based on selection criteria 1-6. The suitable area based on criteria 1-6 is 1459 ha, representing 6% of the total land area. Of this 1459 ha, only 63 ha is located in Schouwen, the western part of the island.

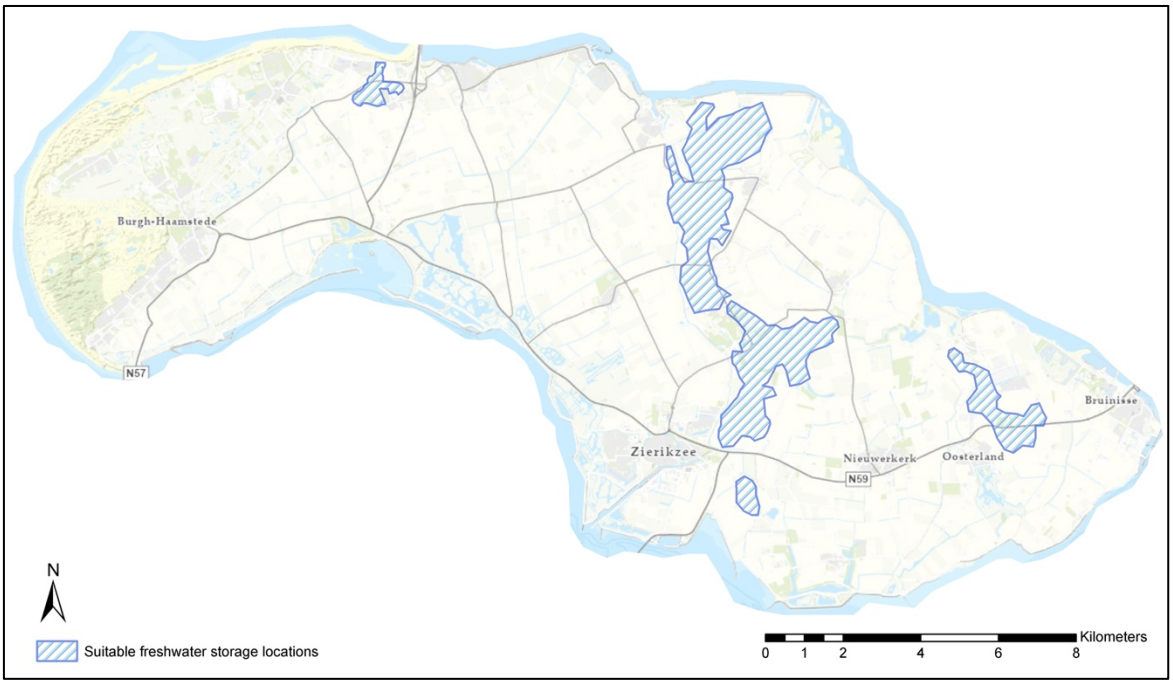

Figure 6. Identified suitable freshwater storage locations (in dashed blue) after implementing criteria 1-6.

4.2 Freshwater volume

The theoretical freshwater storage capacity of the subsoil at a freshwater lens location was calculated to be 44,243 m^3/ha for a fresh-saline interface depth of 15m. For the total suitable area, the freshwater volume would be:

$$44{,}243\ m^3/ha * 1459\ ha\ =\ 61{,}632{,}537\ m^3 \qquad \text{(equation 4)}$$

However, ditches impact the freshwater lens thickness and therewith also its potential volume. The primary ditches incise the potential suitable storage areas in several locations (see figure 7), which hampers the formation of a stable freshwater lens. The areas without primary ditches incising the potential locations are considered to be more suitable for lens formation.

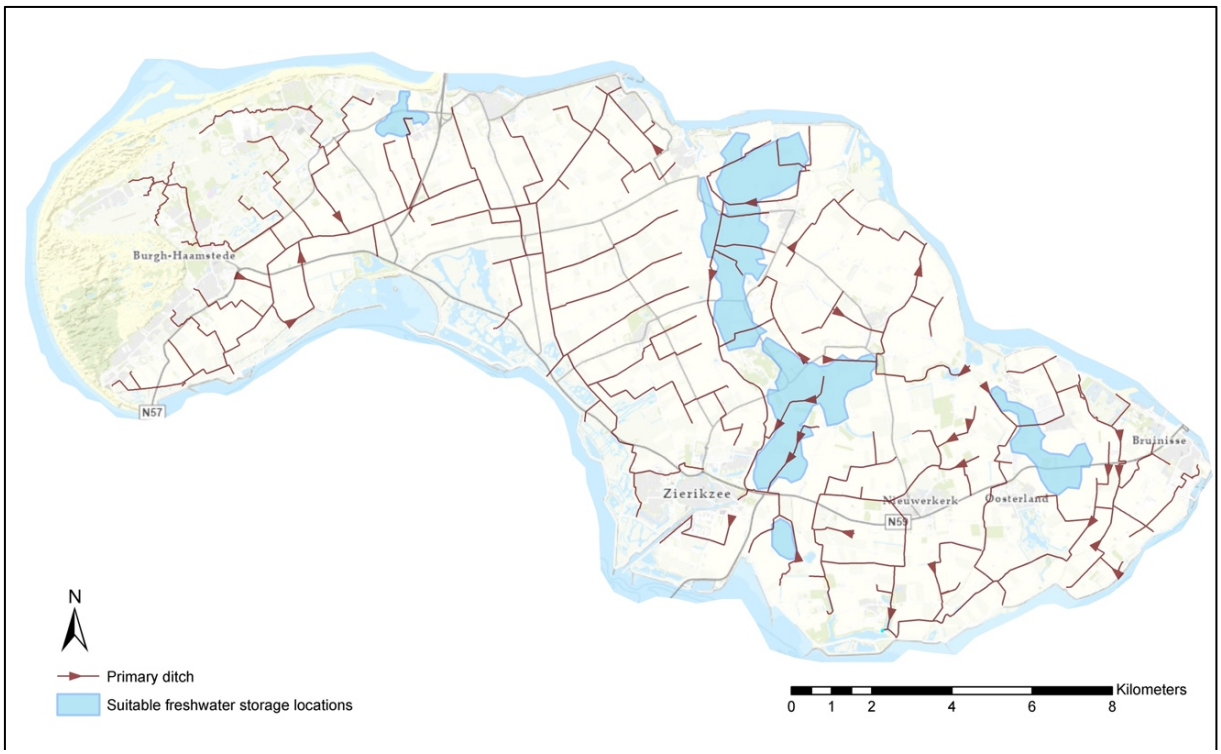

Figure 7. The location of primary ditches (in red) and their direction of flow overlaying the potential suitable freshwater storage locations (in blue).

The secondary ditches are more abundant (see figure 8). All potential suitable locations are cut by these secondary ditches, thus affecting the successfulness of freshwater lens establishment or enlargement of the different suitable locations in a similar way.

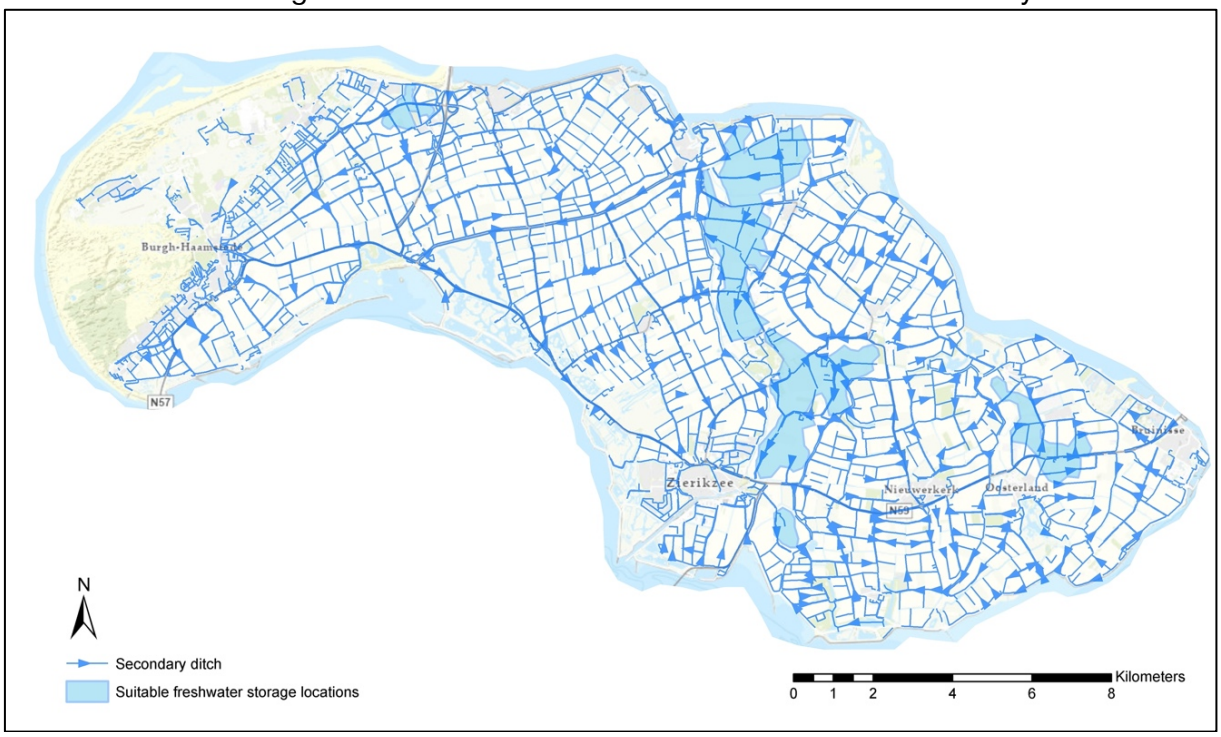

Figure 8. The location of secondary ditches (in dark blue) overlaying the potential suitable freshwater storage locations (in blue). For readability of the maps, the potential suitable area is not marked with dashed lines, such as in figure 6, but by a homogenous blue colour, preventing interference of the marked dashed areas with the indication of the ditch locations.

From the EC-character analysis of the primary and secondary ditches for the area between Brouwershaven and Zonnemaire, it was concluded that the primary ditch is saline (>10 mS/cm) (see figure 9). EC-values between 3.0 - 20 mS/cm were found for secondary ditches close to the Grevelingen. Salinity effects are stronger expressed in summer and autumn. Freshwater values (<3.0 mS/cm) are found in ditches where agricultural drains discharge excess field water on. The flow direction of the ditches is southwards, implying that the saline water observed in the ditches is transported through large part of the potential suitable freshwater lens area.

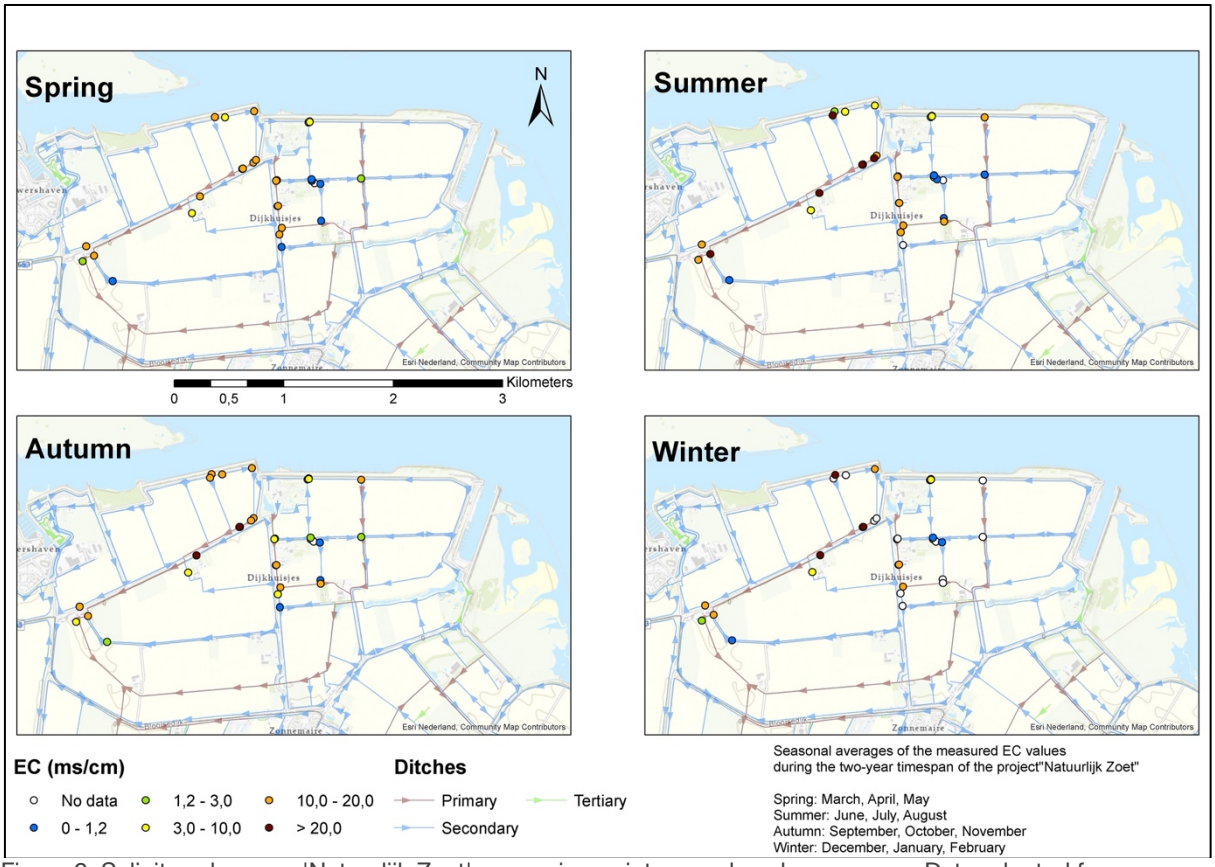

Figure 9. Salinity values per 'Natuurlijk Zoet' measuring point as analysed per season. Data adapted from Natuurlijk Zoet (n.d.).

4.3 Enlargement and future dynamics

Resulting from the ArcGIS analysis in which the FRESHEM data was compared to the total suitable areas layer, it can be concluded that the area from which freshwater can be abstracted can theoretically increase with 874 ha (from 585 ha to 1459 ha). This is an increment of 150 percent in potential suitable area that has an interface depth of at least 15m.

Figure 10 shows which areas within the identified potential areas do not yet meet the 15m depth requirement for freshwater abstraction. An overview of these surface areas, the average depths of the interfaces and the theoretical water volume needed for recharge is given in table 4.

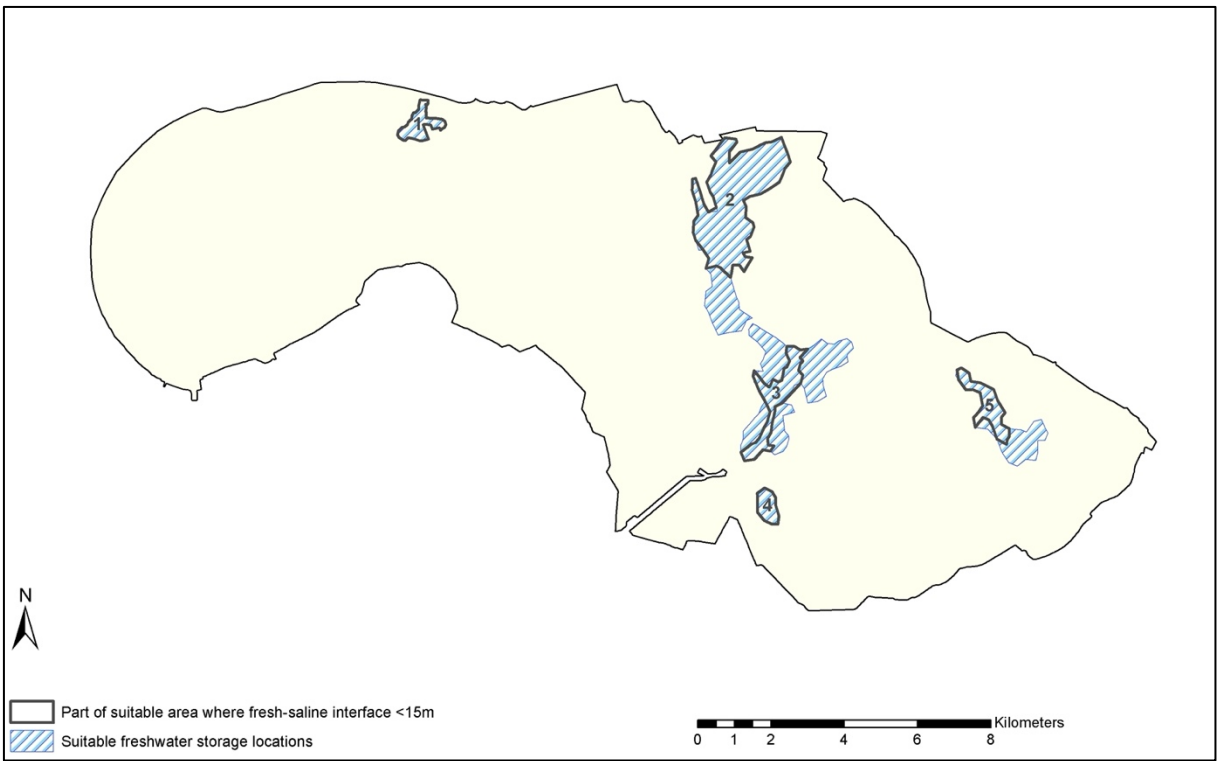

Figure 10. Areas within the identified suitable areas that do not meet the 15m interface depth requirement (as numbered 1 to 5).

Table 4. Overview of the area (in ha) becoming available for abstraction when the depth of the fresh-saline interface is increased to 15m, and the amount of water needed for this recharge.

Location	Surface area (in ha)	Average depth fresh-saline interface (in m)	Amount of water needed for recharge (in m^3)
1	63	10 m	887,099
2	532	7.5m	11,236,588
3	142	12.5m	999,747
4	44	7.5m	929,342
5	93	10m	1,309,527
Sum	**874**		**15,362,303**

The total amount of water needed for recharge is 15,362,303 m^3. From the analysis, it follows that when yearly groundwater recharge (1690 m^3/ha/year) is taken as freshwater recharge source, the entire area that needs recharge to enlarge the freshwater lens receives 1,477,060 m^3/year. This implies that it would take 10-11 years to enlarge the freshwater lens, under the conditions that all water is used for enlargement.

The analysis on groundwater recharge availability under the four KNMI climate scenarios show that only for the most extreme scenario WH (warmer and high change in air circulation patterns) the availability decreases from 169 mm/year to 155 mm/year. For the other scenarios, the effects of climate change are minor or even advantageous for groundwater recharge potential (Oude Essink & Pauw, 2018). In the WH-scenario, the entire area that needs recharge to enlarge the freshwater lens receives 1,354,700 m^3/year. The total groundwater recharge availability will thus decrease with approximately 8% in the WH-scenario.

By implementing the findings by Van Baaren et al. (2016), it is determined by how much percent the volume of a freshwater lens can decrease in a 10 ha radius around the groundwater abstraction point under SLR of 5.5 mm/year (see Appendix D). For each of the potential suitable areas on Schouwen-Duiveland, the range of impact (in % of total SLR) is shown in figure 11. Most of the identified areas will face a decrease of around 10% in volume (see table 5) under projected SLR (based on Appendix D).

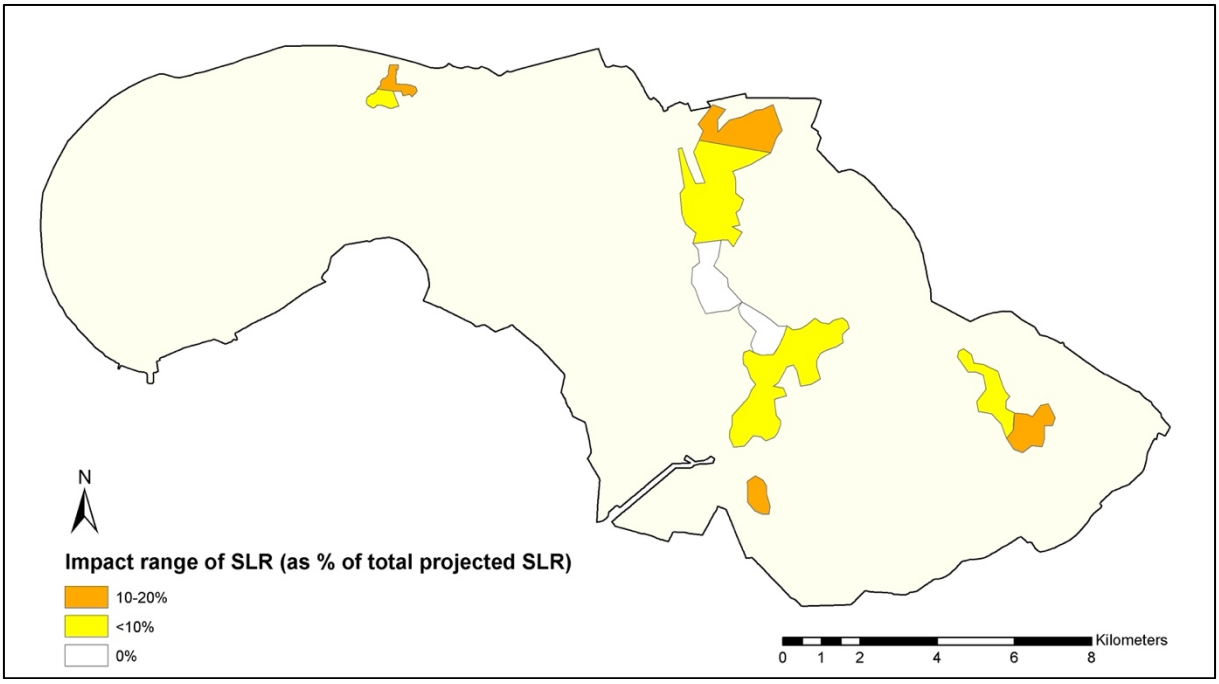

Figure 11. Area of influence of SLR on the groundwater system, as percentage of the total projected SLR under KNMI scenario WH. Data adapted from Van Baaren et al. (2016).

Table 5. Change in freshwater volume under predicted SLR in the WH-scenario for 2050.

	Impact range effect SLR	Relative decrease volume freshwater lens (%)	Total area affected (in ha)	Absolute reduction water volume (in m^3) for the affected area*
White	0%	0	227	0
Yellow	<10%	0 - 9.8%	890	0 – 3,684,418
Orange	10-20%	9.8 - 11.8%	340	1,407,503 – 1,694,781

* Absolute reduction in water volume (in m^3) is calculated with a 15m thick freshwater lens.

Discussion

This research identified suitable locations for freshwater storage in Schouwen-Duiveland and their theoretical water storage capacity. Out of the entire island's surface area, 6% was considered suitable for freshwater lens development. Almost all these locations are located in Duiveland. Part of that suitable area (585 ha, 40% of total suitable area) already meets the 15m fresh-saline interface depth requirement for abstraction to be allowed. Under certain conditions, it is possible to increase the interface depth in the resulting areas that do not meet the 15m requirement yet, as further discussed in this section. The analysis of the impact of SLR under climate change scenario WH yielded that the volume of the lenses decrease with approximately 10% in case of freshwater abstraction, negatively impacting the robustness of the freshwater lenses in the future.

The results of the suitability analysis indicate that characteristics of the top sediments and the subsoil stratigraphy play a crucial role in facilitating freshwater lens development. These characteristics are inherent to criteria 2 and 6, and govern criteria 4 and 5. The inclusion of criterion 6 reduced the potential suitable area with 33% (from 9% to 6% of the island's land surface area). However, the FRESHEM map (Appendix A.5) shows that interface depths of >15m were detected in areas that were identified as unsuitable following from the suitability analysis. This is true for the area in the eastern part of Duiveland, around Nieuwerkerk, Oosterland and Bruinisse. This discrepancy in findings could possibly be explained by a too rigorous approach taken in positioning transect lines and assessing presence of confining layers, thus excluding areas that should have been included. Another explanation could be that a freshwater reservoir is underlying saline groundwaters, which are separated by clayey aquitards (Delsman et al., 2018). These reservoirs can be detected by the performed electromagnetic surveys, and are therefore visible on the FRESHEM map.

Large part of the identified suitable areas are not yet managed to their full potential (874 ha), as came forward from the analysis covering how much water would theoretically be needed to enlarge the freshwater lenses in the areas that meet all six geophysical criteria. The analysis on ditch presence demonstrates that all identified freshwater reservoirs are negatively influenced by the draining function of ditches. If part of this draining function would be limited, by for example lowering the water level in the ditches during wintertime, the enlargement of the freshwater lens would be stimulated (van Duinen et al., 2015). Moreover, ditches are mainly brackish or saline due to occurrence of seepage (Siemon et al., 2019), which was confirmed by the analysis on EC-values in the area between Brouwershaven and Zonnemaire. The EC-values were generally higher in summer and autumn, showing the effects of less precipitation and higher evaporation on salinisation. This analysis covered only a minor part of Schouwen-Duiveland, however, it matches an area that was identified as suitable, but does not meet the 15m interface depth requirement. The latter suggests that the presence of saline ditches is part of the explanation for a reduced freshwater lens thickness. Saline water cutting through potential suitable areas could cause salt pollution of the freshwater lenses, further decreasing their enlargement.

To limit the negative effect of ditches on freshwater lens development, the following measures can be taken: (1) changing the ditch characteristics; (2) changing the ditch pattern. A ditch can be made less deep, to partly prevent the rise of saline groundwater. In turn, to guarantee a similar discharge capacity, the ditch will have to be widened, which costs land. Changing the ditch pattern includes the removal of redundant ditches (Sommeijer, 2013). Moreover, as the goal of changing the ditch pattern is to generate a larger area with fresh surface water occurrence, the type of changes should be mainly informed by the EC-value of the ditches. Actions include reversing the flow direction or

adjusting weir placement to better separate fresh and saline ditch streams (Pauw et al., 2015). As the EC-value analysis was only carried out for part of the study area, it is less certain how high these values are for the primary and secondary ditches cutting the remainder of the identified suitable storage areas.

The water volume (in m^3) theoretically needed to enlarge all suitable areas to 15m depth was calculated to be 15,362,303 m^3. However, this calculation was performed assuming the optimal situation that a depth of 15m (*H*) could be reached. Following the BGH-principle and equation (1), the thickness of the freshwater lens (*H*) is dependent on the groundwater table (*h*). This implies that the water table has to be raised to a certain height to facilitate enlargement of the freshwater lens (Pauw et al., 2015). However, increasing the hydraulic head is not possible at all locations, since this lowers the buffering capacity of the total water system and thus can lead to a higher flood risk in case of extreme precipitation events (Pauw et al., 2015; van Bakel et al., 2014). Thereby, too high hydraulic heads can lead to root deterioration in agricultural fields (Zuurbier et al., 2015). Additional research is required to locate where in the water system is room for raising the water table during winter, so that natural enlargement of the freshwater lens will be facilitated. If increasing the hydraulic head is not feasible, infiltration techniques such as aquifer storage and recovery (ASR) as proposed by Zuurbier et al. (2015) could be considered. These type of techniques are less cost efficient than conventional abstraction, so per implementation case it should be evaluated if these extra costs outweigh the loss in production during dry years.

The presented results are slightly reduced in reliability because of the following assumptions: (*1*) soil types 'clay' and 'peat' are considered unsuitable for freshwater lens development (section 3.2.1); (*2*) suitability judgement of the subsurface is based on single transect lines drawn in GeoTOP (section 3.2.2); (*3*) the borders of the final identified suitable area are manually smoothened; (*4*) an interface depth of *H*=15m can be reached at all identified suitable locations (section 3.3); (*5*) parameter settings for freshwater lens volume calculations are generalised for all identified suitable locations (section 3.3). Therefore, detailed field modelling studies and local measurements are required to assess whether these assumptions represent actual field conditions. Still, the generated results provide a useful overview of locations where this additional research should be conducted, and subsequently where enlargement projects can be initiated.

Furthermore, another limitation can be found in the type of data that was analysed. Although the maps analysed in ArcGIS are the best data available for Schouwen-Duiveland, the presented data is based on extrapolations of measured data points and/or model outcomes. Modelling and extrapolating data involves making assumptions, which causes the results to be an approximation of the actual situation. Moreover, some maps, such as the FRESHEM map, have null values. This caused that these areas were automatically excluded from further analysis, while they could potentially be suitable for freshwater lens enlargement.

Lastly, data on ditch salinity was obtained by using EC-values collected by farmers that participated in the 'Natuurlijk Zoet' project (Natuurlijk Zoet, n.d.). The collection of data for scientific purposes by non-scientists is referred to as 'citizen science' and can be valuable for knowledge generation in hydrological sciences (Buytaert et al., 2014). The EC-values of the ditches were not measured every two weeks at the same location, therefore, the data for most of the measurements in the 'Natuurlijk Zoet' project are considered inaccurate and not suited to be employed as primary dataset. However, the measurements give a good first impression of the state of the ditches throughout the year. Furthermore, this participatory approach in which farmers are actively included in research also adds value to

increasing their willingness to participate in future (research) projects (van de Gevel et al., 2020).

The findings demonstrate that the freshwater lenses are mainly located in Duiveland. Schouwen will thus be more prone to drought stress in the future than Duiveland. The freshwater reserves in the dune area in Schouwen were not included in this research, because of their drinking water provision function. Nevertheless, freshwater exfiltration occurs in the edges of the dune area (Van Baaren et al., 2012). Future research could focus on how this exfiltration water can possibly be used as freshwater source for sustaining agriculture in Schouwen.

This research contributes to the acceleration of working towards a sustainable, climate robust freshwater future for the island of Schouwen-Duiveland. Potential new abstraction locations were identified, so that water availability can be matched to demand where possible. It was concluded that it would take 10-11 years of groundwater recharge capacity to enlarge all suitable freshwater lens areas to a thickness of 15m. Therefore, it is crucial that the waterboard and local users start a freshwater lens management plan for the identified suitable areas. Farmers are also encouraged to take additional action on sustainable water management, motivated by extra funds made available by the Ministry of Agriculture, Nature and Food Quality, as part of the Dutch Climate Agreement (Smit, 2021). The insights acquired in the process of striving for a ‘climate-proof’ Schouwen-Duiveland could potentially also be instrumentalised to increase freshwater robustness in other coastal areas worldwide.

Conclusion

Agriculture in Schouwen-Duiveland exclusively relies on precipitation and freshwater lenses as water source. Long periods of drought in combination with salinisation pose a threat to the island's freshwater provision. Therefore, this thesis aimed to provide insight in the potential for in-situ water storage by means of posing the research question: *What is the future potential for freshwater lens storage on the island of Schouwen-Duiveland?*

Through data analysis in GIS, it was found that 1459 ha (6% of the island's land surface area) would be suitable for freshwater lens development. If a fresh-saline interface depth of 15m is met for all suitable locations, a total of 61,632,537 m^3 could be stored in the subsurface. It was found that 60% of the identified locations have an interface depth of less than 15m. To enlarge the freshwater lenses in these areas, a total of 15,362,303 m^3 is needed. This enlargement takes at least 10 years if groundwater recharge is utilised as water source for enlargement. However, freshwater lens development is hindered by presence of ditches, of which part has high salinity values. Additionally, SLR also impact freshwater lens volume: in KNMI climate scenario WH, the freshwater lens volume decreases with approximately 10%.

It can be concluded that on the island of Schouwen-Duiveland, there is potential for freshwater lens enlargement if a freshwater management plan would be implemented and executed by the waterboard and the land users. It is recommended that this plan includes a focus on water retention and facilitating infiltration, so that Schouwen-Duiveland is not only well prepared for flooding events, but also can cope well with periods of drought.

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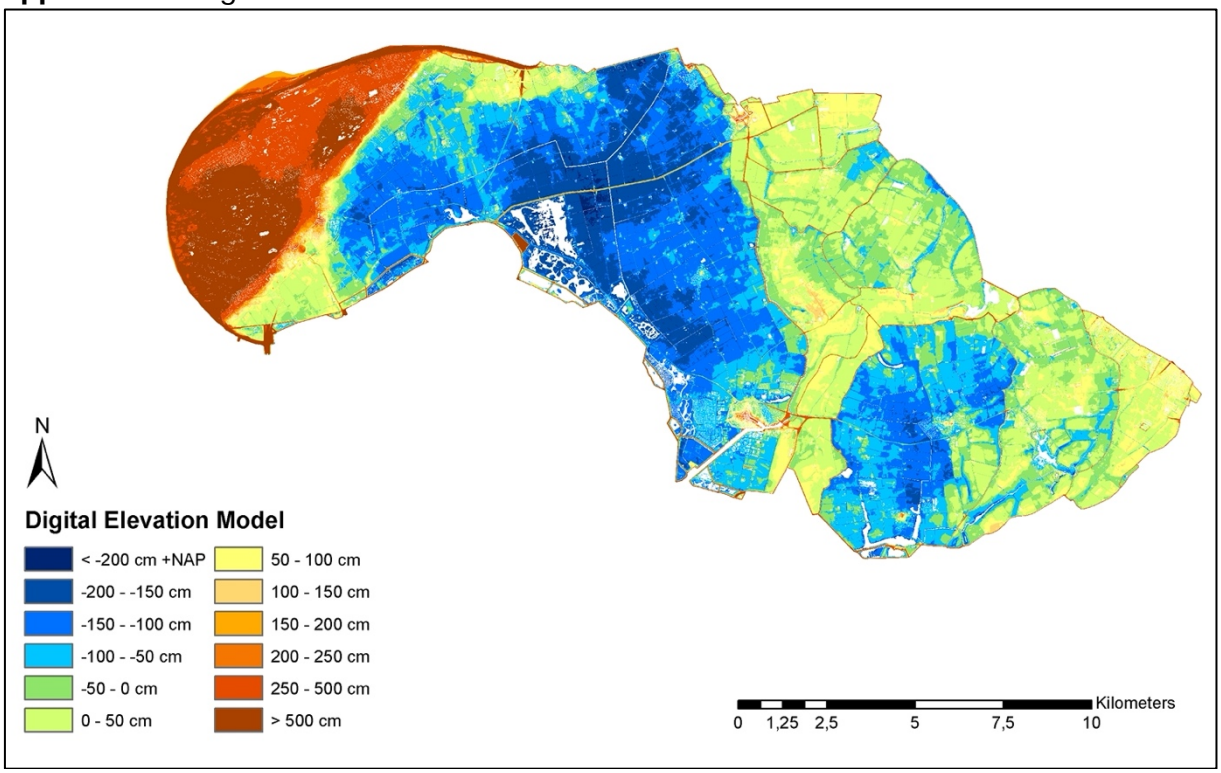
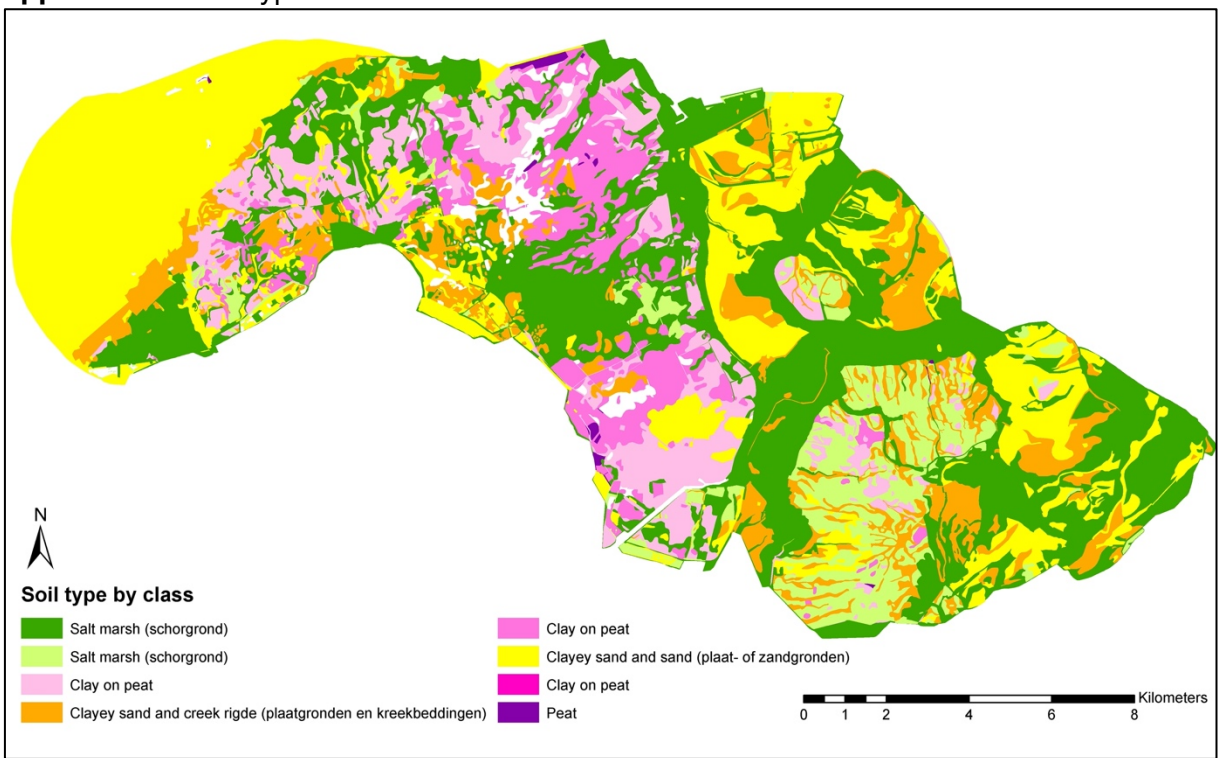
Appendices

Appendix A. Maps displaying features of individual selection criteria

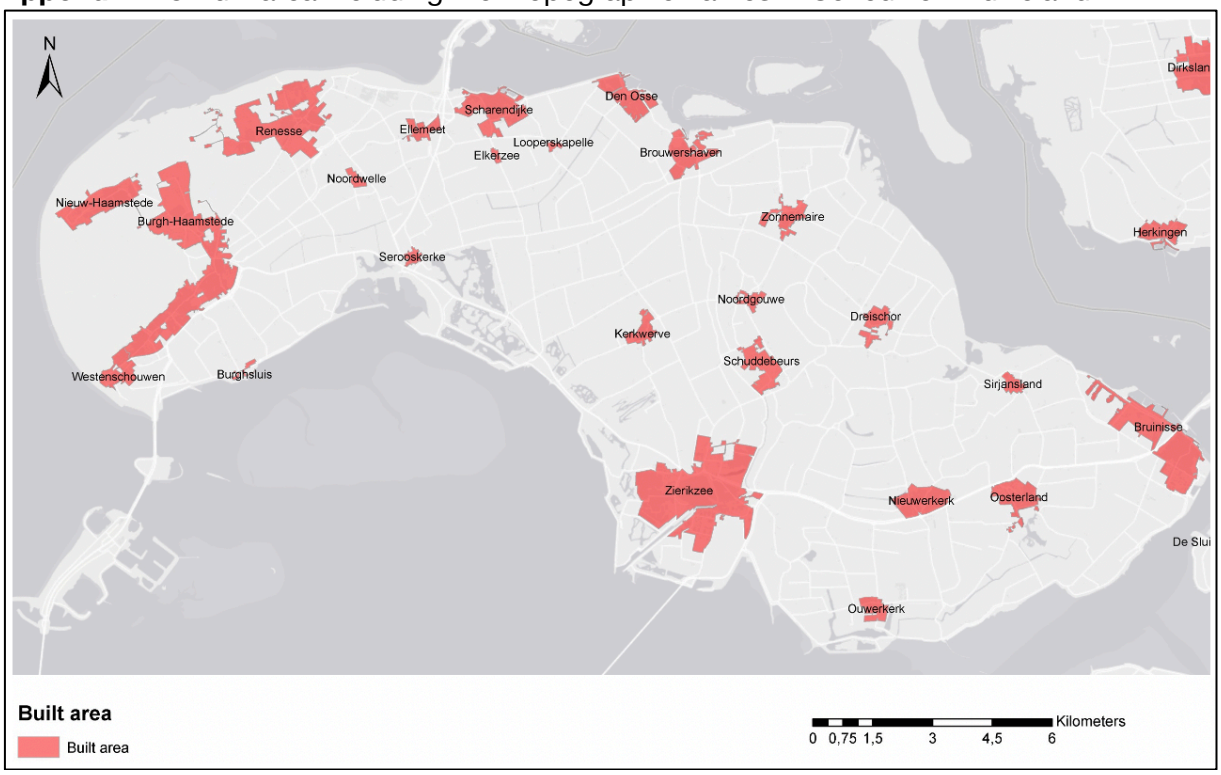
Appendix A.1 Digital Elevation Model of Schouwen-Duiveland.



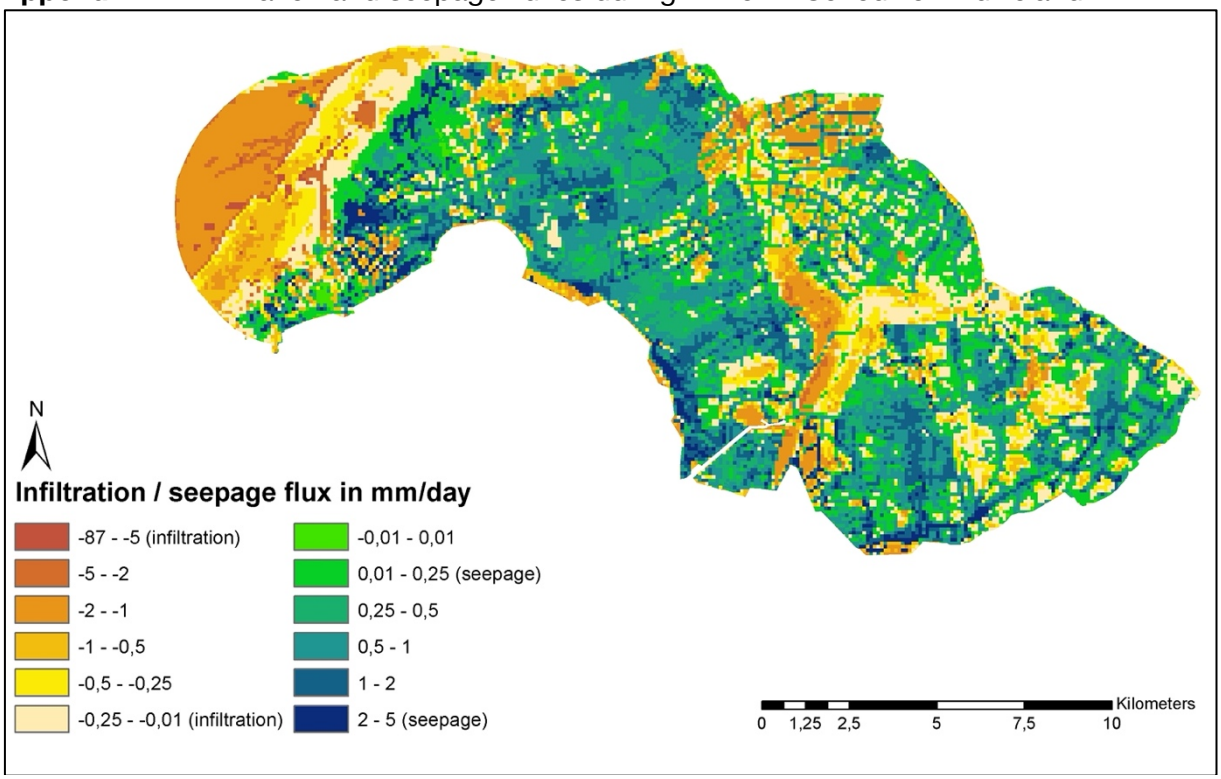
Appendix A.2 Soil type of the first meters of the soil in Schouwen-Duiveland.



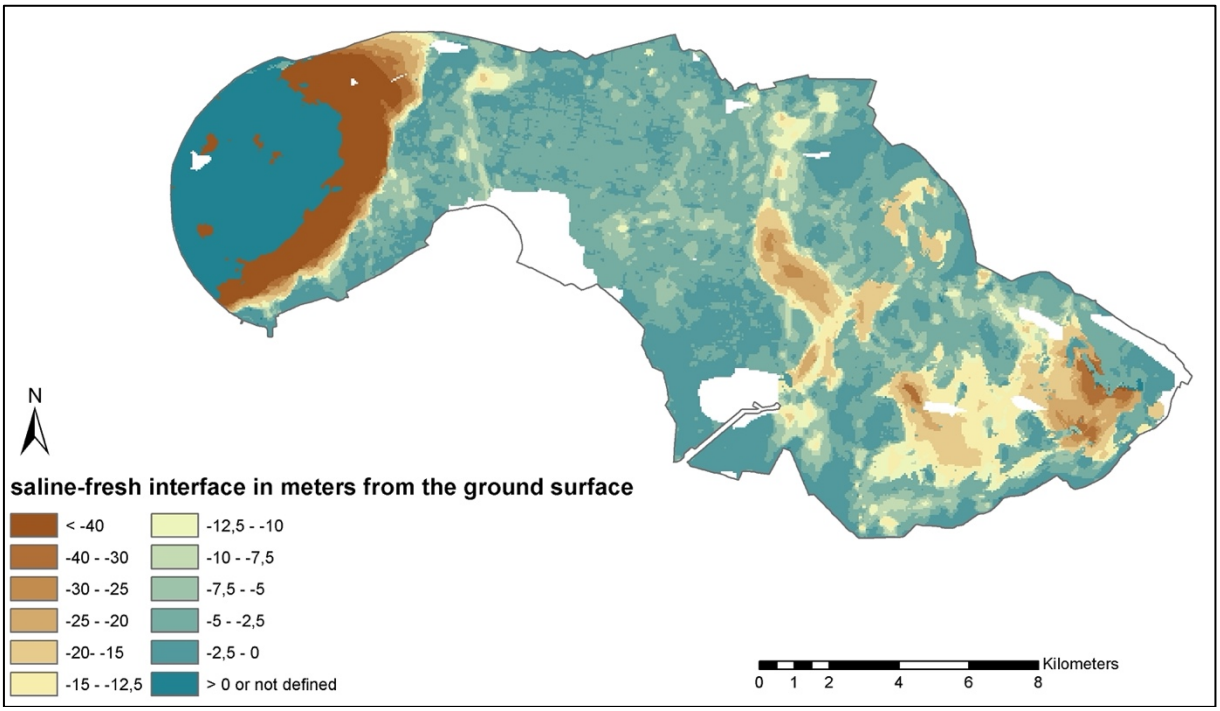
Appendix A.3 Built area including their topographic names in Schouwen-Duiveland.



Appendix A.4 Infiltration and seepage fluxes during winter in Schouwen-Duiveland.



Appendix A.5 Fresh-saline interface as measured by FRESHEM covering most of Schouwen-Duiveland.

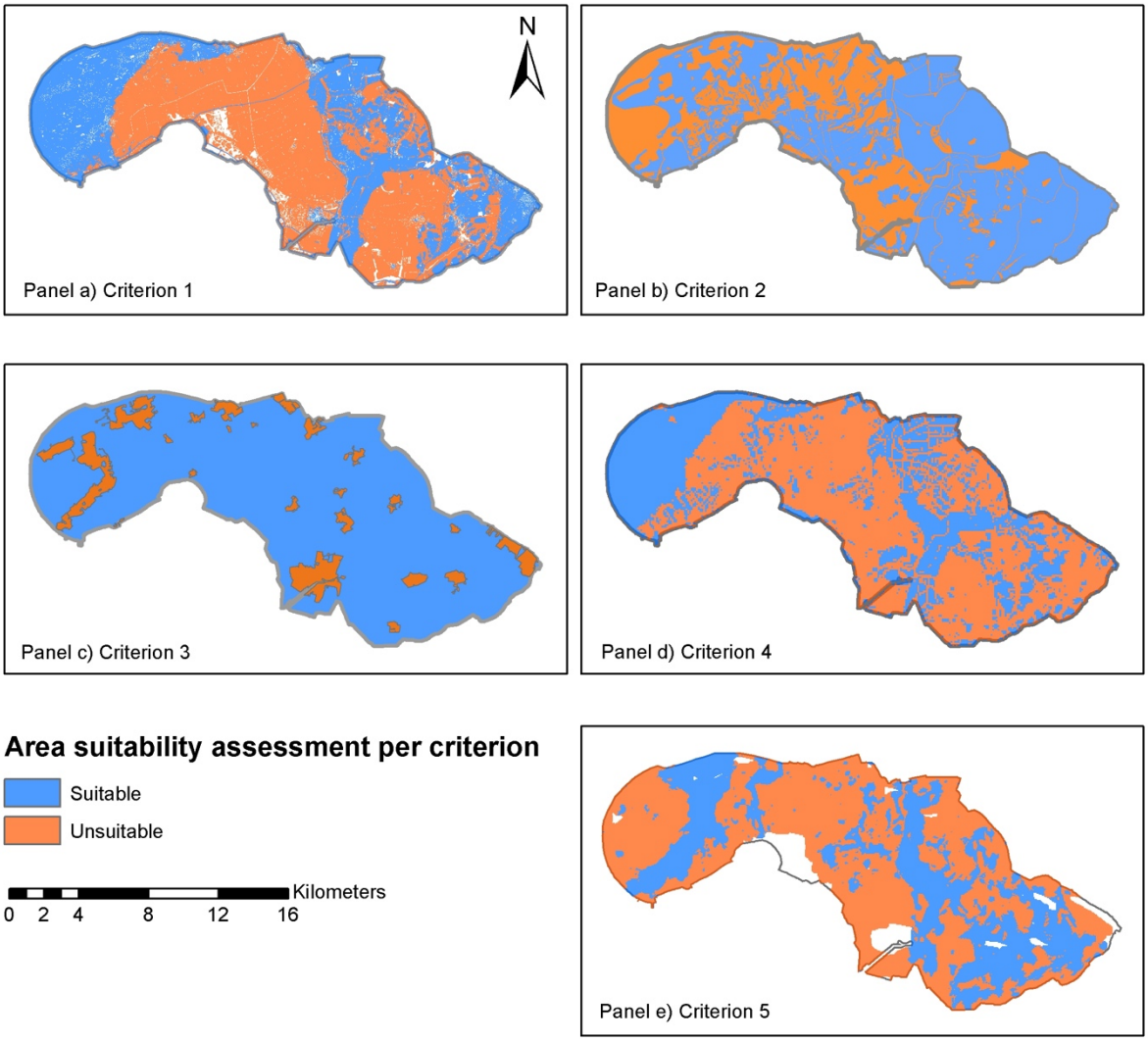


Appendix B. Impact of criteria on area exclusion

Appendix B.1 Insight in the impact of individual selection criteria on area exclusion.

Criterion		Suitable area	
		Ha	*% of total land area*
1	Ground surface should be at or above 0 cm NAP	8,839	38.5%
2	Soil type should not be 'clay' or 'peat'	13,858	60.4%
3	Area cannot be built area	20,690	91.0%
4	The location should be an infiltration area	8,720	38.0%
5	The depth of the fresh-saline interface should be at least 5m below the ground surface	7,775	33.9%

Appendix B.2 Maps showing per criterion which part of the surface area is excluded by that respective criterion (orange) and which part is included in further analysis (blue).

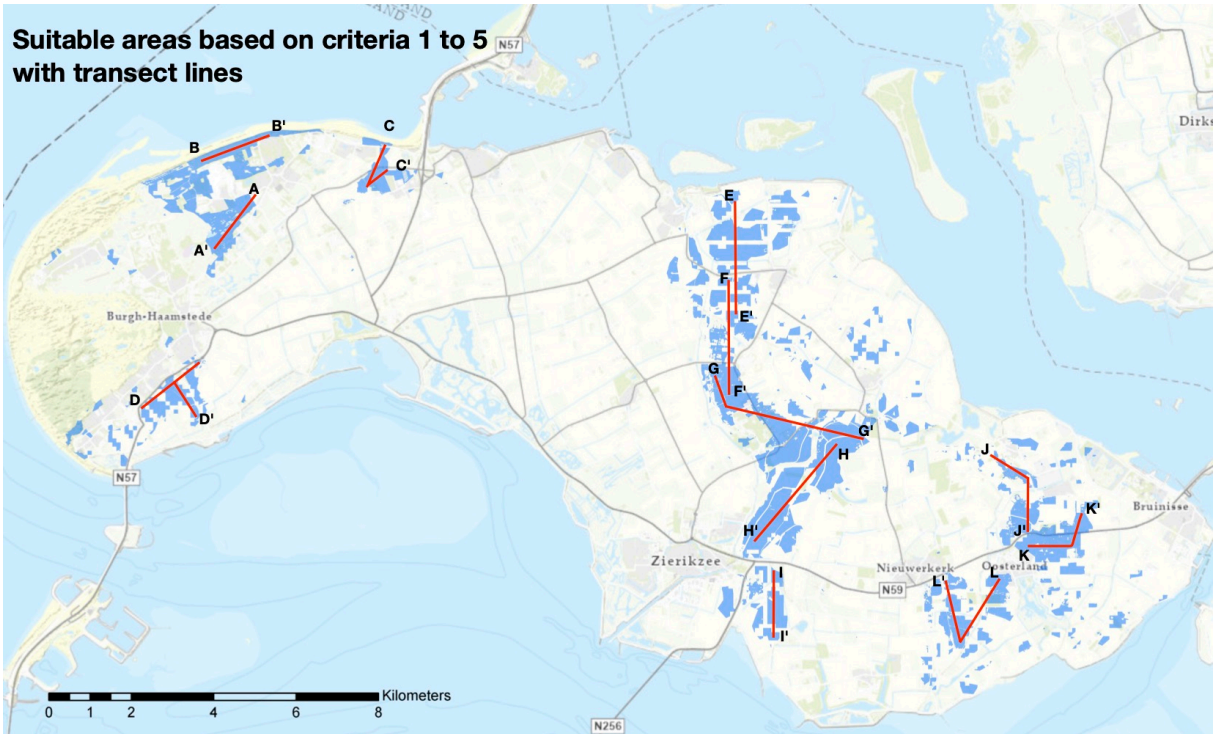


Appendix B.3 Insight in the contribution of each of the selection criteria in combination with other criteria to area exclusion.

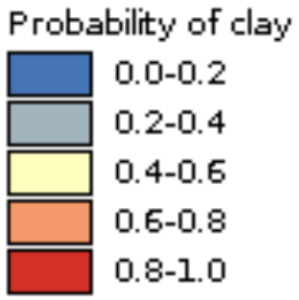
Criterion	Combined with criterion	Suitable area	
		Ha	*% of total land area*
5	1	3,954	17.2%
5	2	5,801	25.3%
5	3	6,913	30.1%
5	4	3,821	16.6%
5 & 4	1	2,963	12.9%
5 & 4	2	2,850	12.4%
5 & 4	3	3,186	13.9%
5 & 4 & 2	1	2,251	9.8%
5 & 4 & 2	3	2,643	11.5%
5 & 4 & 2 & 1	3	2,100	9.1%

Appendix C. Properties of the subsurface

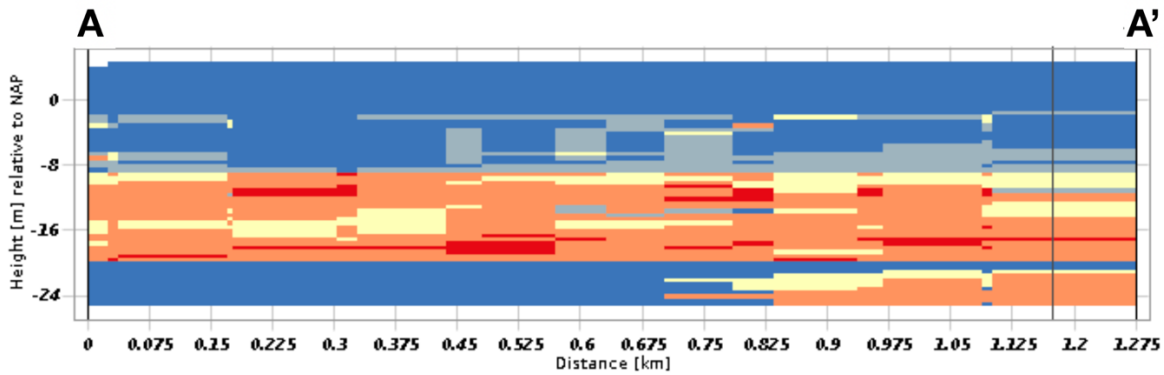
Appendix C.1 Overview of suitable areas (indicated in blue) and the transect lines drawn (indicated in red). The letters correspond with the letters of the vertical cross-sections retrieved from GeoTOP.



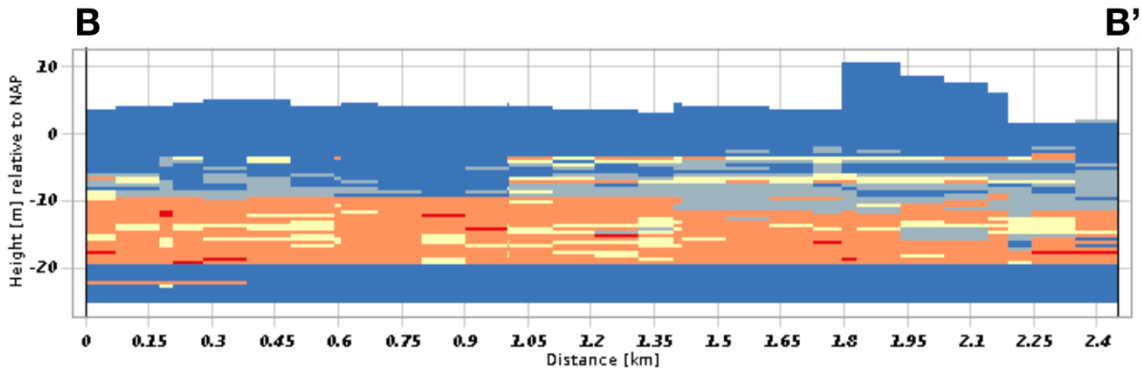
Appendix C.2 Each cross-section presents the probability of clay for each grid cell in that transect line up until 25 meters depth relative to NAP.



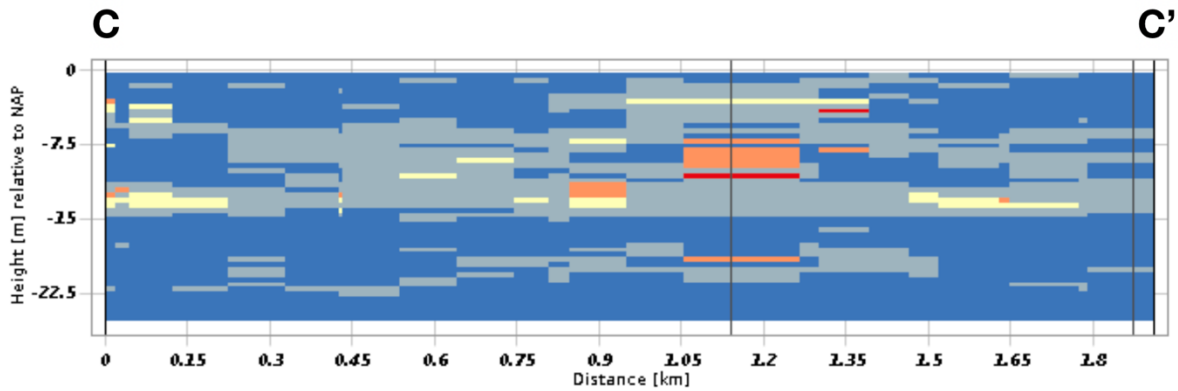
A-A'



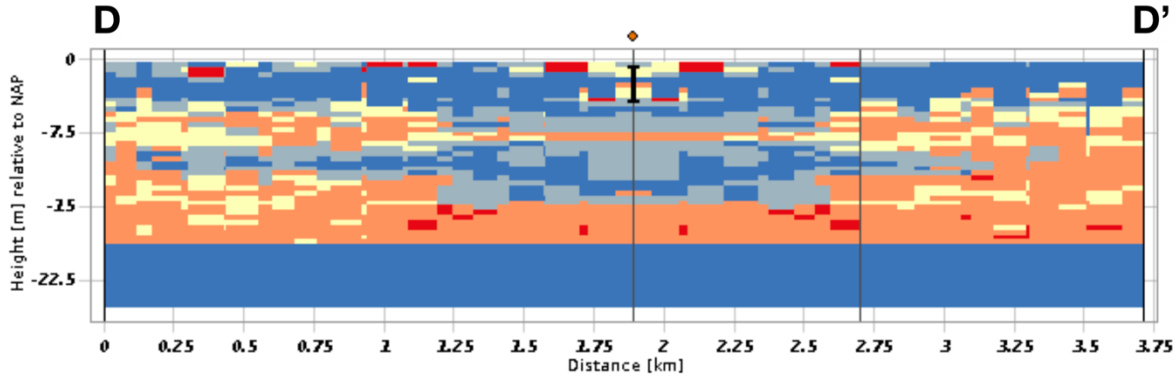
B-B'



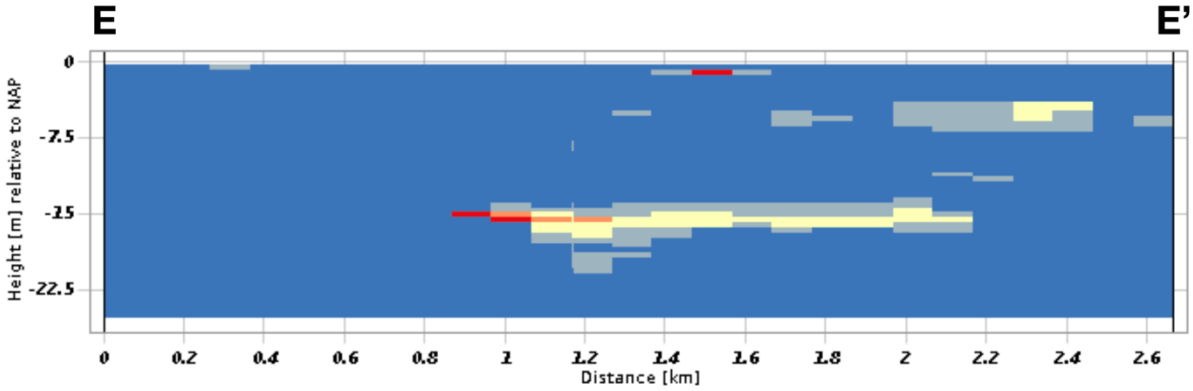
C-C'



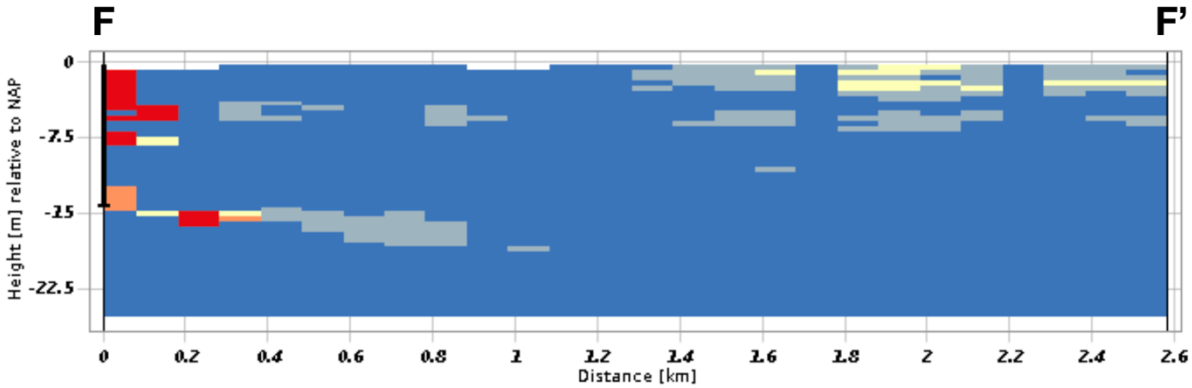
D-D'


D
D'
Height [m] relative to NAP
0
-7.5
-15
-22.5
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
3.25
3.5
3.75
Distance [km]

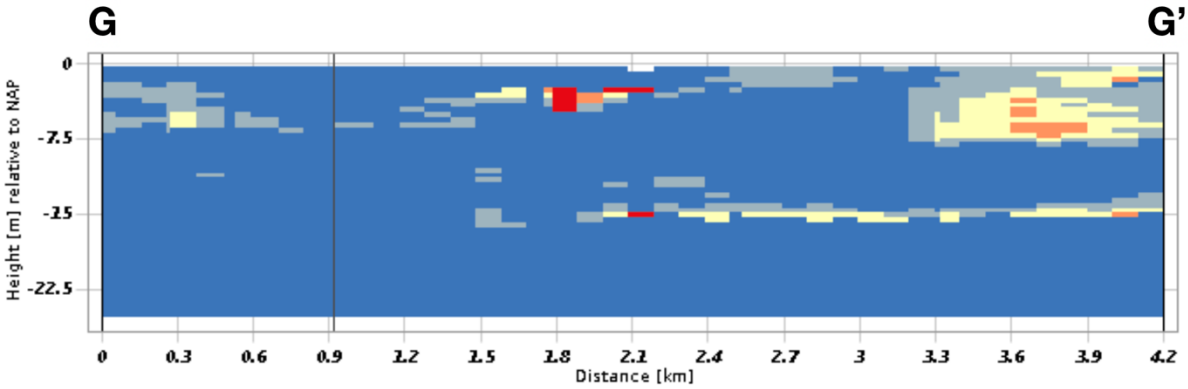
E-E'


E
E'
Height [m] relative to NAP
0
-7.5
-15
-22.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
Distance [km]

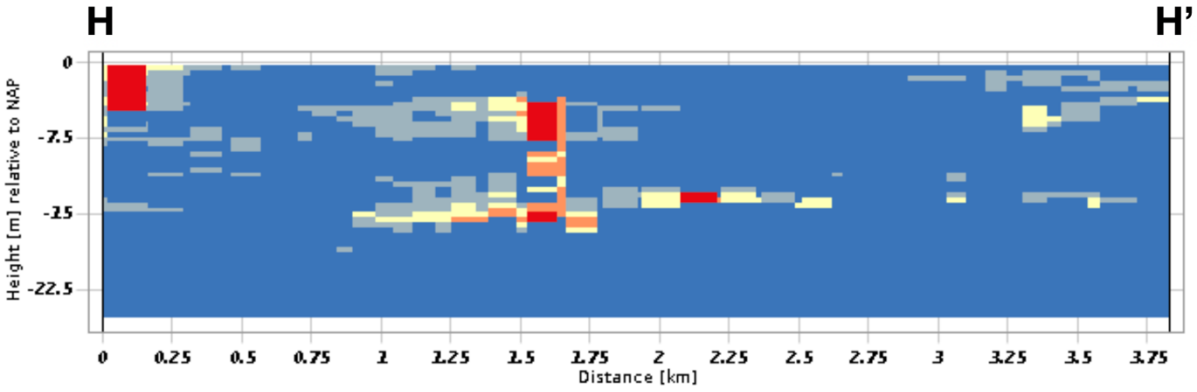
F-F'


F
F'
Height [m] relative to NAP
0
-7.5
-15
-22.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
Distance [km]

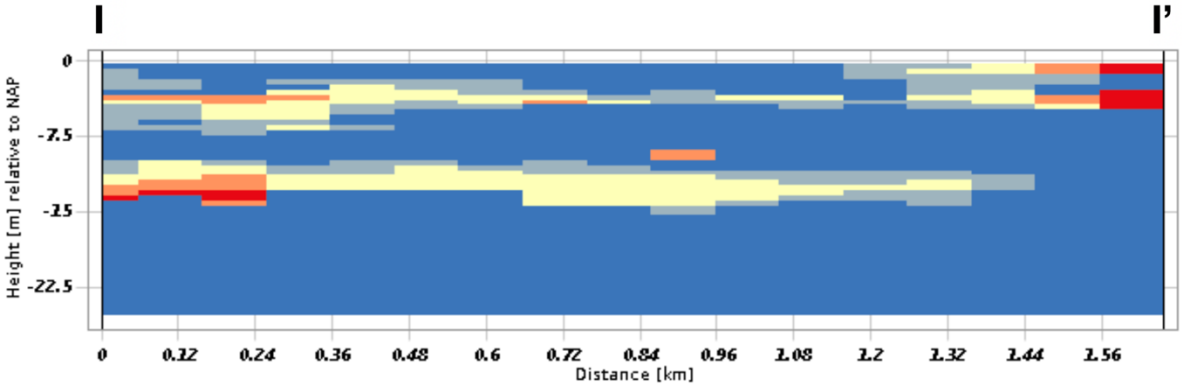
G-G'


G
G'
Height [m] relative to NAP
0
-7.5
-15
-22.5
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3
3.3
3.6
3.9
4.2
Distance [km]

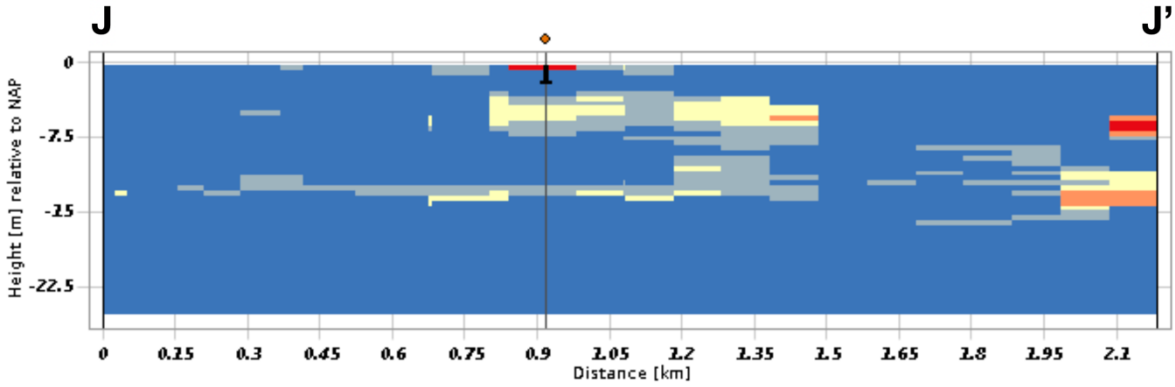
H-H'


H
H'
Height [m] relative to NAP
0
-7.5
-15
-22.5
0 0.25 0.5 0.75 1 1.25 1.5 1.75 2 2.25 2.5 2.75 3 3.25 3.5 3.75
Distance [km]

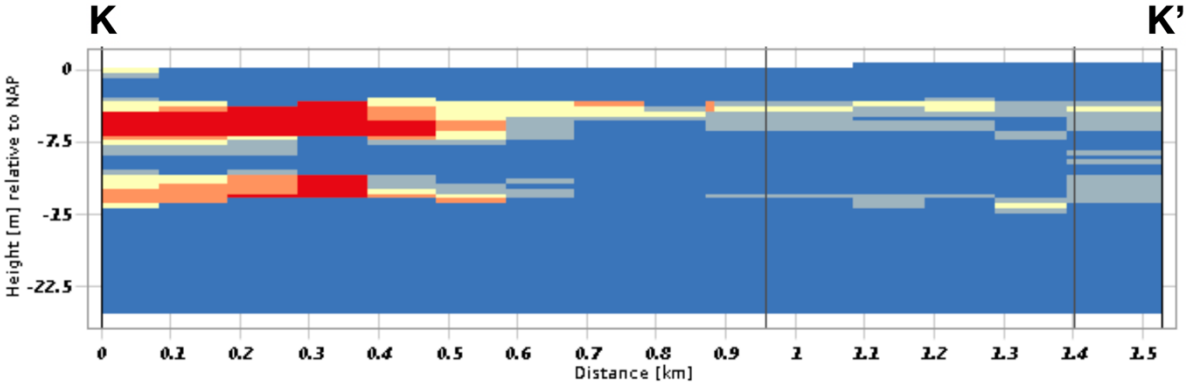
I-I'


I
I'
Height [m] relative to NAP
0
-7.5
-15
-22.5
0 0.12 0.24 0.36 0.48 0.6 0.72 0.84 0.96 1.08 1.2 1.32 1.44 1.56
Distance [km]

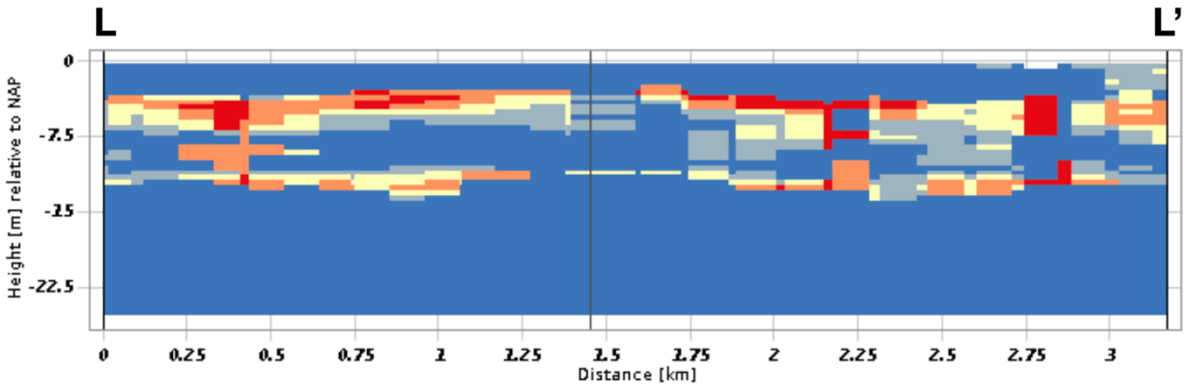
J-J'


J
J'
Height [m] relative to NAP
0
-7.5
-15
-22.5
0 0.15 0.3 0.45 0.6 0.75 0.9 1.05 1.2 1.35 1.5 1.65 1.8 1.95 2.1
Distance [km]

K-K'


K
K'
Height [m] relative to NAP
0
-7.5
-15
-22.5
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5
Distance [km]

L-L'

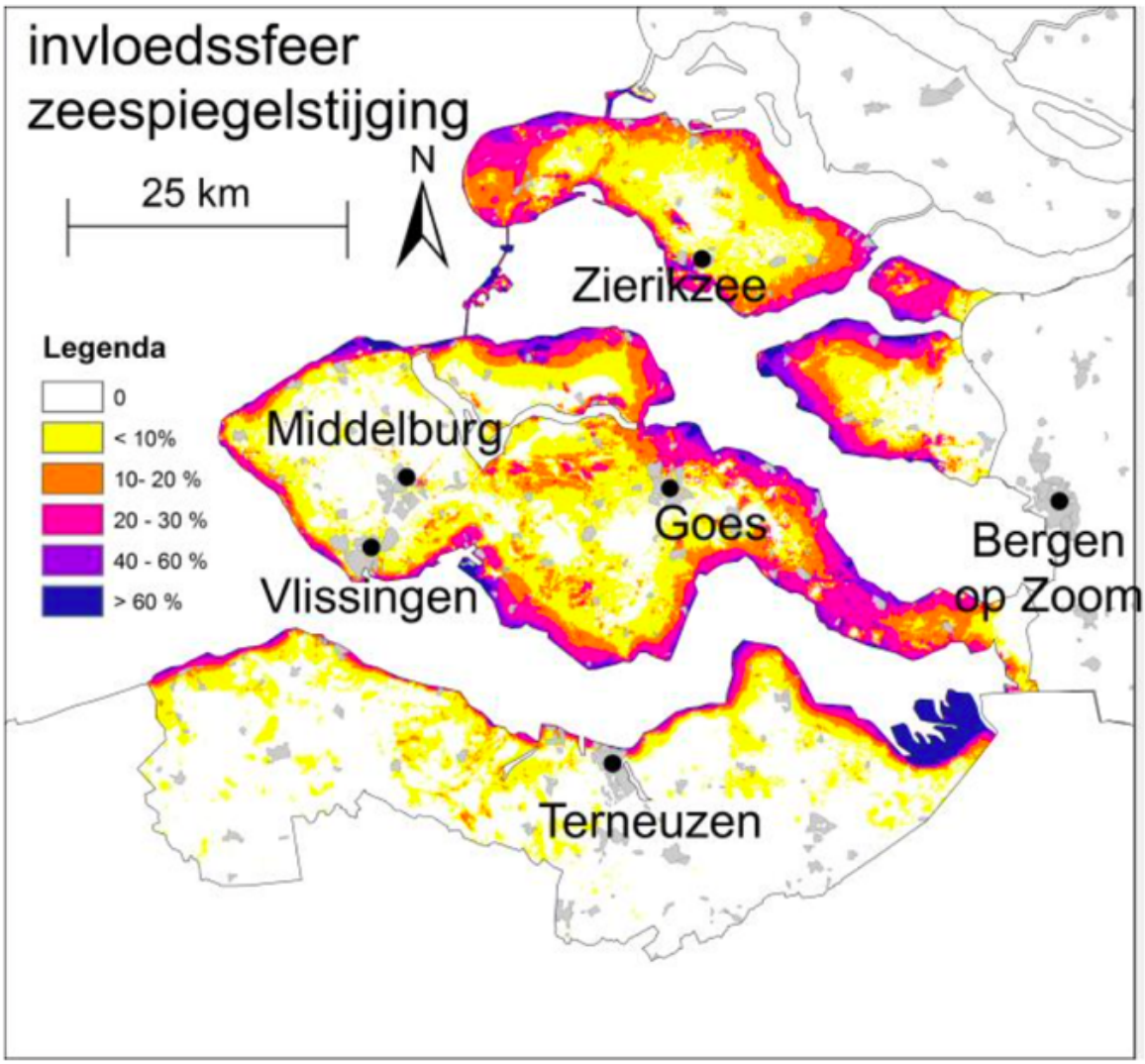


Appendix C.3 The table presents the qualitative suitability assessment of each of the cross-sections.

Cross-section	Suitable (Yes, No, Partly)
A-A'	No
B-B'	No
C-C'	Yes
D-D'	No
E-E'	Yes
F-F'	Yes
G-G'	Yes
H-H'	Partly
I-I'	Yes
J-J'	Yes
K-K'	Partly
L-L'	No

Appendix D. Impact of Sea Level Rise

Appendix D.1 Effect of SLR on the groundwater system in the Province of Zeeland under KNMI climate scenario WH as percentage of the total SLR (Van Baaren et al., 2016).



Appendix D.2 Table showing the relative decrease of the freshwater lens volume 10 ha around the abstraction point for six different SLR and abstraction scenarios (Oude Essink & Pauw, 2018).

Simulation	Relative decrease volume freshwater lens (in %)
SLR 10%, maximum abstraction volume	9.8
SLR 10%, realistic abstraction volume	9.4
SLR 20%, maximum abstraction volume	11.8
SLR 20%, realistic abstraction volume	11.0
SLR 40%, maximum abstraction volume	15.8
SLR 40%, realistic abstraction volume	15.5